# Design of a gearbox interface for robotic control of the SATA mechanism

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# Contents

**Abstract**

Minimally invasive robotic surgery adds benefits to the patients, such as reduced blood loss, less scaring and reduced hospital stay. From the literature research preceding this thesis, some of the major obstacles in robotic surgery are the high costs and limited reusability of the instruments. In order to have more affordable robotic surgery, there is a need for low cost robotics and easily cleanable instruments. The design project presented in this thesis represents a driver interface for robotic control of the SATA instrument and is divided into three detachable subassemblies: a motor unit, a cup interface and a gearbox with angular position feedback. This project also represents an upgrade to an existing design that contains the motors and the gearbox inside a single unit, without any sensorics. Design requirements and goals were establish at the start of the project. Possible solutions were designed in CAD and mapped into a morphological table. Each design obstacle had many possible solutions that were considered before choosing the best suited ones. Two prototypes were build out of aluminium and steel with PEEK bushings and 3D printed outer cases. The range of motion and lateral pulling force of the SATA instrument controlled by these prototypes were tested, together with the assembly-disassembly times and shaft coupling times between the gearbox and motor unit shafts. The experimental results showed very low gearbox exchange times and low coupling times with learning curves that prove the ease of use for new users, all translating into a design that allows fast instrument exchange during surgery. The design requirements were met and physical prototypes built and tested, proving the concept works and is suited for the operating room, heading towards affordable robotic surgery.

# 1 Introduction

## 1.1 Robots and robotic surgery

Robots have become a normality in many fields, including medicine. While laparoscopic surgery showed its benefits compared to open surgery, the next step is to have laparoscopic instruments held and manipulated by robots. The use of laparoscopic instruments brings a lot of benefits to the patient, including reduced blood loss, less scaring (Fig. 1) and reduced hospital stay [1]. Robots can have their instruments made very small and can reach narrow spaces inside the patient that were very hard or impossible to reach with other instruments [2]. The dexterity of robotics could help overcome the human limitations in the medical field, like physical fatigue of the surgeon, range of motion and dexterity. Operational, clinically approved surgical robots have extra features like a mobile platform in order to be better positioned next to the patient and additional appendages with surgical instruments attached that are used directly on the patient during operations. The firmness and precision of the robot overcomes the human limitations in this case, improving laparoscopic surgery. Another improvement done to laparoscopic surgery by making it robot-assisted is the physical fatigue of the surgeon. Surgeons report overall less pain with the robotic surgery compare with open and laparoscopic surgery [3,4]. Because in normal laparoscopic surgery, the surgeon holds the instruments directly while standing next to the patient. In robotic surgery, the surgeon controls the robot indirectly while sitting down and having arm rests. Because of the comfort difference of the positions, robotic surgery is less likely than open or laparoscopic surgery to lead to neck, hip, back, knee, ankle, foot and shoulder pain and less likely than laparoscopic to lead to elbow and wrist pain. However, robotic surgery is more likely than either to lead to eye pain, and more prone to finger pain than open surgery [3]. Between 73% and 100% of laparoscopic surgeries are associated with musculoskeletal disorders, but only 23% to 80% for robotic surgery [5]. This shows another advantage of robotic surgery over laparoscopic.

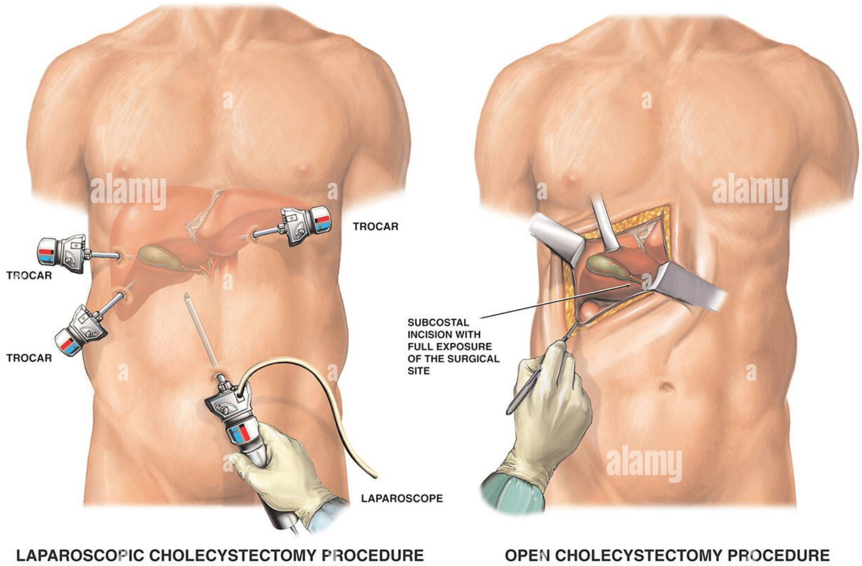



Figure 1: Incision size comparison for cholecystectomy open and laparoscopic surgery [6]

## 1.2 Robotic surgical instruments

When the laparoscopic instruments made the transition to robotics, all the motions that were controlled directly by the surgeon through the instrument's handle (Fig. 3) needed a dedicated actuator so they could be controlled indirectly through the robot. Depending on the number of the degrees of freedom (DOF), the motors need to actuate one or more bending joins, as well as various motions of the instrument. The number of motors is equal to the number of motions or DOF. Motors are heavy and bodily fluids and tissue can short circuit or mechanically block their inner parts. This is why they are not installed on the instrument sections that go inside the body, or close to that end. Laparoscopic instruments are long and thin(Fig. 3), having a distal section going inside the body, and a proximal section outside, on which the movement controls are mounted, either manual like the gears in the handle or electromechanical, like motors.

Sterilization is an essential step in clinical practices to reduce or even eliminate the presence of microorganisms and thus prevent patient exposure to infections and contaminations. Biomedical devices are in direct contact with the patient's tissue and biological fluids and therefore must be sterilized to remove pathogens (bacterial, viruses, fungi and other forms of microorganisms) [7]. The process of sterilization has the goal of inactivating said pathogens by the denaturation of protein and nucleic acid with the consequent deterioration of the cell membrane [8].

Even if the motors were unaffected by the tissue, they would still need to be cleaned and sterilized (C&S), and if the tissue did not damage them, the chemicals and hot temperatures would. For this reason, the currently available surgical system have a clear separation of the motors from the rest of the instrument, allowing the latter to be changed, C&S without affecting the motors. This physical barrier that separates the dirty parts from the clean parts is commonly known as a "drape" in the robotic surgery world and is usually a thin plastic sheet [9].

The motors and the instrument are dirty and clean respectively, therefore they have to sit at opposite sides of the drape (Fig. 2). That means that the transmission from the motors to the instrument has to pass through the drape, along with any other electrical signals from possible sensors.

Because the moving parts, including the instrument tip are far from the motors, such systems need a power transmission mechanism. This transmission can have many forms, cable transmission being the most common one used in the most commercial surgical systems: da Vinci worldwide, Versius in Europe and Hinotori in Japan, all approved for clinical use [10]. Each motor has its own cable that runs around a series of pulleys (Fig. 4) and its kept under tension to minimize backlash.

Cable transmission works well in terms of motion, but the small pulleys and moving cables create the perfect spaces for blood and body tissue to get caught. For that matter, there are special cleaning procedures in place that have to be followed after every surgery go get the instruments as clean as possible [11]. Such procedures are not perfect, as some of the dirt can be stuck inside the instrument. This is why cable instruments have a limited number of uses before they need to be thrown out.

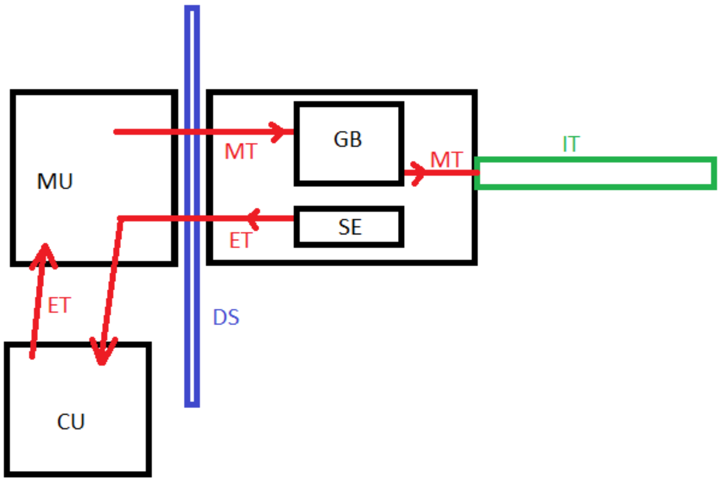



Figure 2: Schematic of the theoretical drive unit. MU - motor unit; CU - control unit; GB - gearbox; SE - sensor; IT - instrument; DS - drape separation; MT - mechanical transmission; ET - electrical transmission

Figure 3: Handle version of the SATA

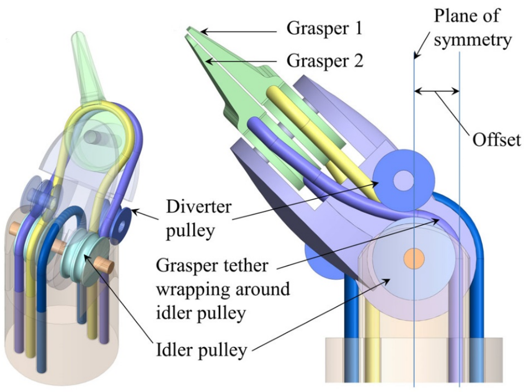



Figure 4: Cable routing in a pulley actuated EndoWrist

### 1.3 SATA and previous gearbox

The Shaft Actuation Tip Articulation (SATA) mechanism (developed by Surge-On Medical) does not use cables, which allows it to be disassembled, cleanable and modular. Its mechanism is suited for motor actuation because almost all of its DOFs are based on rotation.

The SATA instrument (Fig. 5) needs 4 DOF controlled:

- Translation of the inner shaft which closes the forceps (Fig. 6);
- Rotation of the outer shaft against the middle shaft which bends the joint (Fig. 7);
- Rotation of the inner shaft which rotates only the tip forceps (Fig. 8);
- Rotation of the whole body (Fig. 9);

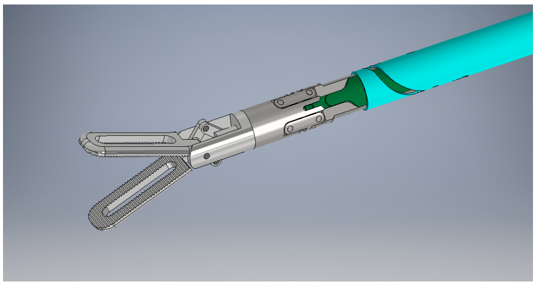


Figure 5: SATA mechanism, nominal position

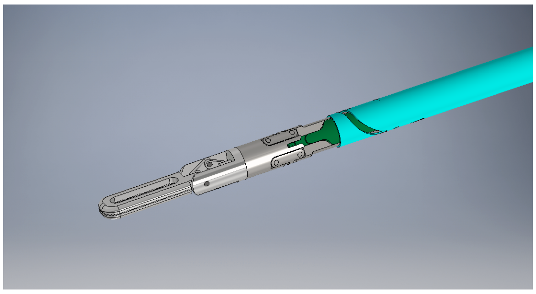


Figure 6: SATA mechanism, tip closed

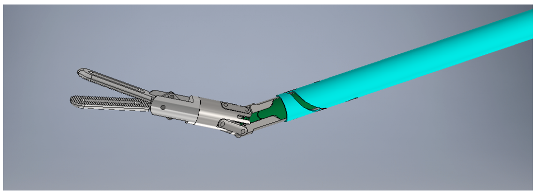


Figure 7: SATA mechanism, bent joint

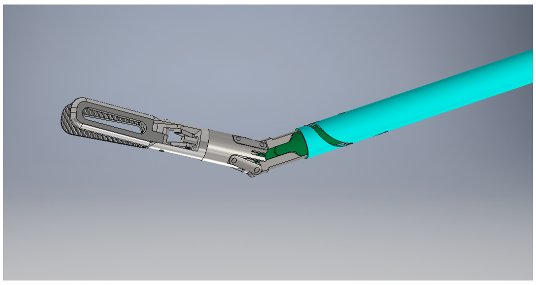


Figure 8: SATA mechanism, rotated tip

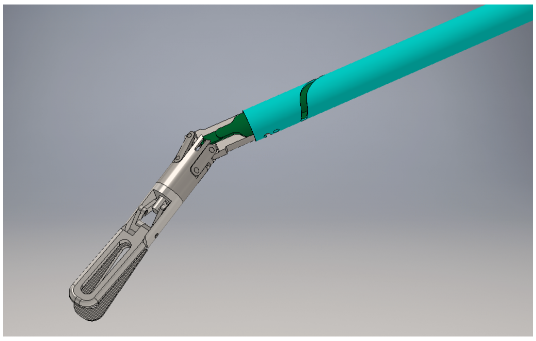


Figure 9: SATA mechanism, rotation of the whole instrument

Previously, it was used as a hand held laparoscopic tool, but the need to control its movements more precisely via a robotic system had lead to the first robotic version, further referred in this paper as "Version 1". Version 1 (Fig. 10) had the motors and the gearbox in the same package (Fig. 14, a). Because the motors would have been affected by the cleaning and sterilization, the instrument detached before the entry point in the gearbox, using a puzzle piece connection. The instrument had to be taken out for exchange towards the patient, which meant that the whole mechanism had to be pulled out by the robot and oriented differently for the exchanged. The additional mechanical weakness induced in the instrument shafts by the cutting of the puzzle piece connection reduced the mechanical strength of the instrument.

