ASTEMA: Design and preliminary performance assessment of a novel tele-microsurgery system

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Abstract: To overcome the challenges of reconstructive microsurgery, a teleoperated robot called ASTEMA was built to help surgeons performing microanastomoses. The surgeons' needs are first analysed then the design steps are summarized. This robot is composed of three orthogonal linear actuators and a spherical wrist with its remote center of motion at the instrument tip. Geometric model of the spherical wrist was calibrated through mathematical optimization in order to compensate for imperfections of machining and assembling. Two preliminary experiments were carried out to assess the ASTEMA performance. The first was performed with a simple circular position trajectory. The second was a complex angular trajectory. Results show a significant improvement of gesture precision with respect to manual trajectory execution. They also show that subjects instinctively compensate the errors from the non-ideal wrist, thanks to visual feedback from microscope.

Keywords: telerobotics, microsurgery, medical devices, design methodology

1. INTRODUCTION

Microanastomosis is a microsurgical act that consists in stitching together two very small blood vessels so as to restore blood circulation. This gesture is performed under a microscope as shown in figure 1. It is used in several delicate reconstructive surgery procedures requiring distant tissue transfer like face allograft, torn member saving, finger replantation and breast reconstruction. In particular, the free flap transfer consists in removing a flap of skin and fat tissue with at least one vein and one artery, and to transfer it to another place on the patient. This procedure requires both speed, to avoid necrosis of the removed graft, and high accuracy to perform efficient microanastomoses and restore blood flow in the graft.

An example of reconstructive surgery is breast reconstruction by DIEP (Deep Inferior Epigastric Perforator) after an ablation due to a cancer. In this surgical operation, the microsurgeon raises a flap from the abdominal wall and grafts it in place of the removed breast. In current practice, the surgeon performing a DIEP flap procedure has to split the pectoralis major and remove a piece of rib, in order to reach the internal thoracic vessels large enough to perform anastomosis safely. Decreasing invasiveness requires using vessels closer to the skin, called « perforator » vessels, with an outer diameter below one millimeter. But this makes anastomoses challenging, mainly because of the surgeon's tremor whose magnitude becomes crippling at this scale as shown in figure 2. This physiological limitation prevents the vast majority of microsurgeons to reach such super-microsurgery skills.

Facilitating the surgeon's gestures through a robotic system would decrease both complexity and invasiveness of these procedures, by making anastomoses easier on tiny subsurface blood vessels.

To reduce the surgeon's tremor and increase gestures accuracy, a teleoperated system seems a good solution. Most of the existing teleoperated surgical systems are dedicated to minimally invasive keyhole surgery. Among other interesting characteristics for assistance to surgery, these systems allow scaling down the surgeon's gestures,

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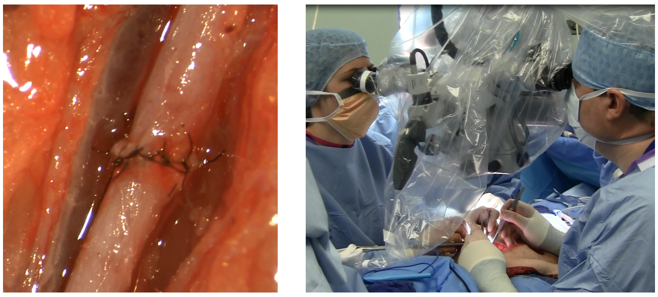

Fig. 1. On left: Microanastomosis with a 1.2 mm diameter vessel. On right: microsurgeons during a DIEP operation.

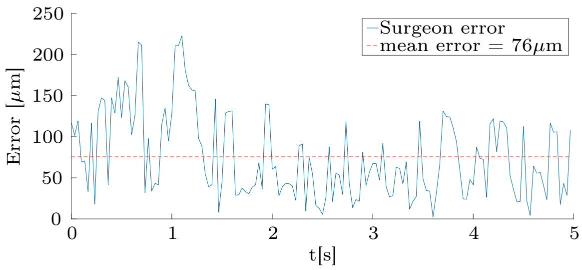

Fig. 2. Surgeon tremor when trying to keep an instrument stationary under a microscope (acquisition at 30 Hz, resolution 6.5 μm/px, optical magnification x40)

filtering his/her movements and reducing unintentional tremor.

