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Mechatronic implementation in minimally invasive surgical instruments

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Abstract— **Minimally invasive surgery (MIS) has proven to be beneficial in providing outstanding results for the patients. However, studies have shown that the surgeon faces significant challenges whilst performing this type of surgery, ranging from poorly designed instrument handles, to potential harm to the surgeon due to awkward postures. Deriving from the crucial need to develop surgical instruments that fully address the needs of the surgeons while applying MIS techniques, a more ergonomic surgical instrument that implements mechatronic characteristics is hereby proposed. This concept instrument is aiming at minimizing post-operation injuries of surgeons and maximizing their kinetic abilities during surgical procedures, whilst also improving speed and accuracy in the performed task.**

I. INTRODUCTION

Although minimally invasive surgery (MIS) has proved beneficial for the patient, studies have shown that, while performing this type of surgery, the surgeon is faced with numerous challenges: restricted vision, difficult handling of the instruments, restricted mobility, difficult hand-eye coordination, no tactile perception, awkward and prolonged postures. During MIS procedures, surgeons can experience significant physical stress as they perform required tasks such as grasping, dissecting, cauterizing and suturing with hand tools; all of this can have a negative impact on the surgeon's fingers, wrists and arms [1]. Research has shown that the surgeon's posture during MIS is one of the main reasons for upper body pain and numbness of the upper extremities [2]–[5]. Furthermore, the current scissor-like handle design of the laparoscopic instruments has also been shown to increase surgeons' fatigue, discomfort and paresthesia in the fingers [3], [6]. Finally, studies have shown that the researched population faces pain in their hand or wrist (67%), back (33%), neck (28%), shoulder (17%) and elbow (11%) [7].

There has been great progress in improving the design of the conventional laparoscopic instrument and its ergonomic functionality, focusing mostly upon the handle. Additionally, efforts have been made to mechanically extend the degrees of freedom (DOF) of the instrument's end-effector. However, hand manipulation and extensive actuation force is still required.

The basic parameters affiliated with multiple injuries in the surgical population have been tackled by either applying ergonomic principles to conventional laparoscopic instruments or by introducing robotic surgery, as a de novo approach, to completely replace the traditional instrument and the laparoscopic techniques used. The Da Vinci surgical system [8], an industrial type of robot adapted for surgical applications, follows the surgeon's directions with the help of a specially modified hand manipulated controller. The controller increases precision by smoothing out hand tremor and confining false movements [9]. The robotic arm is easier to control than the conventional laparoscopic instrument, and its small instruments can reach inaccessible cavities, thus, being more flexible. Furthermore, the system places the surgeon in a more comfortable operating position while it also enables enhanced visualization. The negative aspects include: i) high purchase and maintenance costs, ii) lack of force feedback and tactile sensing, iii) the surgeons must undergo special training to be able to perform using the robot and, iv) large volume of the overall system, which renders it immobile and limits the area of possible applications.

A similar tele-operated approach is adopted by MiroSurge with their instrument (MICA) [10]. Due to the robot's light weight, unlike the Da Vinci system, alternative setups that include ceiling/wall mounting are feasible. MICA is a cable-driven task specific tool with a seven DOF force/torque sensor and a two DOF wrist, as well as a functional end-effector, which are controlled by three motors.

It has been concluded that in order to overcome the economic and technical barriers of applied robotics, surgical robotics could preferentially have an assistive role with respect to traditional MIS procedures, rather than providing a completely new surgical approach [11]. The research carried out by [12] considers an increased number of DOF in the MIS instrument. The authors developed a dexterous robotic hand-held instrument for suturing with a total of six DOF, manipulated with a finger-operated handle. The ergonomic design of the handle and the force transmission system are not ideal, as the current prototype instruments do not produce the required force/torque output for surgical procedures [12].