In this thesis, a new version of the SATA drive will be made, which will seek to improve these remaining issues.

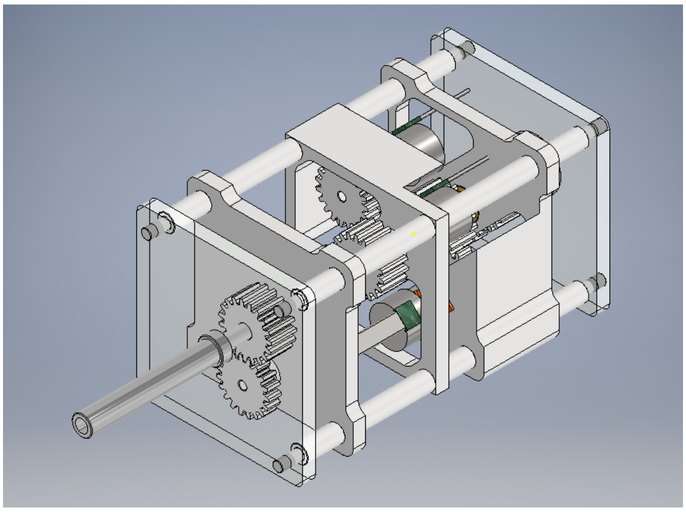


Figure 10: Version 1 with the motors and the gearbox in the same unit

## 1.4 Kinematic chain and idea of motion

To observe the kinematic chain, a preliminary new design was made with the instrument oriented backwards, towards the motor unit. The reason for this was the possibility of changing the instrument by unlocking it away from the patient, without modifying the robot's position. The chosen way of assembly was the one depicted in Fig. 14, c, making it easy for the medical staff to quickly change the instruments on the robot with the gearbox attached, and allowing for separation of the instrument from the gearbox for the cleaning process. Four sets of gears were made, one for the outer shaft (Fig. 13, blue), one for the middle shaft (Fig. 11, orange) and two for the inner shaft (Fig. 12, red and green) because this one needs two types of movements. Figures 11, 12 and 13 show the initial design that was made as a reference for the kinematic chains of the gearbox.

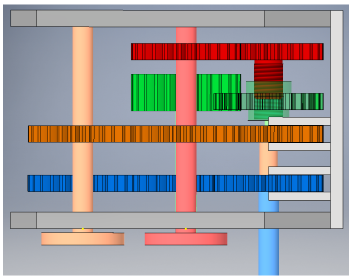


Figure 11: Initial design, left view

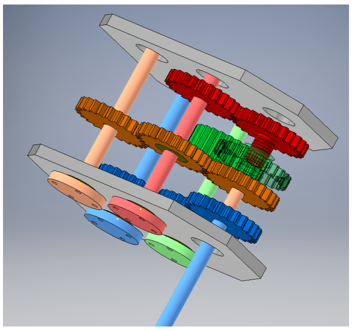


Figure 12: Initial design, isometric

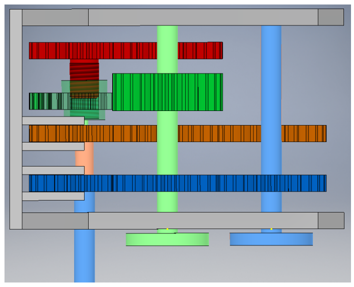


Figure 13: Initial design, right view

## 2 Design requirements

The new gearbox interface, further referred in this paper as "Version 2", needs to be a driver for the SATA instrument, that can be used for robotic surgery. For that, it needs some additional features compared to Version 1, together with some improvements. The features will make Version 2 more suited for C&S, add position feedback and improve the ergonomics, among other things. For a better separation of the clean/contaminated parts, the driver will be split in two: the motor unit and the gearbox unit that holds the instrument. The instrument will also be quick released from the gearbox unit, ultimately making Version 2 be separated into three major components (Fig. 14, c). The decision for separating the motors came as a need for sterilization. The decision to also split the instrument from the gearbox allows for easier cleanability, but also for modularity, not making the instruments dependant to one gearbox. Since the instrument is considered dirty after use and needs to be cleaned and sterilized, so does the Version 2. However, to avoid damage with the included electronics, the instrument and the gearbox could be cleaned on their own, without the electronics. This means that the gearbox should be designed for sterilization, while the motor unit should be easily detachable, with a simple gearbox-motor coupling. The starting requirements are summarized in the following list:

- Include a quick release system of the gearbox from the motors;
- Include a quick release system of the instrument from the gearbox;
- Include position feedback from all the movements, from as close to the end-effector as possible;
- Individually control of three rotations and one translation of the SATA instrument
- Allow for easy and quick detachment of the electronics so they are not damaged during sterilization, or make them sterilizable;

- Include a form of wire management for the sensors and other electronics;
- Include a form of quick connection-disconnection of wires that cross the interface between detachable components;
- Allow for sterilization without affecting functionality;
- Allow for backwards decoupling;
- Allow for the integration of a drape between the motor unit and the gearbox;
- The assembly-disassembly should not require additional tools;
- The parts should be secured in place and not come off accidentally;
- The actuators should allow for controlling the full range of motion of the SATA;

## 2.1 Design goals

- Be as compact as possible;
- Be as light as possible, preferably no heavier than than the previous design, 700g;
- Instrument shafts exchangeable with the handheld version;

The design requirements will guide the design process, having the design goals as convenient additional features once the requirements are met.

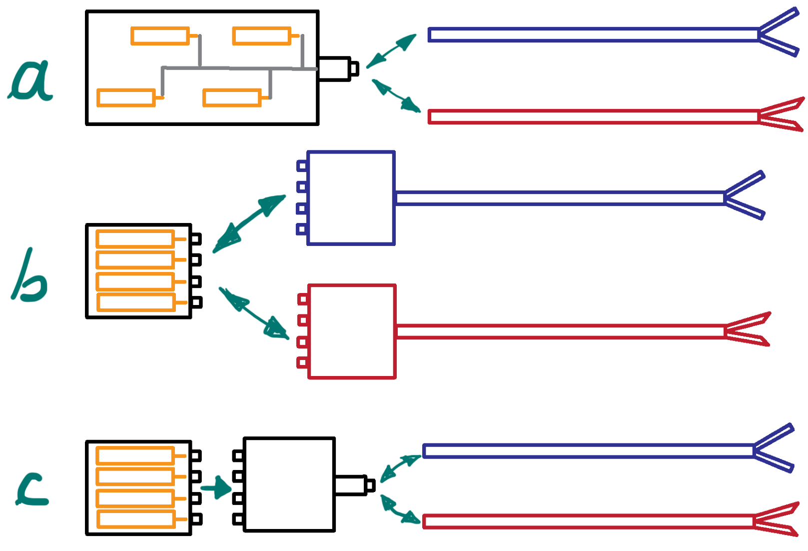



Figure 14: Components assembly a)Initial design with motors (orange) and gearbox in the same package b)Instruments with their own gearbox c)Separate motor house, gearbox and instruments

# 3 Conceptual design

The design requirements can be divided into smaller problems which can be taken care of individually. Bellow, the design challenges are listed together with their respective potential solutions. Instrument attachment to the gearbox

- Driver gear attachment to the middle and outer shafts of the instrument. This is required to be done with a quick release system for easy detachment of the instrument;
  - Fused connection, with dedicated gears attached to each instrument shaft
  - In-gear key, similar to the handheld version, but using a gear that meshes with other gears
  - Parabolic cone, that acts as an interference fit between
  - Fork key, inserted radially and locks the rotation of the instrument shaft
- Driver gear attachment to the inner shaft of the instrument. Goes hand in hand with the previous point, but because the inner shaft needs to both translate and rotate, the attachment method has to be different;
  - Collet system, similar to the one used in the Version 1
  - Bearings + transversal screw lock, method used in coupling motor shafts
  - Threaded in, larger parts that act as gears and have also threaded shafts/holes
- Main gears detachment. If the instrument has to be detached from the gearbox, the main gears that attach to the instrument can either come out with it, or they can remain in the gearbox;
  - 4 bearings clover, uses bearings for fixing position and allowing rotation
  - Detachable piece of case, which holds the instrument
  - Detachable gears from both shafts and other fixed gears
  - Main gears not detachable from the gearbox

Sensor types and attachments

- Sensor type. It influences both the attachment method and the precision of the angular position feedback;
  - Optical, which detects light interruptions through a marked disc
  - Magnetic/hall, which detects the direction of the magnetic field
  - Inductive, similar to the magnetic sensor
  - Mechanical (potentiometer)
- Encoding type. Affects the repeatability of the driver;
  - Absolute, always knows its position
  - Incremental, it does know where it is, but knows how much it rotates
- Sensor positioning on the device. Affects how much error is accumulated from the instrument tip all the way through the kinematic chain to the sensors;

- On the back of the motors, easy to mount but adds the most errors
- On/near the driving gears, adds the least amount of errors, but hard to mount
- At the end of the shafts, relatively easy to mount and does not accumulate much error

- Wire management. Besides aesthetic reasons, wires management can prevent tangling;
  - Lateral tunnel embedded in case, relies on a complex 3D print
  - Wires on the side of the case
  - Inner tunnel between gears, separate part from the rest of the case

Interface (cup) attachment

- Separation clean-contaminated. Affects how well the interface performs;
  - Simple drape, without any cup, placed between the motor unit and the gearbox
  - Drape inside cup, siting securely between two halves of the cup
  - Long cup, guided by rails
  - Small cup with hooks, guided by hooks
  - Small cup with click hooks, guided by grooves and secured by click hooks
- Interface attachment. It must guide the interface in the right position without additional tools;
  - Guide rails
  - Magnet attachment
  - Push in stops, based on the compliant switch mechanism
  - Lateral clips, integrated in the motor unit
  - Inner clickfinger, integrated in the cup
- Motor transmission through cup. It must couple the motor shafts with the gearbox shafts through the cup while shifting the position of the instrument as little as possible;
  - Plate with matching grooves and pins
  - Plate with spring loaded pins
  - Hexagon shaped shafts
  - Rays

Others

- Bushing type/material. Allow for sterilization without losing mechanical properties;
  - Ball Bearings
  - Brass bushings
  - Teflon bushings
  - PEEK bushings
  - Aluminium bushings

## 3.1 Morphological overview

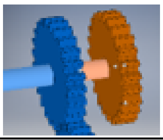
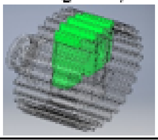
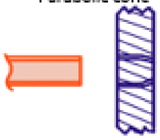
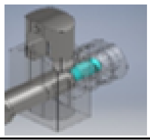
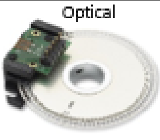
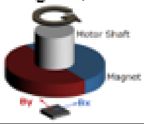
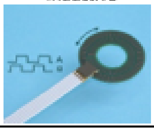
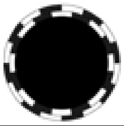
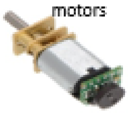
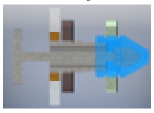
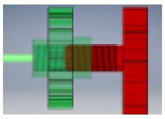
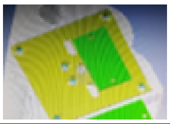
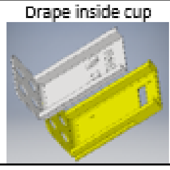
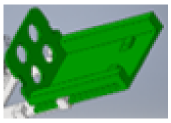
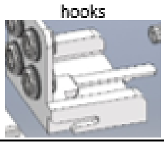
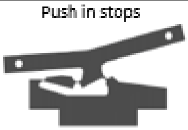
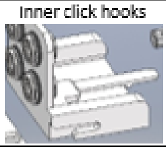
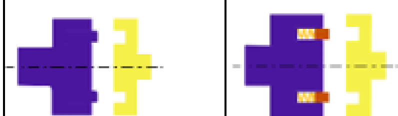
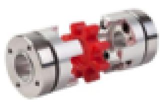
| | Solution 1 | Solution 2 | Solution 3 | Solution 4 | Solution 5 |
|---|---|---|---|---|---|
| Driven gear attachment to the main shafts (middle and outer) | Fused connection  | In-gear key  | Parabolic cone  | Fork  | |
| Sensor type | Optical  | Magnetic/hall  | Inductive  | Mechanical (potentiometer)  | |
| Encoding type | Absolute  | Incremental  | | | |
| Sensor positioning | On the back of the motors  | On the/near the driving gears  | At the end of the shafts  | | |
| Attachment of the inner shaft | Collet system  | Bearings + transversal screw lock  | Threaded in  | | |
| Main gears detachment | 4 Bearings clover  | Detachable piece of case  | Detachable gears from shafts and fixed gears  | Main gears not detachable from gearbox | |
| Wire management | Lateral tunnel embedded in case  | Wires on the side  | Inner tunnel between gears  | | |
| Separation clean-contaminated | Simple drape  | Drape inside cup  | Long cup  | Small cup with hooks  | Small cup with click hooks  |
| Interface attach | Guide rails  | Magnet  | Push in stops  | Lateral clips  | Inner click hooks  |
| Motor transmission through cup | Plate  | Plate with spring | Hexagon  | Rays  | |
| Bushing type/material | Bearings  | Brass bushings  | Teflon  | PE EK  | Aluminium  |

Table 1: Morphological overview

## 3.2 Concept generation

The elements in the morphological table were explored and evaluated. In the following section, possible concepts are compared for the various design problems they need to solve. When choosing a concept, its interaction with the other solutions was considered so there are no conflicts. After all the concept solutions were sorted out, a final design assembly was made in Autodesk Inventor.

