Project Title  _____ Dexterous Laparoscopic Electrosurgical Tool _____

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Executive Summary

Single-Port Laparoscopic (SPL) surgery, as a typical example of Minimal Invasive Surgeries (MIS), has greatly reduced patients’ suffering and risks. Compared with traditional complex manual SPL tools, an electrosurgical tool greatly facilitates surgeons’ operations and makes the surgeries even faster and safer. The dual-continuum structure adopted in such systems, such as the SERS (the SJTU Unfoldable Robotic System [4]), has shown great advantages in dexterity and function compactness and attracts our attention. In this project, we designed a new SPL electrosurgical tool based on the SERS.

The main challenge of this project was to achieve a compact design with a very small port size (1 cm) and minimized actuation unit size ($100 \times 100 \times 250$ mm$^3$), meanwhile satisfying the payload (5 N), workspace ($100^3$ mm$^3$) and dexterity (6 DoF) requirements. These specifications are required so that surgeons can perform various surgical tasks in the abdomen most easily, and patients’ pain could be minimized. After verifying our engineering specifications using the QFD, we generated several concepts and selected the most feasible one.

In our final design, the basic modules consist of a base, a sterile barrier, a transmission unit and a manipulation arm with a dual continuum structure. The EPOS control system gives signal to the motors on the base outside the sterile barrier. The motors then actuate the backbones in the transmission part inside the barrier and drive the proximal continuum mechanism. Through the guiding cannulas, the manipulation arm can be finally controlled. Our tool is designed to be attached to a DENSO industrial robot. Dexterity, compactness and thoughtfulness for practical uses highlight our design.

Tests have shown that overall our prototype meets its requirements. Still, both our design and manufacturing plan are quite complex and have much potential for future improvements. As examples, the actuation size could be further reduced and the sterile barrier should be improved. Actuation compensation [4] should be also taken into consideration. We finally urge later designers to particularly pay close attention to the precision during manufacturing, which has resulted in some issues of motion smoothness in our design.
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1. Introduction

1.1. Background

As a type of minimally invasive surgery (MIS), the laparoscopic surgery has been long attracting surgeons’ and biomedical engineers’ attention. Different from open abdominal surgeries in earlier years (Figure 1), surgeons use long, rod-shaped tools to penetrate the patient’s abdomen through small incision ports. The diameter of incisions ranges from millimeters to centimeters, enabling patients to suffer from less postoperative pain [1], have lower risks of complications and stay a shorter time in hospitals.

![Figure 1: Open Surgery](image1.png)

There are two types of laparoscopic surgeries. On contrast to multi-port laparoscopy (MPL), the single-port laparoscopy (SPL, Figure 2) inserts multiple tools through a single incision (usually the umbilicus), thus further reducing patients’ pain. Both MPL and SPL tools, however, have the main problem that the movements of surgeons’ hands need to be mirrored and unscaled from the movements of tool endpoints because of the pivot point at incision.

![Figure 2: Covidien single-port laparoscopy surgical tools](image2.png)

To address these problems, robot assistance systems have been developed to help surgeons in both SPL and MPL surgeries. Due to its greater potential, SPL robotic systems are given particular attention by researchers. This can be proved by a literature survey, showing that there is an increasing trend of relevant papers in the past ten years. Especially, institutes and researchers in the United States are doing well in the field.
Generally, an electrosurgical tool consists of a distal effector, an arm for motion transmission and an actuation unit. The goal is that surgeons are able to sit in front of a console, see inside the patient's abdomen with inserted digital cameras, and operate through electrical handles. The movements from the handles are then converted into control signals to drive the actuation unit. Finally, motions are transmitted into the abdomen and to the distal surgical tools. With the practice of teleoperation in this kind, intuitive surgeons’ hand movements are thus possible using suitable converting algorithms, making laparoscopic surgeries faster, more precise and safer.

1.2. Problem Statement

In this project, it is required to design a new SPL electrosurgical tool. Several problems need to be resolved. Firstly, the new arm should have sufficient payload capability (like being able to lift up enough weight) so that it could cope with various surgical tasks like cutting, suturing and retraction. Secondly, the arm should be dexterous enough. It is required to approach a targeted organ in various orientations, and the arm should have enough workspace (reaching large space in the abdomen). Thirdly, the skin incision port should be kept small, thus limiting the diameter of arm and requiring it to have a special motion transmission mechanism. Finally, it should be aware that the payload requirement is usually in contradiction with the dexterity and the small incision requirement. It is challenging to achieve a balance.