An example of an ergonomic articulated MIS grasper is the Intuitool [13]. Taking into consideration the basic principles of ergonomic design in order to maximize the functionality of the tool, central injury factors such as the hand size of the surgeon and peripheral injury factors are minimized as it is finger-manipulated through a controller. Research also focused on the different navigation switches and their ergonomic locations. Four different type of controllers, a touchpad, a mouse button module, a mini-joystick module and a micro-joystick placed on an ergonomic location on the handle, were tested. The authors conclude that the ergonomic principles are best served by the touchpad and the micro-joystick controllers.

In order to fully address the needs of surgeons, an er-

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gonomic surgical instrument that implements mechatronic characteristics is hereby proposed. Its mechanical design (Sections II-A and II-D) along with its actuation mechanism (Section II-B) are described and its workspace is analyzed (Section II-C). Finally, its ergonomics are discussed (Section III) and some initial tests are presented (Section IV).

II. INSTRUMENT DESIGN

As the literature suggests, the final instrument should be a complete standalone system and composed of: the articulation mechanism and the force transmission control system with the interconnecting shaft and attaching platform. The assembly must be developed into a rigid structure that can be easily attached to the handle with minimal calibration requirements. This function is of great importance because it will not only reduce the cost of the procedure and device maintenance, by allowing the same instrument to be used multiple times after sterilization, but also different instruments can be mounted instantly using the same handle.

A. Articulation mechanism of the end-effector

The system consists of two components: i) a socket (Fig. 1 - right) that incorporates the railing and wire control components and ii) a ball with a wire crimping system which also acts as a motion stabilizing and positioning factor. The socket encapsulates the ball and has four areas of support on opposing positions on the ball.

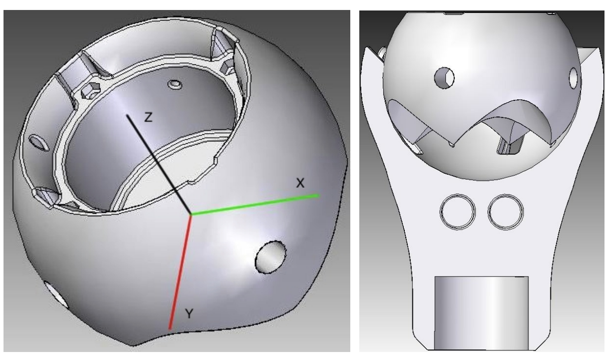

Fig. 1. Ball joint - axes configuration

The desirable motion and control design is inspired by the human eye's movement mechanism, and the way that the muscles control the inner eye ball with absolute precision. It is a perfect representation of a ball joint mechanism with neurons passing through the center of the eye and actuating muscles attached to the surface of the eye ball. Six muscles attached to the external surface of the eye allow a 75° rotation and create a four point control that enables two DOF, while all essential neurons are connected in the center of the eye. With this setup, the center of the eye is positioned by retracting one or a pair of the six muscles [14].

In the similar mechanical setup, the ball joint mechanism (Fig. 1) carries two pairs of wires, attached and positioned in such a way that when actuated, they allow a simultaneous pull and rotation in a similar way to the eye's muscles. When driven by wires attached to the inner surface of the ball and passing through it, the ball has a range of movement of ±28-32° in the pitch and yaw axes within safe breaking limits. This range can be further extended to ±40° by attaching the wires to the external surface of the ball. The two pairs of wires must pass through the ball of the joint so that it does not block their motion, create kinks or damage the wires. To accomplish the desired motion in this approach, the wires are attached at four, diagonally opposing points on the ball's circumference creating a four point control system. The four points share the plane with the center of mass of the ball.

For the Z axis rotation (roll) to be achieved, the ball must maintain a defined alignment within the socket, having the axis of rotation on a fixed orientation according to the unified frame of reference. This is needed in order for the ball to counteract rotational forces when actuating the rotating link (shown in Fig. 2). Although four points are needed to actuate the system, only two points are required to maintain kinematic stability. A positive aspect of this design is that one of the two points is always confined when the ball is rotated, maintaining the ball fixed and, thus, resulting in a constant alignment of the ball. The crimping system used to attach the wires to the ball, was designed to also provide kinematic stability. Four specific areas at the bottom side of the ball allow the desired rotation range without blocking the wires (Fig. 3). These arches allow the wires to slide on the surface of the ball without damaging them. The wires pass through them and are redirected through the rails by changing the initial entry angle.