# 4 Concept solutions

## 4.1 Main gears attachment

One of the starting conditions was to make the instrument detachable from the gearbox for easier C&S. The transmission from the motors to the instrument is done with spur gears, so the gears coaxial with the instrument had to either be removed with the instrument in a way that they could mesh back at reattachment, or stay in place while the instrument is removed without displacing them. For the first way the gears had to be rigidly connected to the SATA shafts while the driven gears (the ones coaxial with the instrument) had to have a mechanical holding point that allow for removal. The "main gears detachment" row in Table 1 shows some of the earliest ideas: a detachable piece of the case that holds all four of the driven gears, a four bearing assembly that holds the shafts in place and a way to lock in the SATA shafts inside on e of the driven gears. In the end, because of the additional alignment and meshing problems that could arise from removing the driven gears, the decision was to make them fixed in place and remove just the instrument. Because the inner shaft of the instrument has to both translate and rotate, its attachment method was made different from the attachment of the other two shafts. The next two subsections are dedicated to them.

## 4.2 SATA middle and outer shafts attachment

The previous gearbox had a puzzle piece connection that made the instrument removal possible before it entered the gearbox, but weakened the instrument's strength. Alternative to the puzzle piece can be found in Table 1, in the first row. The ideas had to keep the shafts relatively intact. A fused connection was tied to the removal of the driven gears. The parabolic cone solution meant pushing the shafts inside the gears, but this solution was based on friction for rotation lock and it risked damaging both the gear and the instrument. The in-gear key lock was adapted from the handheld version, but the button-key had to be integrated in the gear which raised meshing problems. In the handheld version, the corresponding gear was turned by hand and did not mesh with other gears. Finally, to adapt this to the current gearbox, the button-key was made smooth and the chamber in which the button is pushed was separated from the gear, allowing for a significantly thinner gear. Because now the instrument had to be fashioned in a similar way to the handheld version, additional adjustments made to the two chambers with fork locks made Version 2's and the handheld version's instruments interchangeable. The engaging buttons and button chambers in Fig. 16 and 15 were devised. Inside the chambers there are springs that push the buttons up. In this unpushed state (Fig. 15), the lower part of the button, shaped almost as a fork, is in contact with the flattened, parallel walls machined in the outer and middle shafts of the SATA for coupling purposes. When the buttons are pushed, the spring is compressed and the middle hole of the buttons becomes concentric with the SATA shafts, disengaging their rotation and allowing for sliding them out (Fig. 17).

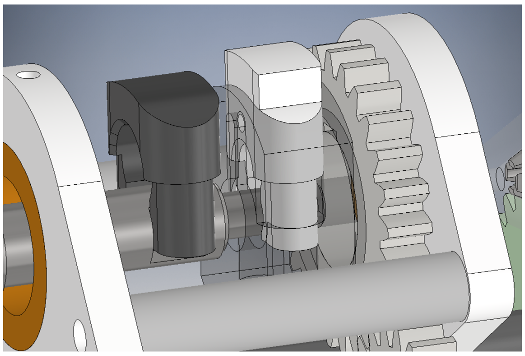


Figure 15: Version 2.0, engaging buttons, not pushed. In this state they are engaging the exterior and middle cylinder of the SATA instrument

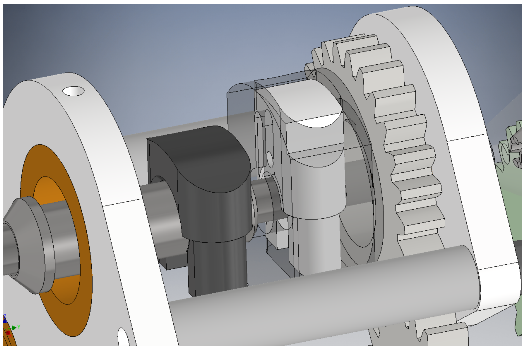


Figure 16: Version 2.0, engaging buttons, pushed. In this state the instrument can be removed

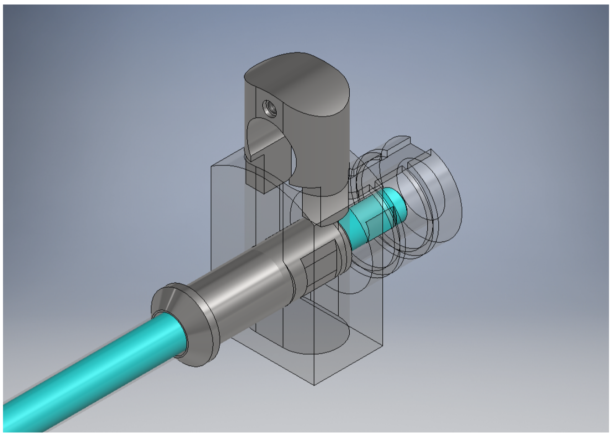


Figure 17: Locking button concept

## 4.3 SATA inner shaft attachment

The inner shaft of the SATA has to both rotate and translate. For that reason the initial design idea was to use two threaded gears (Table 1, attachment of the inner shaft row) while the inner shaft being locked to one of the gears. The decision to make the instrument removable without the gears lead to attachment options, the simplest one being a transversal screw lock. Later, the collet system used in Version 1 was integrated because it did not require additional tools. The collet head (Fig. 18, highlighted in blue) had a conical shape, which occupied a lot of space, while the space inside the rest of the collet was barely used at all. The collet tail (inside the collet head) was built fragile, with very thin bending points that could be easily broken. Version 2.5 brought a new collet, without the conical shape of the collet head (Fig. 23) and a stronger collet tail. A section view of the new collet can be seen in Fig. 29. The final version was a more compact version that made the whole gearbox shorter.

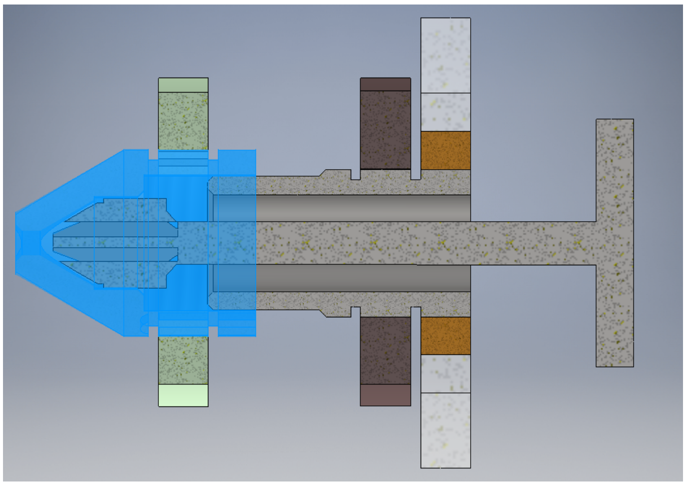


Figure 18: The collet system that holds, pulls and rotates the inner shaft of the SATA

## 4.4 Clean-contaminated separation

The instrument will need to operate inside the patient and for that reason is considered clean. The gearbox is cleaned along and is also considered clean. The motor unit which cannot be cleaned is considered dirty. These parts need to be separated by a physical barrier, in order to keep the instrument clean from the motors and the robot, but also to prevent blood and other tissue to travel up to the motors.

A plastic drape is the "barrier of choice" used by surgical systems on the market. The drape partially covers the robot arm as well for a better isolation. There are some problems that can arise if the cleaning and draping are not done properly, like iatrogenic disease (illness induced by medical treatment) [12]. The drape all by itself has another flaw: it can be torn apart by the rotating shafts that pass through it, or it can block said shafts. The shafts can also transmit contaminants through the drape. Adding O-rings to the shafts to flank the drape was briefly, considered, but the flexibility and the small thickness of the drape did not allow for that. A plastic piece (cup) that would act as an built-in-drape interface between the motor shafts and gearbox shafts was then considered. The cup would be equipped with bushings and hubs that connect to the shafts, but do not allow cross-contamination. One of the starting ideas was to make the cup with two halves that would catch the drape in between, but the desire for simplicity and as few parts as possible lead to a single-body cup. The drape could be then secured between the cup and the motor unit's case. The next cup (Fig. 19, green) had guidance rails to attach to the motor unit and hooks to attach the gearbox. The side through which the shafts pass is essential, while the other side (at a 90° angle) not so much. The latter acts like a guide for the gearbox and the hooks on it stop the gearbox from pressing its shafts too much on the cup and motor unit. It is not essential to have that side very long, so in Version 2.2 the cup is significantly shortened (Fig. 20). The motor unit has been modified so it has metal prongs (Fig. 33) that slide inside the cup, rather than on the side, like in Fig. 19.

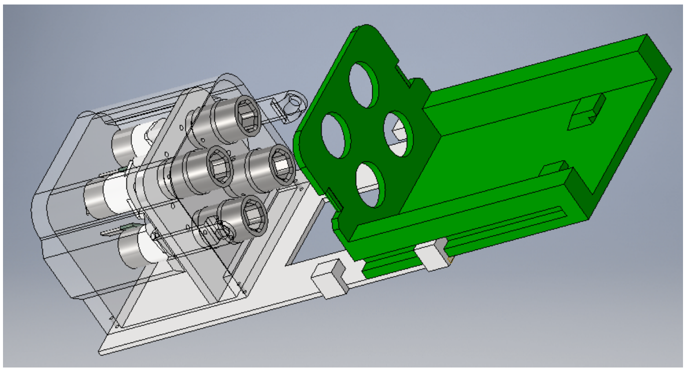


Figure 19: The interface cup (green) of the version 2.0

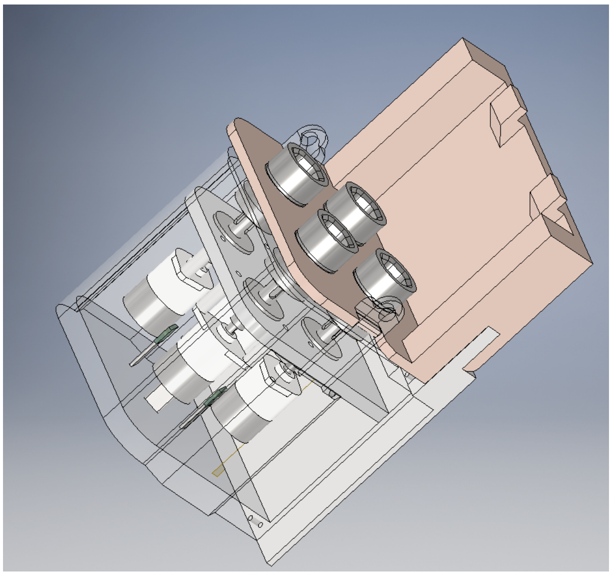


Figure 20: Version 2.2 redesigned shorter cup

## 4.5 Interface attachment

The cup fitted between the motor unit and the gearbox, but nothing was holding them together in case of an external force. In working positions, the cup sits above the motor unit and the gearbox above the cup, so without the instrument pushing against anything, the system will stay assembled. Nevertheless, an external force was still a possibility, leading to a need for a locking method that was easy to unlock if needed but which could prevent accidental detachments. The earliest idea involved magnets for locking, but the stronger the magnets were, the more secure the system, but at the same time harder to unlock if needed. Simple friction with guide rails (Fig. 1, Interface attach) was also lacking a proper locking method, relying solely on friction and gravity. Another proposed method was the use of a compliant mechanism that forms a switch lock (Fig. 1, Interface attach, Push in stops): The metal part from the motor unit that provided guidance in the cup would have a small indent, in which a small hook from the compliant mechanism would enter, locking the cup on the motor unit. The compliant mechanism would act like a simple switch that could be flicked on and off to lock the system. This design was dropped because the cup needed to have a relatively simple design that could be eventually injection molded, while the compliant mechanism was complex and hard to manufacture. Swing bold nuts were also briefly considered, but they required too much time to screw/unscrew. Figure 20 shows another feature: the clickhooks that hold the cup to the motor unit (showed transparent in the figure). They can be pulled on the sides in order to release the cup and bend on their own and click in place when the cup is pushed back in. Version 2.3 added clickhooks for the gearbox as well (Fig. 21), having the same principle. Previously, the cup had only plastic hooks that did not bend and did not prevent the gearbox to be removed by accident. While being upside down and kept in place by gravity, the gearbox could still be pushed out by mistake if the instrument would hit something solid. As the version progressed, the gearbox's got two hooks in 2.4 (Fig. 22), two hooks farther apart in 2.5 (Fig. 23) and finally settled for one big clickhook from version 2.6 on (Fig. 24). The final version has the one big clickhook for the gearbox and two smaller clickhooks for the motor unit (Fig. 25, yellow).