Another problem to be mentioned here is the need for a sterile barrier. The part of arm inserted into abdomen is required to be detachable from the electrical control infrastructure so that it can be sterilized in special liquids before and after surgeries. Consequently, this part should be waterproof. Also, the assembling and dissembling should be fast and convenient enough.

According to these requirements, the project will base on a dual continuum mechanism, which uses the SJTU Unfoldable Robotic System (SURS) [4] for reference. Although there can be difficulties in realizing a remarkable payload capability like what the 2014 Samsung SPL robot (SAIT) [5] did by using articulated elbow mechanism, the dual continuum mechanism can provide more dexterity, more reliability and a smaller incision.
2. Engineering Specifications

2.1. Quantification of Design Specifications

The target customer is set as surgeons, or hospitals. Along the design process, some key factors, including improving the surgery practicability and security, and reducing pain and complications on patients, should be taken into consideration. Accordingly, certain engineering specifications are raised with the target value discussed as well with the SURS as a reference.

Practicability
In light of some tasks like retraction that are almost impossible with small forces, sufficient force is necessary. With regard to some complex surgeries, a dexterous manipulation is required to enable the tip of the arms to move in all directions. Meanwhile, the surgical tool with different end effectors should be able to be exchanged easily for convenience of the surgeons.

The engineering specifications are converted from these requirements. A sufficient payload capability and degree of freedom are demanded to ensure higher dexterity intuitively. Their target values are 5 N and 6 DOF. Another factor will be the dimensions of workspace for the manipulation arms, which is hoped to be 100 mm × 100 mm × 100 mm. Otherwise, a task may fail to be completed due to the limited space. However, for the requirement of quick exchange, there is no closely related specification, with merely the dimensions of actuation unit as a related one.

Security
Security serves a vital part in surgeries, where precise and accurate control of the tools plays an important role. Minute errors can be accepted. Also, the surgical tools should be free from harmful bacterium for sanitation, so a convenient sterilization is necessary as well.

Reducing pain and complications
This can be realized with the small port size, which is effected by the small diameter of manipulation arms to a certain degree. And the target value of the arm diameter is 10 mm with a port size of 25 mm. In this scenario, the backbones in the continuum can be arranged properly, too.

Other considerations
A compact actuation size can be reflected in a specification of the dimensions of the actuation unit, which is asked for a diameter less than 100 mm and a length less than 250 mm. There are some other engineering specifications with no strong relation to any customer requirement, but can make the design meet the requirements better. Two of them are maximum linear velocity and maximum distal angular velocity. Their target
values are set as 50 mm/s and 135 degrees/s respectively. They are calculated with resolved rates by supposing the tools are able to reach the target positions in the highest speed without vibrating around the positions. The other one deserves consideration is the power rating of one manipulation arm.

Table 1 shows the engineering specifications in detail.

**Table 1: Detailed engineering specifications.**

<table>
<thead>
<tr>
<th>Engineering Specifications</th>
<th>Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of freedom of manipulation arm</td>
<td>6</td>
</tr>
<tr>
<td>Payload Capability of manipulation arm</td>
<td>5N</td>
</tr>
<tr>
<td>Diameter of arm</td>
<td>10mm</td>
</tr>
<tr>
<td>Dimensions of work-space</td>
<td>100<em>100</em>100 mm³</td>
</tr>
<tr>
<td>Maximum linear velocity</td>
<td>50mm/s</td>
</tr>
<tr>
<td>Dimensions of actuation unit</td>
<td>diameter&lt;100mm, length&lt;250mm</td>
</tr>
<tr>
<td>Maximum distal angular velocity</td>
<td>135deg/s</td>
</tr>
<tr>
<td>Power rating of one manipulation arm</td>
<td>&lt; 200W</td>
</tr>
</tbody>
</table>

**2.2. Quality Function Deployment (QFD)**

Figure 3 presents the QFD chart.