Some studies demonstrated feasibility and interest of telerobotic assistance to perform microanastomoses with the commercialized da Vinci system (Intuitive Surgical, Inc.) [Katz et al. (2005); Liverneaux et al. (2013)]. However, general motion accuracy and instruments size are limiting factors to perform supermicrosurgery with this robot [Katz et al. (2005); Taleb et al. (2008)]. Moreover, the da Vinci system is cumbersome and difficult to introduce or remove from the operating workflow. The latter constitutes an important limitation as, usually, microanastomosis is only part of a longer procedure that combines acts of normal surgery and microsurgery.

The RAMS workstation from Jet Propulsion Laboratory [Le Roux et al. (2001)] and a recent master-slave system named MUSA from Microsure [Cau (2014)] are microsurgery assistants with higher precision and smaller bulkiness than the da Vinci system. But up to now they double the operation time because of interface limitations [Mitsuishi et al. (2013); Saraf (2008); van Mulken et al. (2018a)]. Other robots were also proposed for teleoperated microsurgery. For example, the telemicrosurgery system developed at Tokyo university for open neurosurgery [Mitsuishi et al. (2013)] or the Robotol system developed at Sorbonne university for middle ear surgery [Miroir et al. (2012)]. However, most of them show the same drawbacks as the da Vinci or are devoted to specific surgical specialties for which microanastomosis is not a major issue.

Another principle is the parallel robotic comanipulation where both the operator and the assistive device hold the instrument simultaneously. The Steady Hand [Mitchell et al. (2007)] and the manipulator developed at KULeuven [Gijbels et al. (2013)] are examples of comanipulated robots. These systems use active or mechanical damping to filter the instrument movements. The Micron [MacLachlan et al. (2012)] is a serial comanipulation instrument. In this case, the surgeon holds a handle that can actively move a needle for filtering the tremor. These comanipulated devices are used for instance in eye microsurgery, for epiretinal membrane peeling or retinal veins cannulation with a very thin needle. However, this kind of pointing task is very different from the anastomosis gesture whose kinematics is much more complex, with higher velocities and accelerations. Moreover, the applied damping slows down the gesture execution significantly and thus increases the time of operation.

In this context, we developed the ASTEMA, Adaptive Scaling TEleMicrosurgery Assistance. It is a teleoperated robot dedicated to microanastomosis and whose purpose is to increase accuracy and dexterity of the surgeon while limiting the increase in operating time. Its resolution, size, workspace and speed are consistent with the specific requirements of the microanastomosis context.

This paper focuses on the design process of the ASTEMA robot. First, it presents the needs analysis made with the help of several microsurgeons. Then it details the implementation of the robot. Finally, it describes and analyses the first experiments showing that the requirements are fulfilled.

2. NEEDS ANALYSIS

To ensure a good matching between the ASTEMA system and the surgeons' requirements, a needs analysis was carried out based on quantification of gestures and discussion with microsurgeons. The main technical requirements associated with microanastomosis are: the workspace corresponding to microanastomosis gestures, the accuracy, the speed of gesture, the force capacity and the ability to change instrument rapidly.

2.1 Instrument workspace

The surgeon movements during a microanastomosis on a 2 mm diameter vessel from a rat were analyzed and quantified using a set of visual markers and a 3D camcorder. The instrument workspace for instrument tip position is encompassed into a cuboid of 40x50x40 mm^3 as shown in figure 3 (left). The workspace for instrument orientation is included into a cone of 87° as shown in figure 3 (right), and an instrument self-rotation of more than 360° is exploited. Experiment details can be found in [Vanthournhout et al. (2015a)].