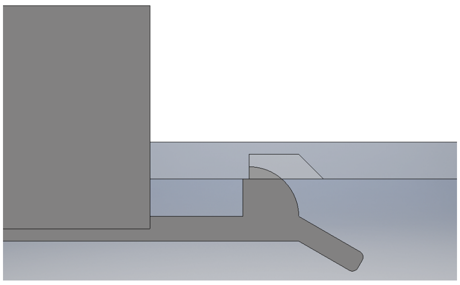


Figure 21: Locking click hook for locking the cup to the gearbox in Version 2.3

## 4.6 Transmission through interface

The transmission method from the motor unit to the gearbox began with two requirements: it had to be easy to assemble and easily correct misalignments. The first requirement is simple because it is just a matter of shape matching. For that, coupling plates or hexagons (Fig. 1, motor transmission through cup) are good enough. However, if the shafts are not perfectly aligned, the coupling geometry will not fit. Fillets and chamfers present in the geometry offered a little compliance, but was still

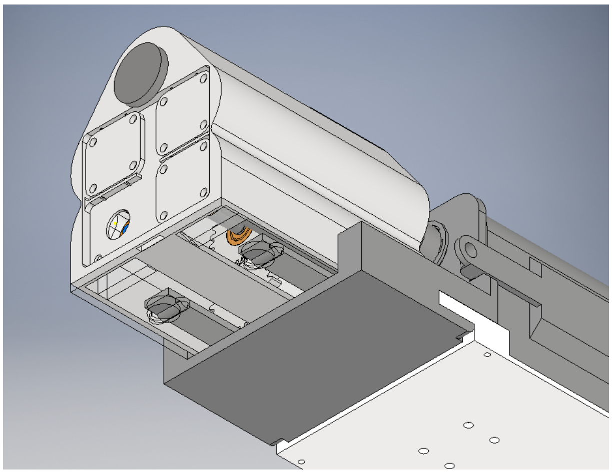


Figure 22: Double click hooks and sensor positioning fixed in the case in Version 2.4

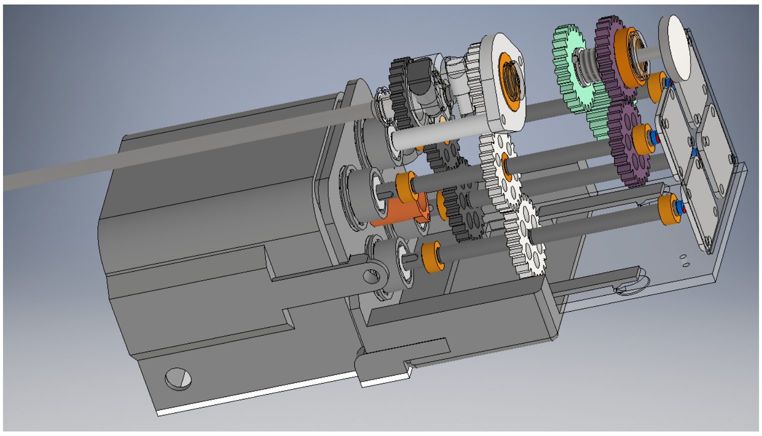


Figure 23: Version 2.5 with redesigned collet

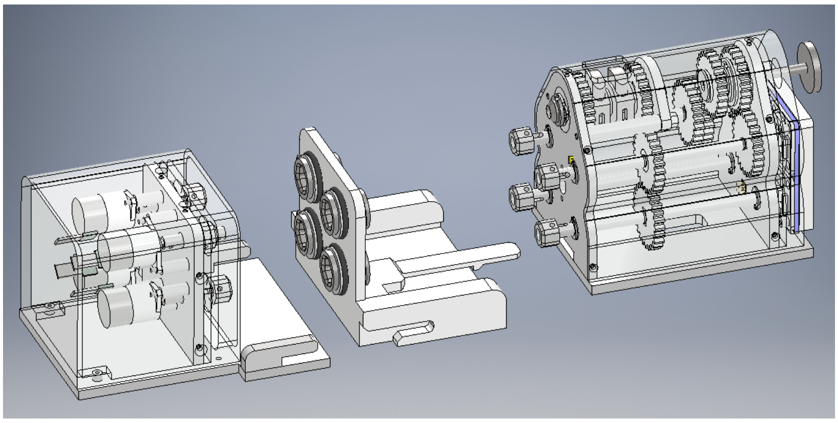


Figure 24: Total assembly of Version 2.6, with one click hook for the cup

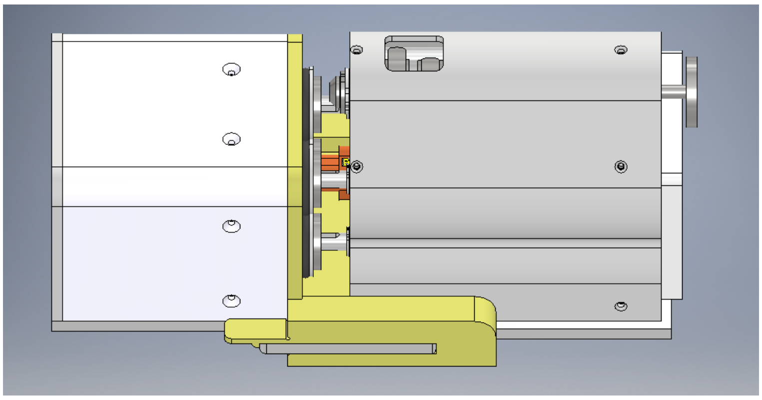


Figure 25: Version 2.8 with click hooks on the cup (yellow) to lock the motor unit

not enough. The solution came from spring loaded parts: as the parts are pushed together, one of them will be spring loaded. After the assemblies are locked, even if the shafts are not aligned, they will still be assembled and coaxial, but misaligned and with a compressed spring. After that, the motors can slowly begin to rotate, correcting the misaligned shafts, which will snap in place at the alignment moment. The springs do two things: they allow the assembly of the larger parts without the need for proper alignment, thus saving time and push the coupling parts into place as the motors align them. The motor travel for alignment depends on the used shape. Here, a third design requirement appeared: in a real situation, during instrument exchange during surgery, the shafts cannot turn indefinitely because of the instrument alignment and range of motion. Therefore, the alignment correction has to be done in as few degrees as possible. Later designs settled on the hexagon coupling. The hexagon geometry is allowing the shafts to couple in maximum 60° of travel in any direction. 30°in either direction if the motors go back and forth. Additional chamfers and fillets in the geometry also help reduce those numbers.

## 4.7 Sensor type and positioning

Stepper motors are in general very precise, but under load or current fluctuations they can skip steps. Without a form of position feedback, the skipped steps will add position error and result in imprecise movements of the instrument. A rotational encoder solves this problem by knowing the position of the instrument shafts in degrees, so in the eventuality that a motor skips steps, the encoder will tell the controller that the target position has not been reached so the controller can add extra steps. The motor's "zero" position resets at every power up, so it is important that the used encoder shows the absolute position. The starting conditions for the sensors were to allow absolute encoding and to be easily detachable from the parts that will be sterilized to prevent damage to the electronics. Mechanical potentiometers are precise and resistant, but they need a good attachment to the rotating shafts. They are also hard to turn compared to other types of sensors, which could add unnecessary load on the motors. To respect the second condition, the decision was made to use non contact sensors, which have a first part (marker) attached to the rotating shaft and a second encoding part (encoder) linked to the controller, with no physical attachment between the two. This way, the first part can be permanently attached while the second part is removed during C&S. Optical encoders have this separation, but the distance between the marker and the encoder is very small and the encoder has to be removed sideways, which can cause inconveniences. The marker

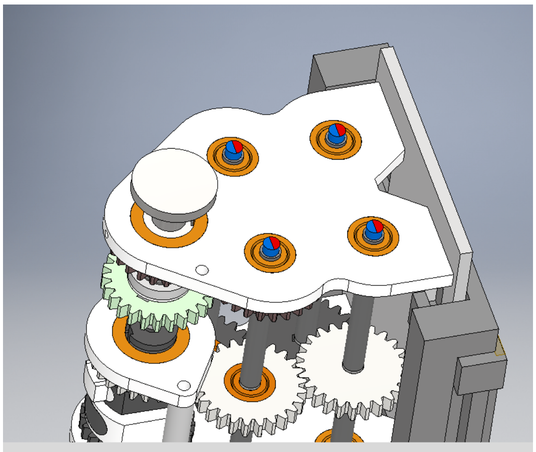


Figure 26: Positioning of the magnets for the magnetic encoder, at the end of the shafts

is a thin disk with markings on it, made of either plastic or metal. Sterilization is done at 134°C, which will not melt but deform the disk. It might also get dirty during use or stained after cleaning. Inductive motors were also considered, but the decision was settled for magnetic encoders. They use neodymium magnets as markers which can be sterilized without getting damage, the marker and the encoder do not need to be perfectly aligned and they do not need to be at a fixed distance. The compliance, ease of use and sterilization-compatible markers have led to the final decision to use magnetic encoders as sensors.

The ideal position for the sensors would be on the instrument itself, but that could not be done without modifying the instrument shape. Another option would have been the driven gears that attach to the instrument which would offer reduced backlash, but the sensor had to be coaxial, and four coaxial sensors would interfere with each other and take a lot of space. Finally, the sensors were placed coaxial with the four shafts of the gearbox (Fig. 26). This offered more backlash than the previous ideas, but was a good middle ground. The position at the end of the shafts allows for easy and quick removal of the encoders from the exterior of the case (Fig. 27) for C&S if wanted, but they could also be sterilized along with the gearbox.

## 4.8 Wire management

Magnetic encoders can be controlled and powered by four wires. Four encoders times 4 wires each equals 16 wires. The power and ground wires can be shared, which leaves a total of 10 wires: one power, one ground and eight signals. The use of the controller's I2C protocol allows to share the 2 signal wires between many sensors with different internal addresses. The sensors used have the same address (being identical) without the possibility to modify it. This lead to the use of a multiplexer which acted as a routing point between the 2 wires coming from the controller and the 8 signal wires coming from the sensors. Placing the multiplexer near the sensors and inside a 3D printed casing (Fig. 27) meant that only 4 wires had to be managed to travel between the top of the gearbox to the bottom of the motor unit.

The necessity to remove the sensors has lead to a need of quick wire detachment. For that, spring loaded connectors (Fig. 37) were used throughout the whole assembly from the top of the gearbox to the motor unit. A more detailed wire path is provided in the Connections section. An early design for wire management had an electrical tunnel built-in the gearbox case (Fig. 1, wire management). The requirements for wire management were to make sure the wires do not interfere with the gears and to keep the design aesthetic and cleanable. Later versions had an electrical tunnel throughout the gearbox, not touching the gears and with spring loaded connectors at ends (Fig. 28 and 29).