![Quality Function Deployment Chart]

**Figure 3: Quality Function Development for the project.**
It can be concluded from the chart that sufficient payload capability weights the most among customer requirements and the corresponding specification also serves as the most important one. With all other requirements considered and balanced, the project goals are coming up with the following items:

1) Adopt a new continuum structure based on but stronger than the SURS continuum arm. Achieve a balance between targeted payload capacity and arm diameter.
2) Redesign a new actuation unit compatible for this new structure, meanwhile increasing its compactness so that the overall size can be reduced.
3) Design a sterile barrier for the surgical arm, allowing fast assembling and disassembling.
4) Solve the current problem of velocity coupling of the SURS.
5) Finally, assemble a new surgical robotic arm, simulate its mechanics, and optimize its control with EPOS controller boards.
3. Concept Generation

A general overall structure of the tool is shown in Figure 4. The E-POS control system will give signal to the motors. The motors will actuate the backbones in the transmission part and drive the proximal continuum mechanism. Through the guiding cannula, the manipulation arm can be finally controlled. The figure is just for illustrating the general function decomposition.

Since the adaption of dual continuum mechanism and the customer requirements have been decided already, the design will mainly focus on the transmission part and the overall arrangement.

3.1. Concept 1

The arrangement of the first design is shown in Figure 5. Its arm position is not along the central axis of the whole structure. And the motors are moved forward, and in parallel with the distal continuum. Since the sterile barrier can only cover the area inside the dotted line, the motors have to be soaked into disinfectant before the surgery and need to be exposed later, which is unpractical for motors. The transmission part used the power screws and the nuts. They have the advantage of enduring sufficient payload. However, with many screws and nuts needed, it will be time-consuming to arrange all of them in a limited space reasonably.
3.2. Concept 2

Figure 6 shows the arrangement of Concept 2. The motors are moved backwards, enabling the sterile barrier to enclose them. This design is more compact than that of Concept 1 due to the use of the pulleys inside the transmission parts. But the combination of pulley and cable has the problem of creeping in steel cable, leading to a negative impact on control precision and life span.

![Figure 6: Arrangement of Concept 2](image)

3.3. Concept 3

Figure 7 shows the arrangement of Concept 3. This structure is symmetric without a linear module, and use the DENSO system to realize overall feeding. Its sterile barrier area is quite clear as well, convenient for exchanging. Moreover, the motors of the structure are not set at the end of the base, which can make the structure too long. Their positions shown in Figure 8 enable Concept 3 to be a compact design. And there are screws and nuts inside the transmission part.

![Figure 7: Arrangement of Concept 3](image)
4. Concept Selection

There are seven criterion determined based on the customer requirements and their weight factors originate from the QFD. Since a large payload and accurate operation are quite important to the security of a surgery, sufficient force and precise and accurate control have higher weight factors among all the decision criterion. Convenient sterilization is essential to sanitary environment as well. Additionally, the product need a small incision to ensure the patients to recover efficiently with few complications.

Table 2: Weighted decision matrix for the concepts

<table>
<thead>
<tr>
<th>Decision criterion</th>
<th>Weight Factor</th>
<th>Unit</th>
<th>Design A</th>
<th>Design B</th>
<th>Design C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation size</td>
<td>0.20</td>
<td>mm</td>
<td>28.5×10²</td>
<td>48.7×10²</td>
<td>70.5×10³</td>
</tr>
<tr>
<td>Quick exchange</td>
<td>0.95</td>
<td>Exp</td>
<td>good</td>
<td>fair</td>
<td>good</td>
</tr>
<tr>
<td>Small incision</td>
<td>1.40</td>
<td>Mm</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Convenient sterilization</td>
<td>0.48</td>
<td>Exp</td>
<td>fair</td>
<td>good</td>
<td>excellent</td>
</tr>
<tr>
<td>Precise and accurate control</td>
<td>2.38</td>
<td>Exp</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Dexterous manipulation</td>
<td>1.43</td>
<td>Exp</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Sufficient force</td>
<td>2.86</td>
<td>N</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

According to the weighted decision matrix for the three concepts shown in Table 2, we finally choose Concept 3 as our final design due to its highest total rate.
5. Final Design and Analysis

5.1. Concept Description

Our surgical tool is designed to be attached to an industrial robot DENSO, as shown in Figure 8. The DENSO provides overall linear motion and rotation for our arm, thus fulfilling the 6-DoF requirement.