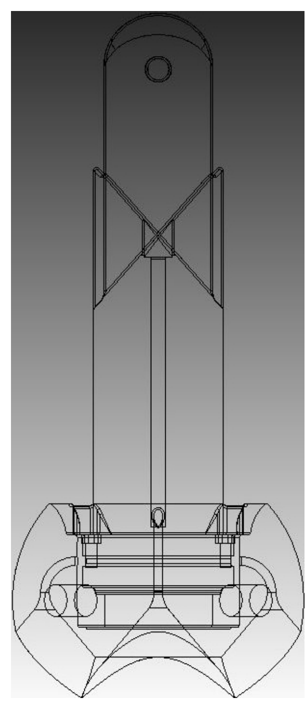

Fig. 2. Ball and rotating link with internal railing system

By positioning two support points for the roll, pitch and yaw axes (see Fig. 1), each rotation about those axes can be actuated by a single pair of wires controlling two diametrically opposing points on the ball. In order to increase the

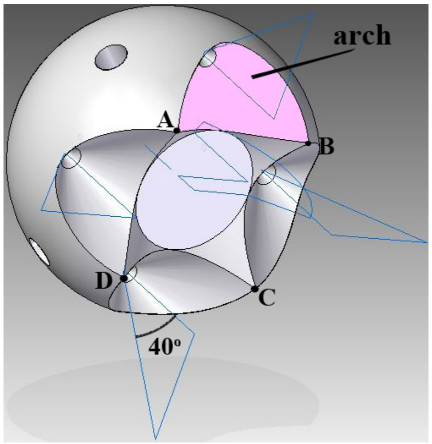

Fig. 3. Ball component

applied force and further improve the control, each rotation is actuated by two servo motors (1.3 Nm maximum torque). In this way, each rotation of the ball is based on four wires. This results in a mechanical structure actuated by symmetrical, isocentric, counteracting and balancing forces. A control tension was achieved by combining all three components (ball, socket and wiring system), giving $\pm 40°$ of rotation and enabling 2 DOF about a unified plane of rotation (pitch and yaw). Two additional pairs of wires are passing through the ball, responsible for the tool's opening/closing and rotation about Z axis (roll).

The arches create a tetrahedron surface (formed by points A-D in Fig. 3) to support the ball even in the far extreme positions. On the first pair of arches, the internal rail following the surface forms a sliding surface. The wires bend in order to enter the inner area of the ball in a vertical direction where the rotating link is positioned. The line of entry is parallel to the ball axis, while the force exerted is in the X-Y plane. The second pair of arches enables the pair of wires to pass through the ball freely without blocking its motion. This is important as the actuating system of the tool is a pulley system and any extra force would cause the tool to close unexpectedly. The ball is designed to allow the rotating link to be placed within the socket, positioned firmly on the internal ball allowing a continuous rotation with minimum friction, while a sealing cap allows a tight fit. The rotating link introduces an additional DOF along the Z axis, giving it 3 DOF in total, supporting the force transmission system at the same time. The internal railing system is shown in Fig. 2.

B. Force transmission system

The force transmission system from the rotating link to the grasper is a unified assembly so that the rotating link acts as a support base for the grasper and when it rotates, the grasper rotates as well. The grasper, the shield part (Fig. 4) and the internal micro steel bars (Fig. 4) create a kinematic chain that can actuate the grasper safely. The top of the rotating link has a positioning point for the grasper, also creating a fixed geometrical point in the kinematic chain of the mechanism. The micro steel bars responsible for the opening/closing of the grasper are positioned in two specially designed slots, so that they can move inside the shield. The slots have been created based on the geometric displacement of the micro steel bars from closed to open positions, enabling the grasper to open up to 45°. The center of rotation of the tool is positioned on that point (Fig. 5), initializing the kinematic chain. Modified linkages at the end of the grasper link with the micro steel bar, following the geometry based on the kinematic chain (Fig. 5).