2.2 Accuracy

The required accuracy is not identical during the entire procedure. The microanastomosis procedure can be broken down into several steps: clamp handling (to close the vessel during the procedure), vessel preparation, stitches with needle insertion, and knots. Not all steps need the same accuracy. The most difficult gesture is needle insertion because of the size of the vessel and because of the importance of insertion position for the impermeability of the anastomosis. Figure 2 shows the tremor of a surgeon who

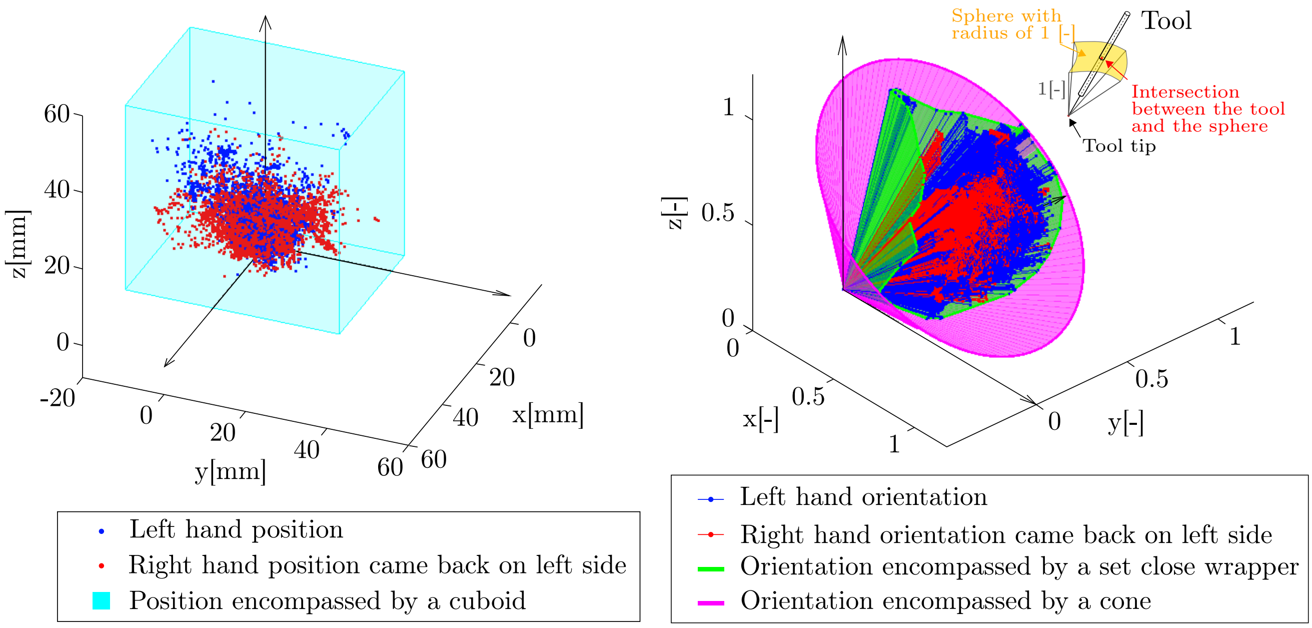

Fig. 3. Workspace of a microanastomosis performed on a rat by a left-handed microsurgeon. The vessel is on the y-axis. On left: instrument tip position. On right: instrument orientation. The angular position is represented by points which correspond to the intersection between the instrument and a sphere centered on the instrument tip with a dimensionless radius of 1. Adapted from [Vanthournhout et al. (2015a)].

tries to keep an instrument tip steady above a target. The average tremor amplitude for a human is around 100 μm with a frequency between 6 and 15 Hz [Veluvolu and Ang (2010); Safwat et al. (2009)] while authors estimate the required precision is around 10 μm for microanastomosis (1% of circle circumference with 0.3 mm diameter).

Very fine gestures like needle insertion need a high positioning accuracy along small angular displacements (around 15 to 20°). Gestures like making a knot need in contrary large angular displacements and are compatible with the human precision (around 100μm).

2.3 Rapidity

The operation duration is also important because if the flap is not revascularised fast enough, the risk of ischemia-related complications such as necrosis becomes significant [Shaw et al. (1996)]. Moreover, the longer the patient is anaesthetized, the higher the risk of complications.