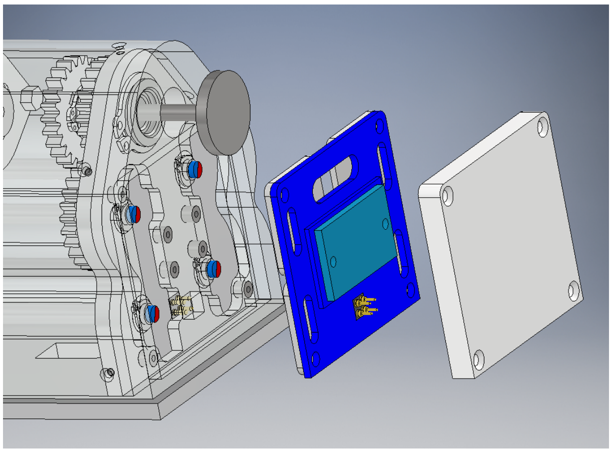


Figure 27: Placement of the multiplexer in relation to the gearbox case and the sensors

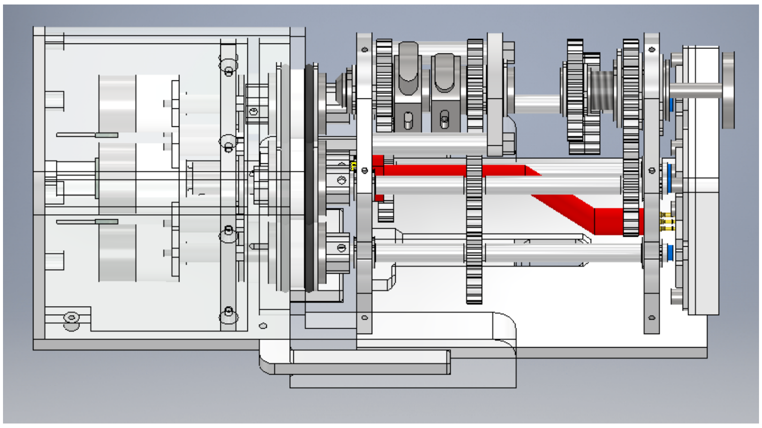


Figure 28: Version 2.7 with cable tunnel (red) for wire management and redesign of the cup and the motor unit's plate

## 4.9 Bushings

Usually shafts are hold in place by bearings, but for this application, bearings will contaminate the clean gearbox, require lubrication and are hard to clean. Even after C&S, the bearings will lose some of their lubrication and become harder to turn. Instead, we used bushings. Version 1 had brass bushings, but here they were made out of PEEK. This material is strong while having a low friction coefficient. It can also support the sterilization temperatures without significant thermal expansion. The cup has to transmit the rotation of the motor shafts to the gearbox shafts. A hexagon hub (Fig.

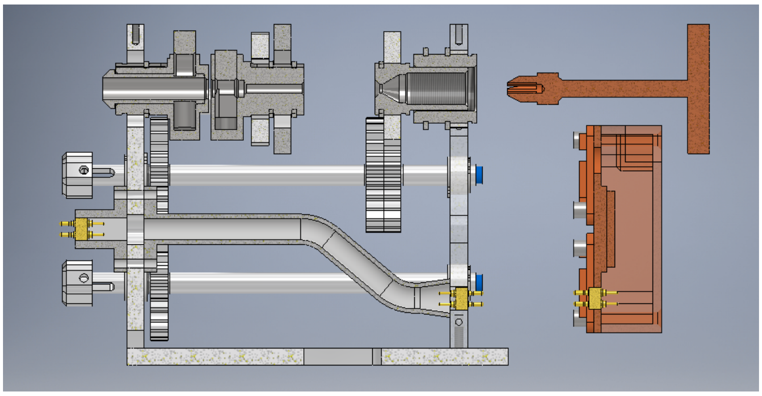


Figure 29: Section view of the gearbox in Version 2.8. The cable tunnels (red and orange) are shown with the spring loaded connectors at the ends

30, grey) that can fit the hexagon heads of the shafts was fitted in the cup. The cup has to block contaminants that can jump from the instrument-gearbox assembly to the robot and back. Rubber O rings fixed in place with snap rings were added for that reason (Fig. 30).

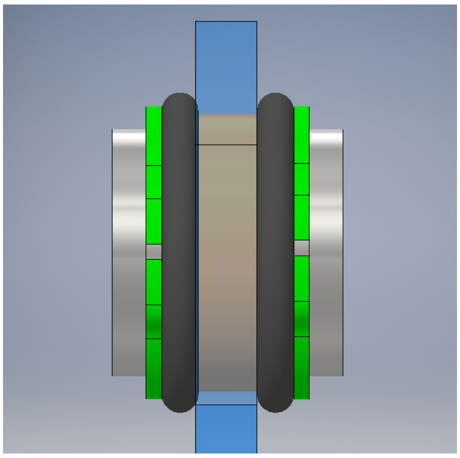


Figure 30: Transmission through the cup (transparent blue), with PEEK bushings (inside the cup, orange), and rubber O rings (black) held by snap rings(green) for creating a contamination barrier

One of the best features in Version 2.0 (Fig. 31) is that it can use the exact instrument from the handle version, no modification required. The first gearbox (Fig. 10) had all the motors integrated in the gearbox, one after the other which made it incompatible with the handheld instrument. In addition to that, for C&S purposes, the instrument had to be detached from the gearbox in a way that made the concentric shafts of the SATA mechanically weaker, because of the difficult coupling on the length of the instrument. The gearbox was given a curved profile, almost as in the shape of the house, which added a better grip without reducing essential space inside.

The combined button (Fig. 32) was requested in order to push just one button to release both the middle and outer shafts from their chambers. The button had to be outside the case but somehow

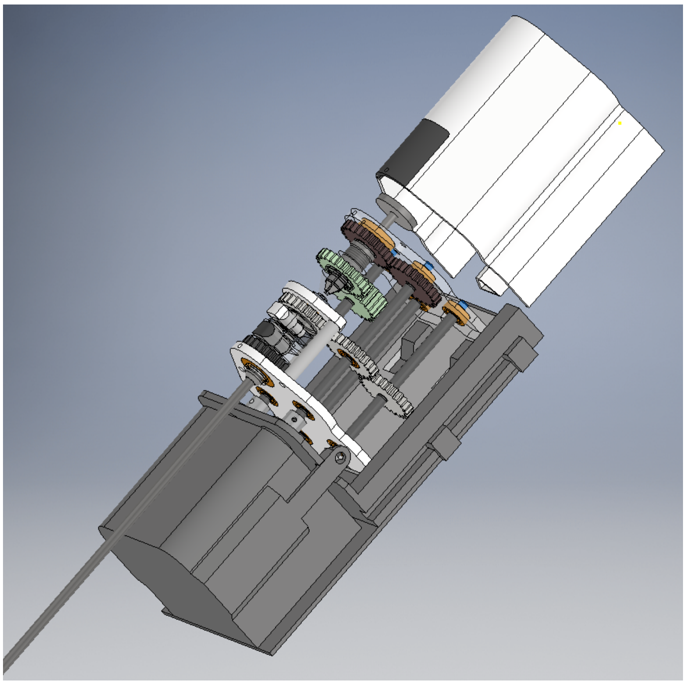


Figure 31: Version 2.0 of the design, adapted so it is compatible with the instruments made for the handheld version

still attached to the buttons. The idea was dropped because the chamber buttons were already small enough to be pushed simultaneously with one finger.

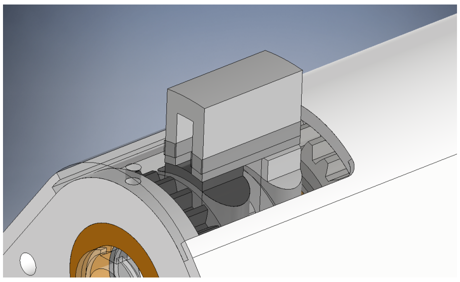


Figure 32: Combined button for pushing the engaging buttons at the same time

# 5 Building process - mechanical

## 5.1 Water jet cutting

The Dienst Elektronische en Mechanische Ontwikkeling (DEMO) workshop water jet cut the parts that had prismatic geometry, including the gears from 4mm thick aluminium (Fig. 33). This was

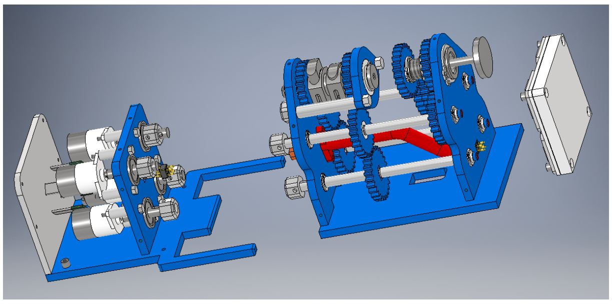


Figure 33: Assembly with water cut parts highlighted in blue

a faster and easier alternative to CNC milling, despite of the rough surface of the cut edges. The gears meshed without a problem, no lubricating solution required.

### 5.2 Lathe machining

The shafts that hold the gears, together with some of the parts were lathe machined by the LIS group. PEEK bushings also.

### 5.3 CNC machining

The shaft chambers and button forks were CNC machined by the LIS group. The intricate shapes of these make it too hard to machine by hand.

### 5.4 3D printing

Parts with too complex geometry and/or too big were 3D printed. The desired material used was either SLA (stereolithography) mechanically tough resin or FDM (fused deposition modeling) Nylon. Because of the higher costs and difficulty to print in those materials, FDM PLA was used. PLA is cheaper and easier to print, which is an advantage for prototyping because at the beginning the part will not be dimensionally accurate because of the tolerances, offsets and settings of individual 3D printers. Some adjustments can be done post-printing, like sanding and filing, but most of the time the part has to be redone entirely.

### 5.5 Store-bought parts and materials

Parts such as the clip rings, screws and springs were standard parts that were store bought. Most of the machined parts were made of aluminium, including the water cut parts, while the rest were made of steel. The bushings were machined from a block of PEEK.

## 6 Building process - electrical

### 6.1 Sensors

The sensors used were AS5600 magnetic encoders (Fig. 34), which are built to be non contact. The magnet can be placed on the desired rotating surface (at the end of the gearbox's shafts, in this case), while the sensor itself can be placed at a distance of 3-5 mm from the magnet, no physical contact necessary. This allowed a design of a plastic case with the sensors attached that can be removed for sterilization without concern for cables or mechanically attached parts. The position of four shafts needed to be encoded, so four sensors were used, controlled with an Arduino board via the I2C protocol. This protocol allows for control of up to 128 slave devices using only 2 wires. The disadvantage of this setup is that each slave device has to have an unique address. The AS5600 are mass produced with the same unchangeable address, which makes the I2C protocol useless by itself. For that problem, an Adafruit multiplexer (Fig. 35 was used, which allowed for control of up to 8 devices with the same address using the I2C 's two wires. There were four wires coming from each sensor to the multiplexer (power and ground included) to a total of sixteen, but those wires were short and soldered tight together, having only four wires in total traveling from the sensor-multiplexer assembly, through the gearbox and the cup, to the motor house.

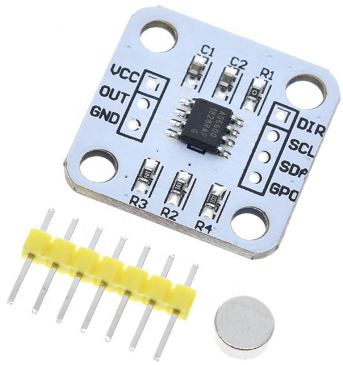



Figure 34: AS5600 magnetic encoder

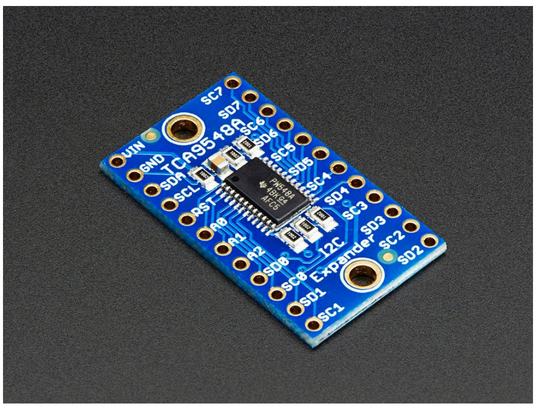



Figure 35: Adafruit multiplexer

## 6.2 Motors

The motors chosen for this application were stepper motors. Their construction allows for precise control of movement that is necessary for fine control of surgical instruments. The model used was GM12-15BY, TT Motors. This model is small, with a step size of 18°, but with their integrated 20:1 and 50:1 gearbox ratio configurations, the output step sizes become 0.9° and 0.36°, respectively. The integrated gearbox adds torque and allows for stronger movements, at the cost of reduced speed.

## 6.3 Drivers and controller

DRV8825 was used as a stepper driver. It allows for multistepping, but considering that the output of the motors goes through a gearbox that increases the total output number of steps, the driver was used only in full step mode. A simple Arduino Uno board was used for controlling the whole prototype, from taking user input from the computer's keyboard, to processing the signal from the sensors and ordering the drivers to move the motors accordingly.