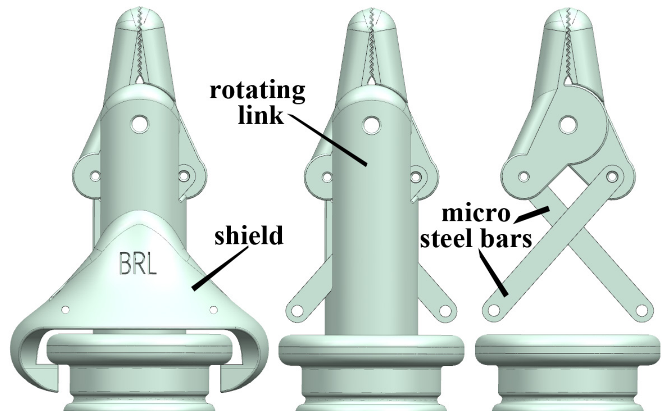

Fig. 4. Grasper assembly

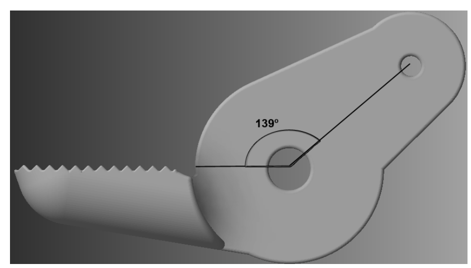

Fig. 5. Geometry of the grasper

The other side of the micro steel bars is connected internally to the shield to enable a linear force transmission and allow the control wires to be attached to the grasper-shield-micro steel bars subsystem. The shield completes the kinematic chain. It joins the rotating link, incorporates the micro steel bars on the top, and hooks to a steel needle thrust bearing. As seen in Fig. 6 the inner shaft of the thrust bearing is on a fixed alignment with the attached control wires but can rotate freely. While the link internally rotates, it also rotates the shield and the grasper. This link, connected to the shield part and the rest of the assembly, can transfer constant force in a linear fashion using minimum friction configurations.

In order to comply with medical safety requirements, this unified force transmitting system was created in such way that it does not harm the patient while moving or coming in contact with tissue. The shield part has a task-oriented shape to enclose all moving components and to insure the functionality of the grasper. Finally, the part bellow the thrust

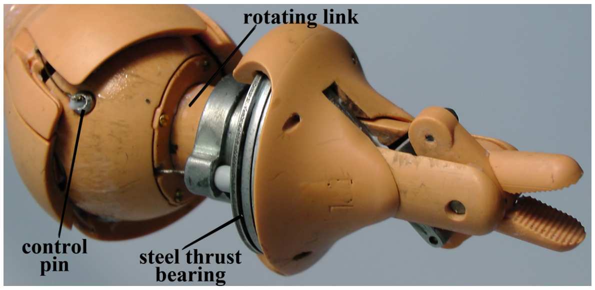

Fig. 6. Grasper assembled with the steel thrust bearing

bearing allows safe positioning of the wires inside the shield.

C. Motion theory

The ball joint is designed to allow a $\pm 40^\circ$ range in two DOF without affecting the inner passing wires or blocking the mechanism. The motion is not interrupted even if all functions are used at the same time, allowing to simultaneously open/close, rotate and position the grasper of the instrument. Apart from the additional DOF (roll), the difference between the human eye and its mechanical equivalent lies in the actuating techniques. In order to increase the force output of the articulation mechanism, the rotation per axis is handled by two motors instead of one muscle.