Figure 8: Tool attached to DENSO

The overall design of the tool can be divided into several function blocks, as shown in Figure 9 and Figure 10:

- The base is where the motors and their control cards sit. Power from the base is then transmitted through the sterile barrier to the sterile side, driving the manipulation arm (with the assistance of transmission unit).
- The sterile barrier isolates the electronic parts (the base) with the frequently sterilized, changeable mechanical surgical tool. Power should be smoothly transmitted through.
- The dual-continuum manipulation arm uses Ni-Ti backbones to transmit proximal continuum segments’ bending to distal segments. The distal end can thus move and bend freely inside abdomen (with assistance of DENSO). A gripper (end effector) is also implemented.
- The transmission unit transforms rotational motion from motors to linear pushing/pulling force on input Ni-Ti backbones, allowing proximal/distal segments to bend. An anti-buckling structure for the flexible backbones is also stressed.
A flexible cannula is covered outside the distal continuum segments. During surgeries, the tube goes through the incision port on the abdomen. Details will be given in following sections.

Below we give detailed design descriptions of all function units. The engineering drawing of all parts will be attached in Appendix B.
5.2. The Base

5.2.1. Description of Functions

Structure of the base is shown below in Figure 3. It surrounds the bucket-shaped sterile barrier (white in Figure 11). Through series of gears (1M24/18/30T), the motion is transmitted along radius to the center. The motion is then transmitted outside the base through the sterile barrier by couplers. There are in total five motors (and five control cards), four of which are in charge of driving the input backbones and one is for driving the gripper.

![Figure 11: Base: front (left) and back (right)](image)

5.2.2. Synthesis

Four 5 mm-thick plates are responsible for the positioning of the gears, motors and couplers. Plate 004 need to be thick in order to hold the weight of whole arm when attached to DENSO. So as it is with Plate 001 since it needs to be connected to the transmission unit. The two plates in between should have enough thickness to fit the bearings. The diameter of the plates (200mm) are determined by those of the sterile barrier and the Maxon DCX 22S motors. Some holes are cut on the plates to reduce overall weight.

The axial positioning and rotational locking between the plates are achieved by aluminum tube columns, shafts within and nuts (black in Figure 11). The spacing in between (12mm/30mm/83mm) are determined respectively by the height of gears, couplers and motors. The gear ratio is kept at around 1 to 1 (24:30). Without special notice, every moving part in our design rides on bearings.
5.3. The Sterile Barrier

5.3.1. Description of Functions

The aluminum alloy sterile barrier (Figure 12) has a shape like a bucket with a diameter of 120 mm. We use three-segment couplers in our design to transmit motors’ motion from base to the sterile barrier then to the transmission unit. So the middle segments of the five couplers (red in Figure 12, with flanges) are designed to be trapped between two bottom plates of the sterile barrier (grey in Figure 12). When the transmission unit and arm are detached from the barrier, this design prevents small coupler segments from falling out.

![Figure 12: Sterile barrier (section view) and middle segment of a coupler](image)

Note that small spacing is specially allocated here. When attached both sides with the base and the transmission unit, the middle segments are not in touch with the two positioning plates. Hence no bearing is needed here.

5.3.2. Synthesis

Plate 002 in Figure 12 is connected to Plate 001 by screws and nuts. Plate 001 is weld with the tube body of the barrier. The thickness of the two plates (4mm/2mm) is determined by thickness of the fringe.
5.4. The Dual Continuum Manipulation Arm

5.4.1. Description of Functions

The dual-continuum arm is shown in Figure 13. Its working principle is very similar to the counterpart in the SURS [4]: the bending of the proximal segments will lead to unbalanced length change of the Ni-Ti backbones in both proximal and distal segments. The distal segments will thus bend in the opposite direction. For details of this design, we refer readers to [4].

For the differences in our design, first, our whole manipulation arm can move linearly in one flexible cannula inserted at the incision of patient’s abdomen (blue in Figure 13). This is because though the linear motion of the distal end can be achieved by simultaneously pulling/pushing backbones, the maximum possible velocity is too small compared with the linear velocity of bending. We also note that the effective length of the first distal segment, i.e. the length of continuum coming out of the flexible guiding cannula, is flexible in our design. This further enlarges its workspace. Finally, between the proximal and distal continuums are rigid cannulas guiding the linking backbones.