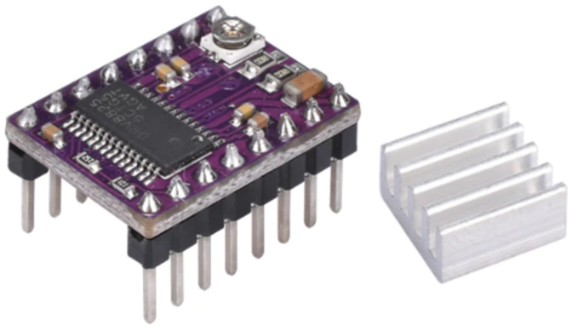


Figure 36: DRV8825 stepper motor driver

## 6.4 Connections

Spring loaded connectors (Fig. 37) were used in some critical areas where quick and compliant connections were needed:

- Between the motor unit and the cup;
- Between the cup and the gearbox;
- Between the gearbox and the sensor lid;

The intent of the gearbox is to be cleaned and sterilized before surgery, but this treatment is not desired for the sensors, which were placed inside a removable lid. All the mentioned connections exists to transfer the power and signal wires from the sensors through the gearbox and cup to the motor unit. From there, all the wires (including the power and control for the motors) continue further down to the controller and to a power source.

Figure 37: Spring loaded connector pins

### 6.5 Final build

All parts were built and assembled. The whole prototype was build twice. The first one built had some misalignments that slightly hindered the meshing of the gears, making them harder to turn. The second prototype built took care of the misalignments, making the gears to turn smoothly, but some errors in the CNC mill caused some faulty machining in the chambers. There were also some errors in the machining of the collet, which caused the inner shaft of the instrument to sometimes slip out of the collet. The following section will show the tests done on the second built prototype, showing how the it behaves on working conditions.

## 7 Experiments and proof of concept

### 7.1 General mobility

The system has 4 DOF. The used actuators are stepper motors which can rotate continuously without limitations, therefore the mobility limits of the system are the same as the ones of the instrument used.

**Method**

The motors will be manually controlled from the keyboard with small step increments until the instrument reaches its movement limits. The reason the increments are small is not to force and damage the instrument when it reaches its end of range.

**Results**

The following limits were reached. Note that for both rotations (Fig. 39, d2 and d4) there is no maximum angle as they can rotate indefinitely. However, in order to prevent accidents inside the body during surgery, their rotation can be limited to a desired number, the default here being 720°.

- Fig. 39, d1: Articulation: -64 to 64° (Fig. 38)
- Fig. 39, d2: Rotation of the tip: 0 to 720° (continuous)
- Fig. 39, d3: Beak clamping: 5 mm translation of the inner rod

- Fig. 39, d4: Rotation of the whole instrument: 0 to 720° (continuous)

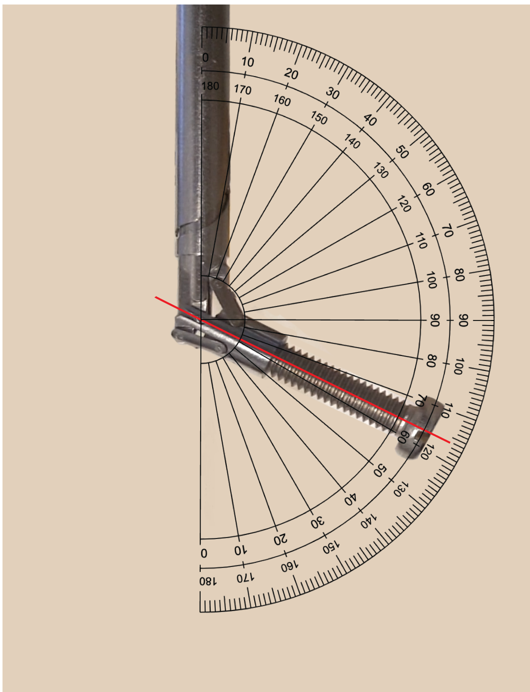


Figure 38: The maximum angle of the articulated instrument

**Discussion**

The main difference between the handheld instrument and the robotic controlled instrument is the movement precision. Thanks to the angle precision of the stepper motors and the angular position feedback from the sensors, the instrument can be moved with smaller increments, but ultimately to the same limits. Because the instrument is interchangeable between the handle and the gearbox, its range of motion does not depend on the two, but on the instrument itself.

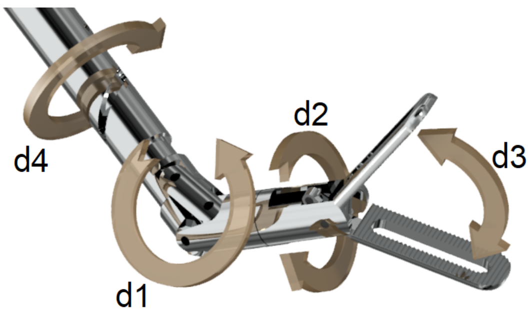



Figure 39: The possible movements of the SATA mechanism

## 7.2 Articulation force

During surgery, the instrument needs to be able to grab and pull tissue. The pulling force necessary can come from the robot itself, but in certain cases when the angle does not allow that, the instrument has to be able to do it from its articulation force.

**Method**

In order to measure the articulation force, the setup in Fig. 42 was made, where both the gearbox and the end of the instrument have supports. The weight m is hanged from the tip of the instrument, 2 centimeters away from the articulation point (Fig. 40). The articulation of the SATA can be done by rotating the outer shaft against the middle shaft, while the latter is kept still (Fig. 41). They are both rotated simultaneously to rotate the whole instrument. Increasing weights starting from 130g were tested both for articulation and whole rotation. Every weight was tested 3 times, in case of flukes from the code or from the motors.

Figure 40: Experimental setup for articulation force, weight down

Figure 41: Experimental setup for articulation force, weight lifted

**Results**

The attempt was successful for the lightest objects, but failed for heavier objects (Table 2). It was concluded that the maximum articulation force supported by the current motors is 2 Newtons.

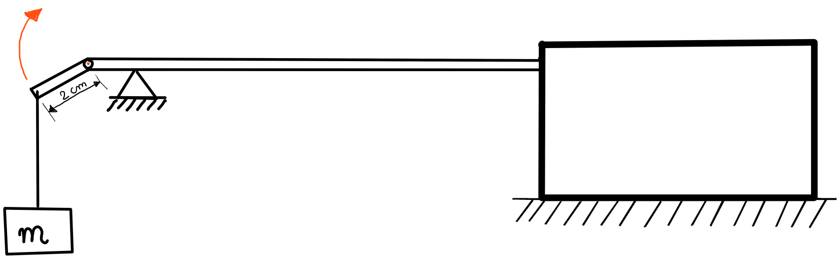



Figure 42: Setup of the articulation force experiment

| Weight of m [g] | Success of articulation (Fig.39, d1) | Success of rotation while articulated (Fig.39, d4) |
|---|---|---|
| 130 | Yes | Yes |
| 170 | Yes | Yes |
| 200 | Yes | Yes |
| 250 | No | Yes |
| 390 | No | No |

Table 2: Articulation force tests and their success

**Discussion**
Abbott et al claim that 0.5 N of lateral force is insufficient to manipulate tissues within the GI tract [13]. Lehman et al developed a feasible in vivo robot with 5 N of force [14]. Tissues vary in necessary pull force, therefore, in this case, the higher the force the better, because it can suit a wider range of applications.

## 7.3 Ease of assembly-disassembly

This experiment seeks to measure the user friendliness of the design in the eventuality of instrument and/or gearbox exchange during surgery. For that, time will be the measured factor of the disassembly-assembly(DA) process for users that see the Version 2 for the first time. Additional hindrances that slow down the process will be observed and noted.

**Method**
Ten participants will be shown an instructional video with all the steps necessary to complete the process. The participants come from a technical background, all from 3ME. Three of them are from the Materials department (all Master students), the other seven from the MISIT lab (five Master students and two PhD candidates). The instruction video will show the process from three different angles for the cup and gearbox, for a better perspective. Captions in the video will communicate additional instructions. The process will play out like this:

— DISASSEMBLY —

1. The process starts with the 4 assembled components: motor unit, cup, gearbox and instrument. The motor unit is rigidly attached to the table or the robot arm, so the whole assembly is secured in place

2. The big clickhook (BC) is pressed with the index finger while the gearbox is gently pulled out of the cup, being held between the thumb and the remaining three fingers. When the BC disengages, the press can stopped and the gearbox can be pulled all the way out. The gearbox is set aside. (Lap 1. Marker: gearbox is set on the table)

3. The small clickhooks (SC) are gently pressed up while the cup and the motor unit are pulled apart slowly until the SC disengage. After that, the cup and the motor unit are fully pulled apart and set aside. The SC are fragile so they have to be handled with care. At the same time they do not need to be bent very far in order to disengage. (Lap 2. Marker: cup is set on the table)

4. The collet tail is loosened half a turn. The engaging buttons are pressed simultaneously and the whole instrument is pulled out from the gearbox. The instrument is set on the table. (Lap 3. Marker: instrument is set on the table)

   — ASSEMBLY —

5. The process starts with 4 separate components:
   - The instrument with all its shafts already assembled - free to move;
   - The gearbox, with the case and sensors screwed in - free to move;
   - The interface cup - free to move;
   - The motor unit - attached to the table or the robot arm;
6. The small chamber's button is pressed as the middle shaft is pressed all the way in. The button is released and the shaft is gently turned back and forth a few degrees until the button comes out and clicks. With the chambers angled at 90° from each other, the process is repeated with the big chamber and outer shaft. The collet tail is screwed in until it firmly catches the inner shaft, about half a turn. (Lap 4. Marker: the collet tail is screwed and the participant takes the hand off it)
7. The cup is gently pressed into the motor unit, entering from an angle and continuing straight, without forcing the SC. When the motor unit's fork is pressed all the way in, the SC will click and the two parts should be secured in place as long as the SC are not touched. (Lap 5. Marker: the SC click)
8. The gearbox is gently pressed into the cup, making sure the BC is not overbent. When the gearbox is pressed all the way in, the BC should click and without touching it, the gearbox should be secured in place. (Lap 6 marker: the BC clicks)

The subjects will be timed while doing the DA on a laptop, not on a smartphone, to prevent touch screen errors. The time combinations can be found in Table 3. The time ends when they successfully finish the whole DA process.

| | D gearbox | D cup | D instrument | Total disassembly | A instrument | A cup | A gearbox | Total assembly | Total DA time |
|---|---|---|---|---|---|---|---|---|---|
| Lap 1 | | | | | | | | | |
| Lap 2 | | | | | | | | | |
| Lap 3 | | | | | | | | | |
| Lap 4 | | | | | | | | | |
| Lap 5 | | | | | | | | | |
| Lap 6 | | | | | | | | | |

Table 3: Times measured in the Ease of assembly - disassembly experiment

**Results**

The resulting times of this experiment can be seen in Fig. 43. Figure 44 shows four sets of time combinations. Ten participants have done the DA process seven times while being timed in six laps divisions, as seen in Table 3. In Fig. 44, the gearbox total exchange time is calculated by adding the times from laps 1 and 6, while the instrument exchange times, from laps 3 and 4. The rest are according to Table 3, 1,2,3 and 4,5,6, respectively.

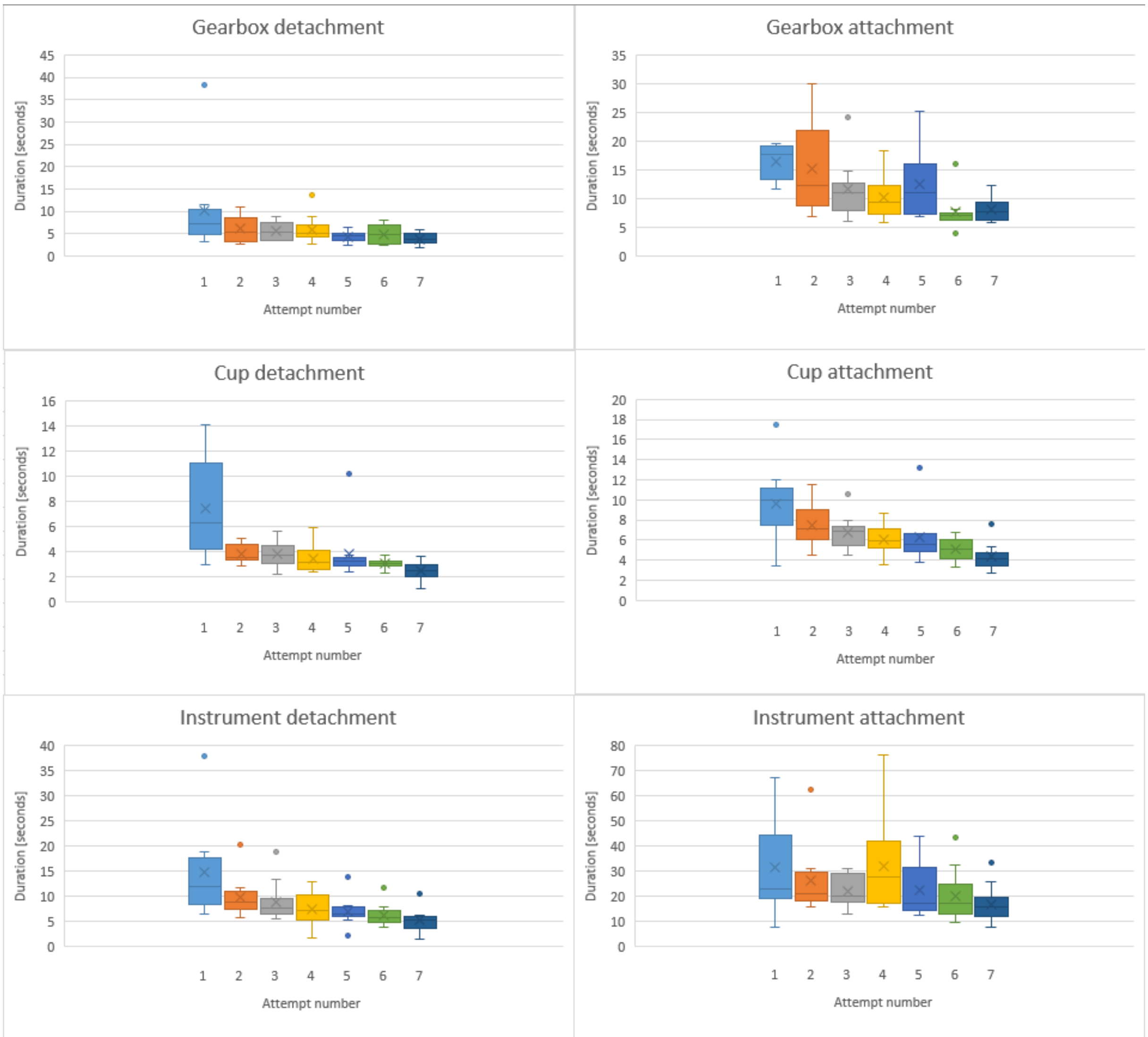


Figure 43: Box plots of the lap data. Each box has data from 10 participants during one attempt