The ball has four crimp terminals (control pins in Fig. 6) attached to two pairs of wires controlling the motion of the ball. Accordingly, the socket has four spacings that the pins are placed within, as well as 1 mm rails, in order for the wires to pass through and reach the ball. As the ball reaches extreme positions, the control pins can leave the socket spacings. However, since the size of the pins differs per pair of wires (6 mm and 6.92 mm), there is always one control pin inside a socket spacing for every position and rotational degree per axis, providing substantial stability, fixed alignment and minimized manufacturing tolerances of the articulation mechanism. In this way, there are only four positions (45°, 135°, 225° and 315°) within the ball's workspace that are handled by only one motor, thus increasing control stability.

In order for the ball joint to be actuated, a specific layout of the wires must be achieved. In Fig. 7, a 3D illustration depicts the position that the wires must have in order for the mechanism to be driven. The two pairs responsible for the actuation of the ball are positioned perpendicular to each other. The remaining two pairs follow the same pattern, placed with a 45° offset. As shown in Fig. 4, a 9.12 mm displacement along the Z axis (axis of the shaft) is required to provide a 45° functional opening for the grasper with a 0.2 mm/degree ratio. Consequently, the final size of the rotating link is 42 mm, forming the reachable workspace of the tool.

D. Wire control gear box

For the instrument to be a standalone device, a wire control gearbox was made integral to the shaft. In order to meet the requirements of handle ergonomics, the mechanical design has to be further optimized, also delivering a robust force output at the end-effector. This mechanical assembly

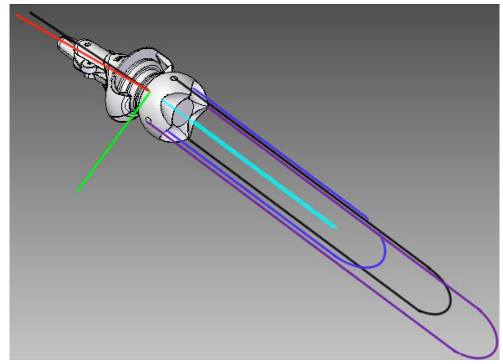

Fig. 7. Eight cables positioned for actuation of the tool

actuates the components and applies tension control through the gearbox. The shape accommodates the motors to provide a compact design as presented in Fig. 8.

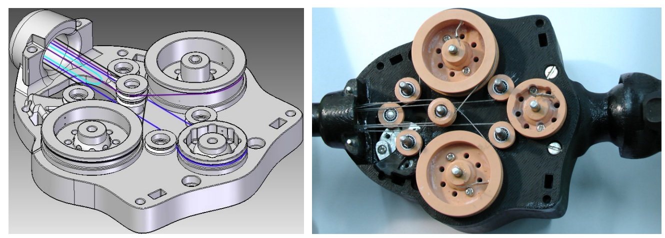

Fig. 8. Gearbox assembly with wires setup

The gears' diameter is determined by the driven side's diameter, adding friction parameters and mechanical force distribution restrictions to the equation. The curvature of the box houses the motors and allows easy detachment of the handle. The same handle can, therefore, be used with different instruments. Redirection bearings allow the control wires to be guided through specific paths. The layout of the wires is crucial for the actuation of the mechanism. The position of the bearings and the gears allows the appropriate positioning of the wires with respect to the connecting shaft. The layout of the bearings and the wires is shown in Fig. 8.

The gear box has a simple calibration technique for resetting the position of the gears along with the initial position of the articulation mechanism. By pulling the mechanism to a direct, straight position, the attached wires force the gears to be reset to their initial position, enabling a direct attachment to the servo motors. Aiming at space and material reduction, a protective surface was designed to cover the moving internal parts. The whole assembly can be easily disinfected and sterilized, therefore it can be safely used for a number of procedures thus reducing the cost of the surgery even further without reducing the efficiency or the safety of the operation. The 3D assembly of the prototype instrument is shown in Fig. 9.