5.4.2. Synthesis

To make our design more compact, we adopt a nested proximal continuum structure (Figure 14). The diameter of outer segment cannot be too large so as not to interfere with parts in the transmission unit when bending. The diameter of inner segment is restricted by the outer one. After calculations and simulation, we see that in extreme bending cases the diameters shall not exceed 50 and 25 mm respectively.
To achieve enough payload in our design, we use eight evenly arranged output backbones (one every 45°) for each segment. The thick, straight cannula (with spacer rings in it, see [4]) guiding in total 16+1 output backbones is thus designed to have a diameter of 1mm. The thin, curving cannulas with 0.8mm diameter each guide one 0.7mm Ni-Ti backbone.

The radial offset (28mm) of the backbones passing their thin cannulas will increase friction. Thus sufficient axial distance is needed to relieve this effect. After experiments, we see that 70mm is an optimized distance without sacrificing overall size too much. The whole structure sits Plate 003 on the transmission unit, fixed by screws and nuts.

5.5. The Transmission Unit

5.5.1. Description of Functions

On the other side of the sterile barrier, the third segments of the five couplers transmit motion from motors to drive power screws. In Figure 15 below, it can be seen that some extra shafts and couplers are used to link the gap between sterile barrier and the power screws.

Figure15: Transmission unit with power train illustration
On each proximal segment, 4 input backbones first drive the rings to bend. Then this bending causes the output backbones to differ in length. In total the 8 input backbones for two segments each requires one nut on one power screw to drive them. Still, every two symmetric backbones should always move the same length but in opposite direction. And that is why we only need 4 motors to drive the 8 backbones. To achieve this, we duplicate the motion of each driving power screw, i.e. the ones directly connected to couplers, by two connecting gears (Figure 16). These four pairs of gears thus drive the other four power screws and nuts.

![Figure 16: Top view of the four pairs of gears linking power screws.](image)

When pushing the eight input backbones, buckling shall happen. To address this issue, we design an evenly spacing and positioning structure. In Figure 17, this anti-buckling structure looks like window-shutters. It should have variable length with the nuts and backbones moving axially.

![Figure 17. Overview of anti-buckling structure.](image)
5.5.2. Synthesis

The cover of the whole transmission unit has outer diameter 120mm and length 158mm. A large diameter further makes the radial offset of input backbones mentioned above bigger, thus requiring larger axial length. The steps towards these optimized values are not trivial.

First, from kinematic analysis of the manipulation arm we conclude that the required backbones’ actuation lengths are 60mm and 30mm for the second segment and the first segment. This is hence the minimum values for the power screws’ lengths. But we notice the actuation length for the gripper is only 5mm, allowing us to arrange the gripper screw and one 30mm screw to share the same axis. In final design we add much tolerance for the power screws (150mm/100mm, Figure 18).

![Figure 18: Section view.](image)

Each nut needs at least one slide rod to guide, and each input backbone needs independent anti-buckling structure. Each anti-buckle structure further needs two slider rods to guide. According to calculation the size of the anti-buckling structure is 6mm*40mm. Diameter of the slide rod is chosen to be 3mm. The best arrangement is shown in Figure 19 below, where the anti-buckling shears are arranged along radius. This arrangement can reduce the maximum backbone offset to the smallest.

![Figure 19: Spatial arrangements of transmission unit (top view).](image)
Plate 002 and Plate 003 are the most important structures of the tool. It constrains the position of the slide rods and power screws. If there exists some small misalignment the nut would stuck and the structure will fail. Or, the backlash will make the control inaccurate. We use four long smooth rods with threaded end (Figure 20) to constrain the relative position of the plates and use four aluminum columns to fix the distance between Plate 002 and Plate 003. The smooth rods can provide good positioning. The threaded ends can provide enough force to lock the slide rod between the plates. Each sliding rod has an outer diameter of 3mm with both end threaded with M3. Double nuts are used to fix these slide rods. The power screw is 1mm shorter than the distance between plate 002 and plate 003 to avoid over-constraining, and we use a bearing lid to press the bearing so that backlash can be eliminated.

Figure 20: Constrain and positioning structure
The nut has an outer diameter of 14mm and length of 18mm. We design a structure which can fix the anti-buckling sheers and the slide rods (Figure 21). The nut we selected is A180SRM-1418TRX1.5 which means the material is A180, being human-body safe. Its pitch diameter is 8mm and lead is 1.5mm which can take 500N on the 1.2mm backbone. We use 6 M2 screws to lock the backbone onto the nut under the assumption that the friction coefficient between backbone and steel is 0.25 the pressure on the screw is 90Mpa. The pressure on the 1.2mm backbone, 442Mpa, is also safe.