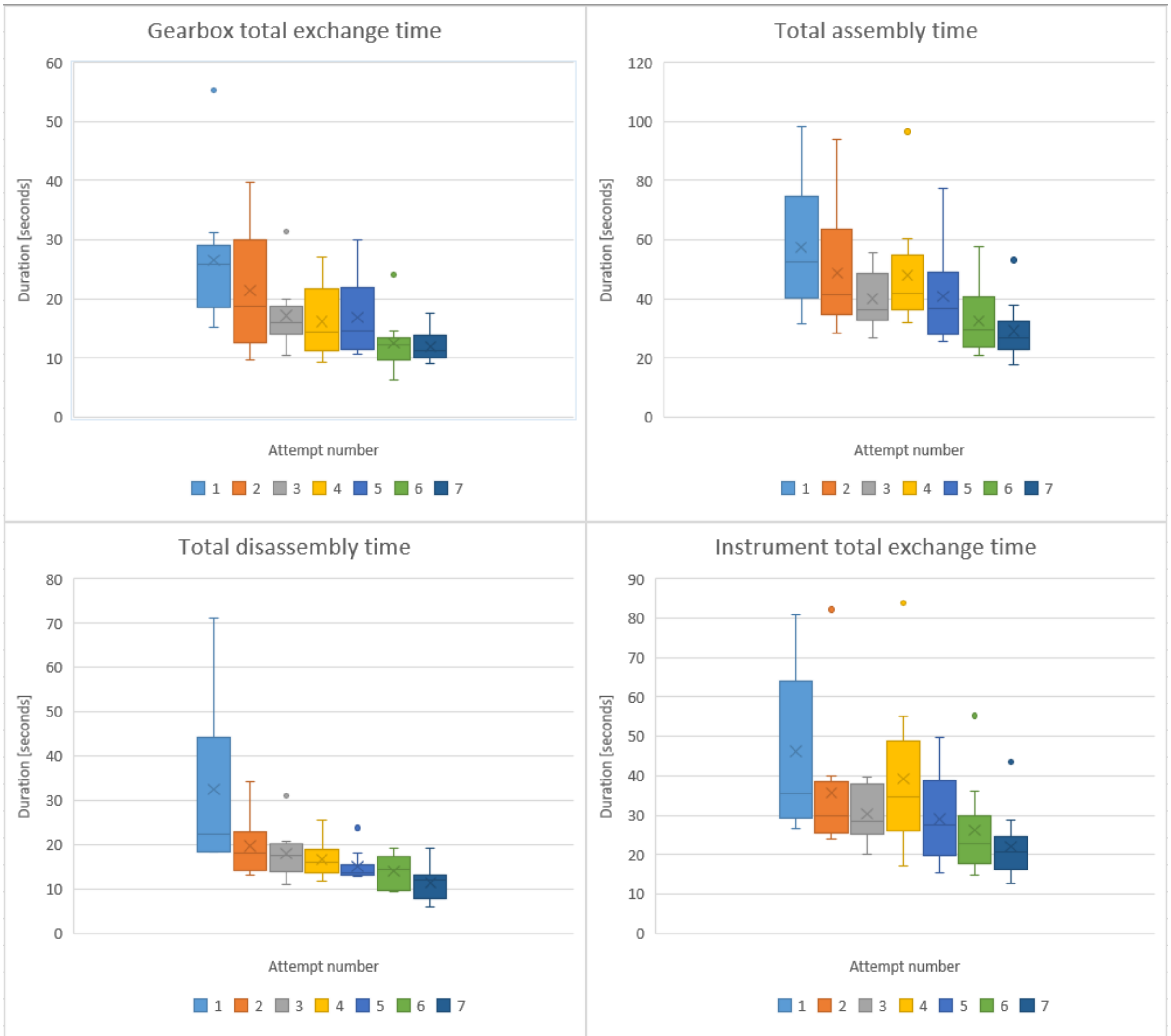



Figure 44: Box plots of the experimental assembly-disassembly results. Each box has data from 10 participants during one attempt

**Discussion**:

Notes:

1)Initially, the process contained more laps to get rid of the dead times, or "travel" times, for example after setting the gearbox down to the grabbing of the cup. This times were in practice so short, that were considered insignificant, being less than half a second.

2)This experiment seeks to measure the time that depends on the user who does the instrument exchange. The shaft coupling between the motor shafts, cup interface hexagon hubs and gearbox shafts is dependant on the motor rotation and is done by the controller and dependant on the motors. The coupling time is not dependant nor influenced by the user or the assembly process. Therefore, the coupling time will not be measured in this experiment, but will be part of another.

The instruction video that is shown to each participant before the assembly represents a constant in the task explanation which makes sure the participants have the same starting conditions. During the experiment, a supervisor was always available to provide help if needed, to time the participants and to stop the process if necessary. The fragility of the SC might have led to additional spoken instructions that reminded the participants to handle them with care. A clear learning curve can be seen in the gearbox exchange time and total disassembly time, even though the curve does not seem to properly flatten. This could be attributed the the participant's perceived fragility of the system that made them act with more caution. Nevertheless, they were still improving at the end of the experiment. The gearbox exchange is the easiest way to change instrumentation during surgery, because in order to remove the gearbox, only one "button" needs to be pressed, then the whole gearbox can slide out. For putting it back, it needs to enter the groove in the cup then it can click in place. If we want to remove just the instrument, the collet needs to be loosened, then two buttons need to be pressed. To put it back, the button's chambers need to be oriented at 90° and clicked in place, which turned out to cause inconveniences for the participants. The high times of the instrument total exchange come mostly for the assembly of the instrument. In the gearbox exchange time, the last two bars show times between 20 seconds. The total assembly time depends on the instrument assembly time, therefore the times are higher and do not show a curve as clear as in the total disassembly time, even though the times do seem to go down. In the operating room, where time is essential, the fastest way to exchange instruments, based on the data, is to have individual gearboxes for each instrument and exchange them all together by dealing only with the gearbox's attachment mechanism. After 6 tries, all participants could disassemble and reassemble the gearbox in less than 20 seconds.

## 7.4 Motor coupling

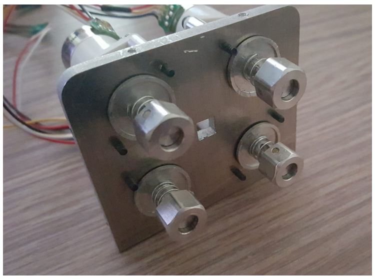


Figure 45: Hexagon male coupling of the motor unit

Figure 46: Hexagon female coupling hub of the cup

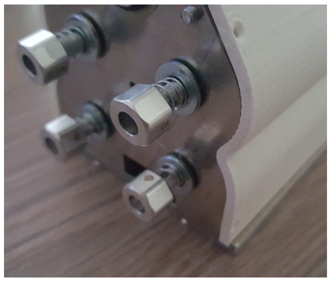


Figure 47: Hexagon male coupling of the gearbox

This experiment seeks to find the coupling time between the motor shafts (Fig. 45) and the gearbox shafts (Fig. 47) via the hexagon female coupling hubs in the cup (Fig. 46). Because of the springs that push the male hexagon parts, the assembly can be done between the motor unit, the cup and the gearbox without worrying about the coupling. After assembly, the turning of the motors combined with the chamfers on all the hexagon parts and the loaded springs will make the shaft tips settle in and couple with the cup hub. The coupling time is not dependant on the users who do the assembly, nor on the assembly time.

**Method**

The coupling time has to be measured from a random angular position of the shafts. For that reason, the experiment will unfold in the following manner:

1. The motor unit, cup and gearbox will start from assembled positions. The presence of the instrument does not affect the outcome, so it will be left out.
2. The controller will rotate the motors to a random position. After that, the gearbox is detached and set aside. Now the gearbox has its shafts in a random position.
3. The controller will rotate the motors to a random position for the second time. After that, the cup is separated from the motor unit. Now the cup has its hubs in a random position, different from the gearbox.
4. The controller will rotate the motors to a random position for the third time. Now the motor unit shafts are in a random position, different from the gearbox and the cup.
5. With all three parts in random positions, they are reassembled. If some of the shafts happen to be aligned with the hexagon hubs and fit together without motor driven nor user driven shafts rotation, they will be left undisturbed.
6. The coupling program in the controller is started, along with the timer. This program will alternate the position of the shaft, from +30° to -30° from the starting position. Angular feedback from the sensors will ensure the precision of these movements. After all 8 shafts are coupled, the timer is stopped along with the program.
7. Now that everything is both assembled and coupled, the experiment will be repeated for a total of 30 times. Step 6 can be done with just one random pair (motor unit - gearbox) of shafts, or with all four at once. Separate graphs with mean coupling time of one or all shafts will be done with resulted data.

**Results**

Faults in the motors and manufacturing of the shafts have hindered the testing of all shafts at once, therefore the test was ultimately done with one shaft at the time. The resulting times can be seen in the graph in Fig.48. The shaft coupled really fast, sometimes in less than a second. Three times, the shafts clicked instantly. After 30 attempts, there were two outliers, of 28.49 and 23.16 seconds. Without these two, the average coupling time was 1.29 seconds. With them included, the average time was 2.93 seconds.

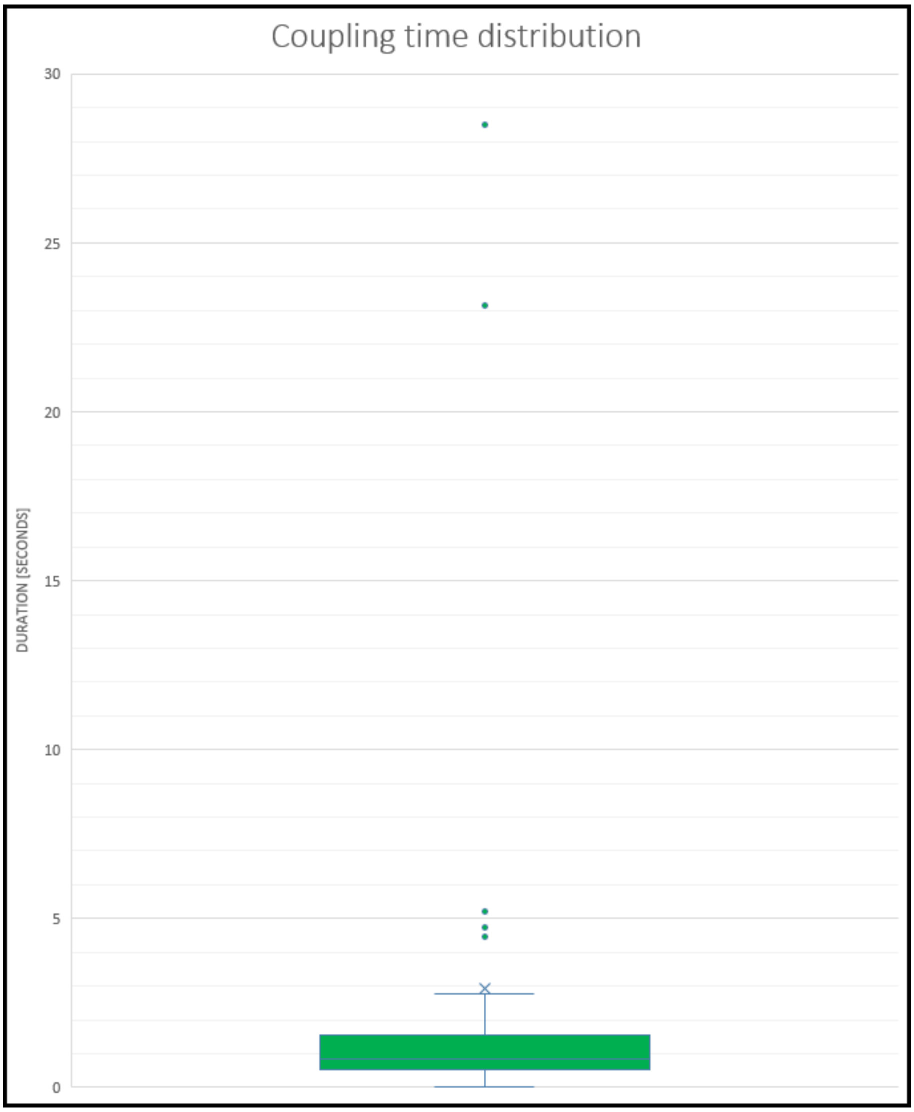



Figure 48: Coupling times for one shaft, 30 attempts, with an average time of 2.93 seconds