III. HANDLE ERGONOMICS

Different parameters must be considered in addressing an optimal ergonomic design. The designed handle, when fully gripped, must be a continuous extension of the axis created

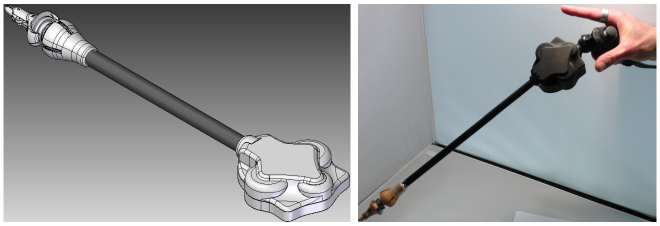

Fig. 9. Designed instrument and manufacturing result

by the central carpal tendons of the hand. This involves the Flexor carpi radialis and the Palmaris longus tendons responsible for the gripping ability of the palm.

Based on [15], a three-digit control concept was selected for the handle design. Grip and stability was achieved by placing the shaft underneath the index finger and pairing it with the inline grip, thus providing an anti-slip protection by design. In order for the traditional inline handle design to be improved, the final design must implement certain functional characteristics and meet specific ergonomic criteria. The proposed improvements are:

- Manual shaft positioning at a preferred angle provides certain degrees of rotation through a joint
- A quick fit technique addresses the hand size problem with anti-slip areas
- Navigation switches are ergonomically positioned
- The center of mass must be positioned as close as possible to the center of the palm
- The tool shaft must be aligned to the central carpal tendon
- Structural rigidity should be maximized whilst minimizing weight

Certain design configurations could not be avoided in this version of the instrument, such as the use of the motor box. Although it increases the total weight of the instrument (which is 604 gr in total), this solution is cheaper, safer and more functional. Smaller actuators and more compact gears could be used so that the motors and gear box could be avoided by inserting the motors into the handle, thus reducing the total weight and size of the instrument. However, an ergonomic handle part was created, enabling the same handle to fit a variety of shaft sizes.

A. Handle Design

The basic design configuration must enable the same handle to be used with a different set of instruments, while it can fit a wide range of hand sizes. To accommodate both requirements, the handle assembly is composed of two parts, as seen in the exploded view of Fig. 10 (1, 2, 3, 5), in order to support the motor box and incorporate the control and electronic elements. An ergonomic handle specifically developed for the task can be positioned underneath, completing the assembly (Fig. 10 - 4). The rigid body of the handle, composed of the two handle parts and the motor box (Fig. 10 - 1, 2, 3), is designed as a physical extension of the shaft.

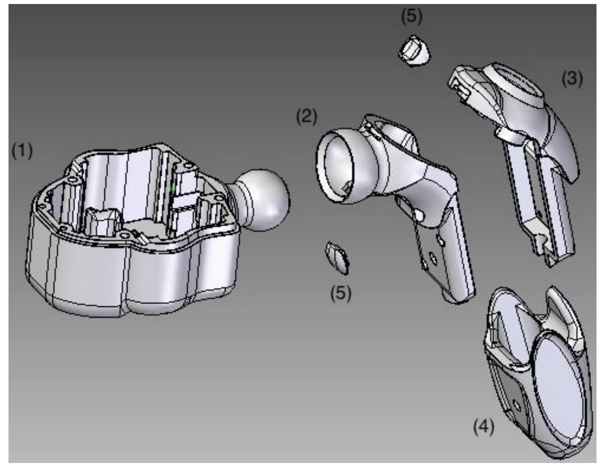

Fig. 10. Full design in exploded view

B. Navigation switches and location

Appropriate positioning and layout of the navigation switches and the thumbstick can increase the ergonomic efficiency. Their mounting onto the handle, with respect to the fingers and the thumb, is of great importance as it can greatly decrease the functionality of the mechanism. In order to explore this, different handles were built and analyzed, taking in consideration different hand sizes. An example is shown in Fig. 11.