Figure 21: Nut

For the anti-buckling structure, we need to know the maximum spacing between the contact points along backbone direction. Using Euler equation for the proper buckling model the maximum distance is 10mm. Then we calculate the elastic deformation threshold of the anti-buckling sheets and finally conclude that the smallest size and total number of pieces are reached when thickness of the sheets is 0.2mm and maximum spacing is 2mm. These pieces are welded in a way that when the structure is stretched the spacing in between is distributed evenly (Figure 22).

Figure 22: Elastic deformation of anti-buckling structure.
6. Manufacturing Plan

The material list of the machining parts is shown in Appendix A.

6.1. The Manipulation Arm and Dual Continuum Segments

a) Note that all backbones in this section refer to output backbones. Input backbones are those directly driven by the transmission unit (motors).

b) Use laser cutter to obtain preliminary steel parts – spacer rings (Fig. 23) and anti-buckling spacers of proximal continuum (See below in Fig. 27).

![Figure 23: Spacer rings on distal segments.](image)

Obtain the proximal connection ring and the tool connection platform from suppliers. Cut and process guiding cannulas with appropriate lengths and shapes. Purchase the gripper (end effector). Cut and process the outer covering steel tube.

![Figure 24: Covering steel tube (yellow), guiding cannulas (red) and proximal connection ring (green).](image)

d) Process and assemble the distal continuum segments; cover them with spiral strips and braided tubes.

![Figure 25: Spiral strips (yellow) and braided tubes (red).](image)

e) Weld the tube for gripper’s positioning. Weld gripper’s backbone with the
gripper. Weld the gripper on the positioning tube. Guide this backbone through its guiding cannula.

f) Laser cut the spacer rings inside the covering steel tube and weld the rings with the inner wall of the tube.

g) Guide the guiding cannulas through the covering tube. Let the cannula for gripper specially protrude from the tube (Fig. 26).

![Figure 26: The protruding cannula and backbone for gripper](image)

h) Weld the anti-buckling spacers to assemble the proximal continuum segments. Test their bending performance.

![Figure 27: Proximal continuum segments – outer (left) and inner (right).](image)

i) Adjust (balance) the arrangement and configuration of the guiding cannulas. Then solder them to the connection plate.

j) Guide all the other backbones into their own cannula. Compress (fix) them on the connection rings placed at the end of proximal segments.

k) Weld the connection rings at the end of proximal segments.

l) Finally, roughly test the bending transmission from proximal to distal segments by bending proximal ones with hands.

![Figure 28: The assembled dual continuum tool.](image)
6.2. The Base and Sterile Barrier

a) Put all gears to their corresponding shafts. Fix with set screws.
b) Place bearings on both sides of the shafts.
c) Place the above combinations on the plates. (All the above are from suppliers.)

d) Assemble the four shafts and aluminum columns on the base. Place couplings on the input/output shafts.
e) Assemble the sterile barrier: put the middle segments of couplings at the bottom of the barrier bucket and fix their positions with the covering plate. Fix the plate on the bucket with screws and nuts.

f) Test the movements of the middle segments of couplings.
g) Connect Maxon motors and their EPOS control cards.

Figure 31: Motors and control cards.

h) Assemble motors and EPOS control cards on connection boards. Then fix the boards around the sterile barrier.

Figure 32: The positions to place motors and control cards (red).

i) Make the motors align with shafts and couplings. Make three segments of couplings align with each other.

j) Fix the sterile barrier on the base by using nuts on shafts. Roughly test the motion transmission from base into the sterile barrier.
6.3. The Transmission Unit

a) Assembling the eight sets of screws, nuts, nut covers and anti-buckling structures:

- Preliminaries: Nut cover and nut (from suppliers), nut washer, nut side compressing bar (for compressing backbones), nut side compressing plate, long power screw, 2 nut lids, 3 long M2.5 screws and 3 small nuts, 6 M2 screws, 2 sliders, several washers.
- The anti-buckling structures to be connected are manufactured by laser cutting and soldering all the steel sheets.

![Image](image1.png)

Figure 33: Preliminaries. Anti-buckling structure for one input backbone on the left (red).

- Place the nut in the nut cover. Place the nut washer on top of it and use screws and nuts to fix the washer.

![Image](image2.png)

Figure 34: Nut, nut cover and nut washer.