**Discussion**

Coupling is done really fast, sometimes in less than a second, which saves time in during instrument exchange in the middle of a surgery. Three out of 30 times, the coupling time was 0. The chances of the shafts being perfectly aligned are low, but the compliance given by the chamfers in the hexagon hubs, hexagon male couplings and springs allows for coupling even if the shafts are in a few degrees offset. There are, however, times when it takes considerably more time, over 20 seconds, to couple. These are not considered the norm. Notes:

The hexagon shape means that a misaligned shaft will have to rotate 60° in one direction in order to find the right alignment in the hub as the spring will press it in and secure the coupling. Because during surgery, if the instrument with the gearbox are both exchanged, it is desired that the new instrument will keep the same position and orientation. During recoupling, a 60° turn in any of the shafts could lead to undesired, too wide moves in the instrument. In order to reduce that, the coupling program will instead rotate the shafts 30° in one, then in the other direction. The total angle will still be 60°, but the position deviation will be just 30° on either side. There is no automatic mean to detect the correct coupling of all the shafts, therefore the user has to stop the program manually when correct coupling is visually confirmed. Future versions could take care of this problem.

# 8 Final design

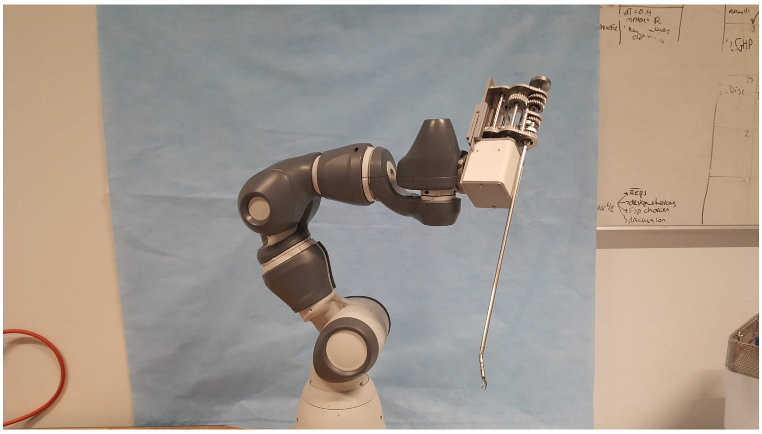


Figure 49: Version 2 gearbox attached to the robot

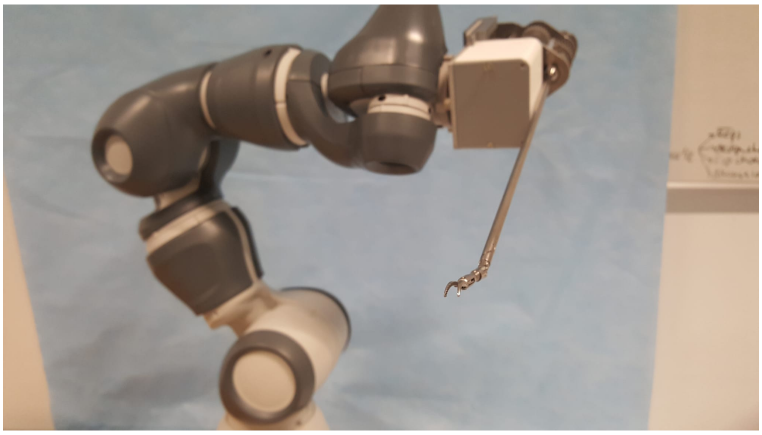


Figure 50: Version 2 gearbox attached to the robot

Figure 51: Version 2 gearbox attached to the robot

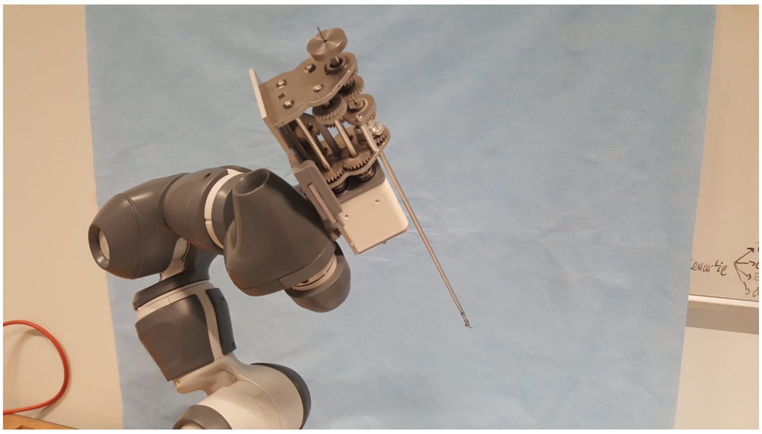


Figure 52: Version 2 gearbox attached to the robot

# 9 Discussion

## 9.1 Meeting design requirements and goals

The Version 2 gearbox was successfully built, together with a motor unit and a cup interface. All design requirements were met. The four subassemblies that compose the prototype (gearbox, cup, instrument and motor unit) can be disassembled easily and fast even by people who see the product for the first time, as proved experimentally. The most important time from the DA experiment is the gearbox total exchange time, because during surgery the instruments will be paired with their own gearbox, therefore if an instrument exchange is needed, the medical staff needs only to remove the gearbox from the rest of the assembly and attach a new gearbox with a different instrument. Hence the importance of the gearbox total exchange time. According to the experimental data, after 7 repetitions all participants could do the gearbox exchange in less than 20 seconds, with an average time of 11.9 seconds. If we add the average coupling time of a shaft (2.93 seconds) from the coupling experiment, we get an average of 14.83 seconds for a ready-to-operate exchanged instrument. Surgery has to be paused while instruments are exchanged, so lower times there mean shorter interruptions in the OR. The high total assembly times are mostly caused by the instrument attachment to the gearbox. Here, the concept was easily grasped by the participants, but sometimes the instrument clicked right away in the chambers, other times the instrument was blocked and clicking it in caused complications. The faulty machining of the chambers and keys might also play a role in the instrument having problems entering the chambers or the keys clicking out with the instrument in position. The collet tightening is also impaired by the faulty machining, sometimes the inner rod is fixed in place, other times it slips. The participants mentioned that the 90° offset of the chambers is not intuitive enough. The reason for the offset in the instrument is that the handheld version is assembled this way, so the necessity to assemble it this way was purely due to lack of materials. A newer version shafts could be machined differently so there is no need to offset the chambers before assembly.

Position feedback was successfully implemented by installing the magnetic encoders. Each shaft has a permanent magnet attached to its end, with the encoders attached to the gearbox case. The encoders can either be removed during sterilization, together with the case, but can also be sterilized. The wires that go through the gearbox are inside a protective tunnel, so gearbox can be sterilized with all its components in place, without affecting functionality. The wires have the spring loaded connectors at their ends, allowing for quick connection-disconnection.

The instrument is oriented in the gearbox in such a way that they are both detached from the motor unit away from the patient. All the detachments of the four subassemblies do not require additional tools. When the four subassemblies are attached together, they are secured and cannot come off accidentally. The instrument can articulate at 64° in either direction and can rotate its tip and its whole body indefinitely. The motors can develop a moment of force of 4N-cm in the articulation tip, as the instrument can articulate with 200g hanging at 2 cm away from the articulation point. This shows how grabbed tissue can be laterally pulled by the instrument from the articulation point with 2N of force. Higher torque motors paired with smoother surface gears can increase the maximum lateral pulling force for better tissue manipulation.

The design also allows for the integration of a drape, secured between the motor unit case and the cup. In combination with the design of the gearbox and the possibility to separate it from the motors, this creates the possibility of tests in the OR, with a cleaned and sterilized instrument and gearbox, while the motors and the robot arm are shielded by the drape.

The design goals were also met, Version 2 being made as light and compact as possible, with the instrument shafts interchangeable with the handheld version.

## 9.2 Comparison with previous version

Among the added features of Version 2, the most important ones are the cup mentioned above and the position sensors. The sensors allow for a finer control of the instrument, because stepper motors can skip steps. The motors can have their position, speed and acceleration fed forward, but under load and without ideal conditions they can give errors. The feedback from the sensors minimizes the errors and ensures a finer precision of position and speed from the instrument.

Version 2 offers additional layers of complexity for sterilization, like the separation of the motors and sensors from the parts that will be in possible contact with human tissue and fluids during surgery. If needed, the sensors could be cleaned together with the gearbox. The cup was specially designed for the accommodation of the plastic drape that covers the motor unit and the robot arm, establishing a better clean/contaminated barrier.

The previous version (Fig. 10) had thicker gears and a larger volume. The gearbox presented in this paper has a significantly shorter gearbox, which is made possible mostly by the separation of the motors from the rest of the assembly. All parts together, Version 2 is slightly bigger than the previous version (187x84x86 compared to 165x66x66), but the removable gearbox is smaller (117x82x70 compared to 165x66x66). The shape of the gearbox makes it easier to handle because of the improved grip it offers.

The direction of the instrument relative to the motors was also flipped in Version 2, so the gearbox-instrument assembly is removed away from the patient. The attachment method of the instrument is more solid than on the Version 1, because of the removal of the puzzle piece cut that reduced the instrument's mechanical strength.

# 10 Conclusion

This thesis showed the building journey of a new interface for robotic surgery using the SATA instrument. The built version has a removable gearbox and quick release system for detaching the instrument from the gearbox. This version was built to be compatible with the instrument used in the handheld version.

The instrument is oriented towards the motors, thus allowing for the removal of the instrument-gearbox assembly away from the patient, without the need to reorient the robot. The separation of the motors from the rest of the assembly and the inclusion of a plastic cup interface for compatibility with a drape allow for a proper cleaning process that does not involve the motors. The position feedback from the sensors and the use of stepper motors give this prototype high position accuracy and feedback. Some improvements compared to Version 1 were made and all the design requirements were successfully met. The physical prototype was built and tested for range of motion, articulation force, coupling time and ease of assembly-disassembly for a new users.

Robotic surgery adds many benefits to the patient, but it is expensive. New platforms for affordable, reusable instruments and drive systems for robotic surgery allow it to be available for more people everywhere. The design presented in this thesis could act as a step forward towards affordable robotic surgery.

# 11 Limitations and future improvements

The gearbox design presented in this paper works, but that does not mean there is no room for improvement. For a better user experience, the coupling system can be improved with more compliant geometry and automatic detection of correct coupling. The small clickhooks on the cup are easy to break, but their fragility was observed in the PLA test prints. The cup was designed to be made out of stronger materials (PEEK or Nylon) that are more resistant to loads and fatigue. Because of the metal parts that slide in the cup and constrict the movement to one translation, theoretically on clickhook will suffice. A solution to their fragility could also be to make them longer and stronger, like the one that secures the gearbox. However, that would mean a harder to manufacture cup and additional impediments for the drape. While the whole assembly is lighter than Version 1, improvements can still be done in terms of volume and weight. The gears are currently made of 4mm aluminium, but they could be made out of thinner plastic to reduce the weight. The flanges and the plates from the gearbox and the motor unit are also 4mm aluminium, but they could be made in theory from 3mm aluminium, because neither deals with high loads that would need high mechanical strength. Additional tweaks in the design for better ergonomics and aesthetics, such as a cup that can be attached/detached with one hand, could be a bonus for user experience. The product is functional, but a better care in manufacturing could make for smoother turning of the shafts and a more precise machining of the chambers, keys and collet. Larger motors could help developing higher forces in the instrument and overcome the leftover friction in the transmission, making it easier and faster to close the beak and easier for the instrument to articulate.

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