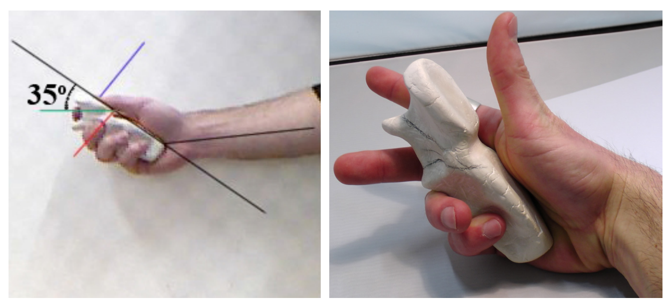

Fig. 11. Left: Grabbing axes analysis. Right: Fingers' angle

A comfortable angle for the thumbstick was determined to be 35° with respect to the palmar axis and the hand's palm line. The navigation switch positions were determined based on the three fingers when extended, as seen in Fig. 11. Placing the navigation switches in these locations allows the handle to be stabilized by the two smaller fingers and the palm, with further balancing between the middle finger and the index. The fingers and thumb can control all the switches and the thumb-stick simultaneously.

C. Handle position joint

The handle's joint with the shaft can increase the ergonomic efficiency of the design even further. The shaft of the traditional laparoscopic instrument is rigidly connected to the handle, limiting the mobility of the surgeon. As a result, the surgeon is forced to adapt his/her position to the tool. The joint connecting the handle and the motor box (Fig. 12) allows for an angle of up to 32° between the two. This provides better positioning for the handle, and improves the surgeon's posture and ease of use of the instrument.

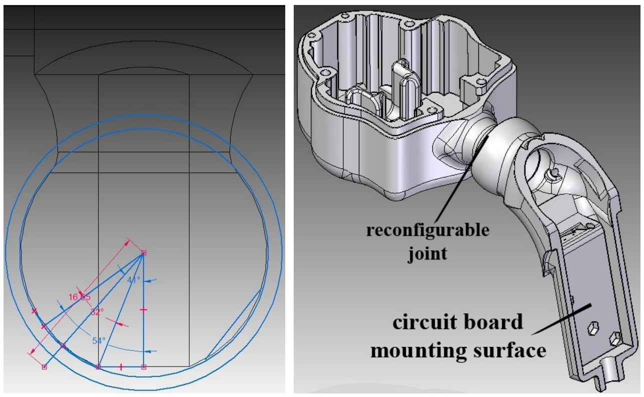

Fig. 12. left: Joint overview. Right: Motor box

The joint is hollow, which allows the motors' wiring to be passed through and get connected with the circuit board positioned inside the handle (Fig. 12 - right). The appropriate spacing was considered to ensure the free movement and rotation of the positioning joint. To address the problem of replacing or using multiple instruments, the motor box was incorporated within the handle. The shape of the motor box and the accompanying gear box on top utilizes the least possible material while retaining the best possible configuration for the wires' layout and the embedded motors (Fig. 12 - right). While the shape curves around the motors, it creates a stable support base for the gears, thus minimizing losses due to vibrations. The internal space was shaped to keep the motors tightly in position while creating an internal railing system for the wiring.

IV. CONCLUSIONS AND FUTURE WORK

Regarding its ergonomics, the presented instrument provides better manipulation whilst reducing muscle fatigue by using actuated motion of an extended number of DOF in the laparoscopic instrument. This is achieved at very low cost, especially when compared to complicated surgical robots. Combining multiple ergonomic characteristics, the positive aspects introduced by this device can be easily distinguished:

- Reduced range of hand and finger movements to achieve grasping and rotation
- Reduced muscle and tendons fatigue as less physical force input is needed by the user
- Faster and safer positioning for the instrument's end effector
- Potential for reducing overall surgical procedure time, while increasing performance of the surgeon

A user study, where the same task is performed initially using a conventional laparoscopic tool and then using the proposed mechatronic instrument, is currently in progress. The task is to grip an elastic ring and place it on one of 7 target pins.

The final product will be of a positive contribution towards the surgical world, as it will provide the hands of the surgeon with low-cost cutting edge technology instruments.

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