- Use compressing bar and then compressing side plate to fix the input 1.2mm backbone onto the nut cover. Then assemble the anti-buckling structure and the sliders. Use M2 screws to fix the compressing structures.
b) Assemble the separation platform for gripper’s backbone and nut. Assemble the columns and sliders for this platform.

c) Hammer the plastic bearings (white in Fig. 36) into the plate.

Figure 36: The assembly of backbone driving structure for the gripper. Note again that the gripper’s driving nut needs a much shorter actuation length than the others.
d) Assemble the power screws on the plate and their washers. Then screw in the nuts (the backbone driving structures).

![Figure 37: The transmission unit in assembling.](image)

e) Now place the top plate. Adjust the positions of power screws and sliders so that the top and base plates for power screws are strictly parallel. Assemble the supporting shafts and aluminum columns.

![Figure 38: The transmission unit after placing the top plate (red).](image)

f) Adjust again to make sure all aluminum columns are bearing the weight of top plate evenly.
g) Put the whole unit upside down: assemble on the bottom plate the linking shafts for couplers. Place the other four aluminum columns.

![Figure 39: The transmission unit from upside down.](image)

h) Assemble the couplers. Then restore the whole unit upright. Place and fix the opposite gears on top plate with set screws.

i) Assemble the covering gear/shaft lid. Adjust the positioning screws so that every power screws will not suffer from backlashing. Finally assemble the outer fixing nuts.

j) Test the performance of this transmission unit, especially whether the friction is acceptable when the nuts are moving on power screws.

![Figure 40: The assembled transmission unit.](image)
6.4. Overall assembly

a) Assemble the dual continuum on the transmission unit:
   ✔ Guide all the 1.2mm input backbones through their guiding cannulas, then through the proximal segments. Lock them as well on the connection rings at the ends of proximal segments.
   ✔ Fix the dual continuum tool on the transmission unit by welding the cannulas.

b) Assemble the base and the sterile barrier on the DENSO with M6 screws.

c) Insert the transmission/continuum tool into the sterile barrier. Make sure the coupling segments are aligning.

d) With hands, one can fix the above sterilized tool on the barrier bucket simply by screwing in four set screws.

e) Perform electrical tests of the whole tool.

7. Test Results

The main challenge of this project, is surely to achieve a compact design with very small port size (1cm) and minimized actuation unit size (100 × 100 × 250 mm³), meanwhile satisfying the payload (5N), workspace (10³ mm³) and dexterity (6 DoF) requirements. We could see that now that our prototype manufactured from the final design is working normally, and most of the requirements above are self-evidently fulfilled. For the payload capability, we see that the surgery robot can pick up a 500g weight and complete movements like translation and rotation. The arm is not bending seriously.

8. Discussion

The design is overall reasonable in theory, but due to delicate design, the manufacturing process is quite complicated and for many parts high precision is required. Friction is hence the biggest (underlying) issue for our design. Not only does this issue increase the burden of motors, but it also leads to possible motion smoothness issues.

Lack of experience results in the non-optimization of manufacturing process. Rework for some parts makes our schedule much tighter than expected. In some cases, these problems lead to difficulties in assembly; they even further increase the friction.

Besides, there are as well small bugs in our current design. Examples are like the interference between the gripper nut platform and the anti-buckling structure; and for the root plate of guiding cannulas, the straight inserting holes make the cannula’s radius of curvature suffer from a sudden decrease, making the friction unacceptably large.
Still, our design has obvious advantages. The dual continuum is extremely compact and flexible. Many design ideas, criteria, and manufacturing processes from our design imply huge potential and could serve as inspirations for later developers.

9. Recommendations

For future designers, we urge them to put efforts in eliminating the small bugs in our design, and more importantly, to improve the manufacturing process, especially in term of precision. For improvements, the actuation unit size could be further reduced and the sterile barrier should be improved. We finally recommends them to research into the issue of actuation compensation, as mentioned in [4].

10. Conclusion

To facilitate surgeons’ operation and further reduce patients’ suffering and risks in minimal invasive surgeries (MIS), our team designed and manufactured a delicate electrosurgical tool for single-port laparoscopy (SPL) surgeries. Dexterity, compactness and thoughtfulness for practical uses highlight our design. Surely for a project on this scale, many improvements could be done in the future, but we have managed to fulfill most of the expectations and requirements set at the beginning of this capstone project.

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References

http://www.beltina.org/pics/open_surgery.jpg