Figure 4 shows the speed of gesture during a stitch according to the position. These data come from the workspace experiment described in section 2.1. Gestures performed close to the vessel (e.g. needle insertion) are slow (≤25 mm/s) and are associated with the higher required accuracy. In contrast, when the instrument tip is far from the vessel (e.g. to pull the thread), velocity rises up to 130 mm/s and precision is less important. An intermediate area, where the surgeon makes the knots, shows a mix between slow and moderate speed (≤50 mm/s).

2.4 Force capacity

To insert a needle, the force varies between 30 and 50 mN [Mitsuishi et al. (1997)]. It is often so low that

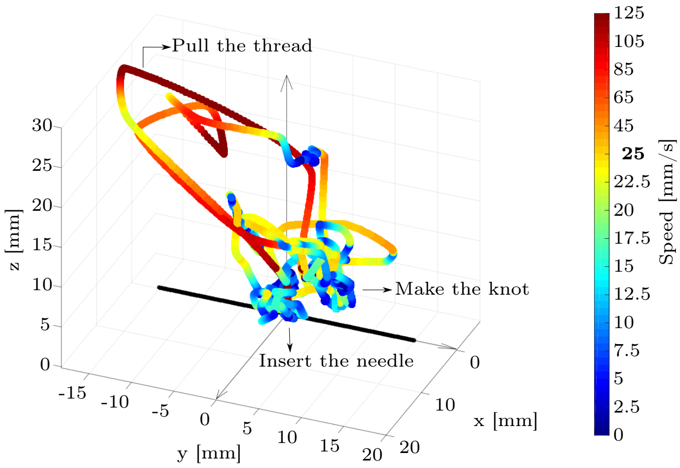

Fig. 4. Speed of surgeon's main-hand according to position during one stitch followed by a knot.

the surgeon can hardly feel it [Panchulidze et al. (2011)]. Currently, the surgeon gauges the applied force from visual feedback of the tissue deformation. The clamping force is around 10 to 80 mN to hold a blood vessel and 1 to 2 N to hold a needle or a thread [Mitsuishi et al. (1997)]. Here, force feedback is more important because of the risk to bend or break the delicate needle. Indeed, to make an anastomosis on vessels under 1 mm diameter, a needle with a diameter below 50 μm (needle reference 11/0 or lower) is required.

2.5 Instrument exchange

The surgeon uses different types of instruments according his/her habits. The most popular instruments are a clampgripper for handling the clamp, micro-scissors to cut vessel and thread, a curved or straight micro-gripper and/or a needle holder to handle vessels, tissues and the needle. Analysing microanastomoses during DIEP procedures indicates that the mean time for instrument exchange is 6 seconds while an admissible upper limit for these exchanges is 10 seconds.

To sum up, the requirements imparted to the ASTEMA design are:

- a bimanual instruments holder;
- overall dimensions suited to the microsurgical environment microscope;
- a positioning accuracy of 10 μm;
- a force capacity of more than 2 N;
- a minimum workspace in position of 40x50x40 mm^3 and a workspace in orientation encompassed by the close wrapper of the figure 3;
- a speed of 100 mm/s in translation, of 56 $^\circ$/s for the transverse angular velocity (velocity without the self-rotation axis) and of 700 $^\circ$/s for the self-rotation axis angular velocity. These speeds include 99.9% of data [Vanthournhout et al. (2015a)];
- no force feedback except the clamping force feedback;
- a possibility to change the instruments in maximum 10 s.

3. IMPLEMENTATION

As mentioned above, the ASTEMA should be a bimanual telerobotic system designed for one surgeon. In a first step however, we developed a prototype of the right hand device only. This prototype complies with the above requirements.

3.1 Topology

Six degrees of freedom are needed for controlling the instrument position and orientation. So the topology we chose is a classical decoupled structure with a remote center of motion (RCM) like the ones proposed in [Miroir et al. (2012)] for middle-ear surgery or in [Mitsuishi et al. (2013)] for general tele-microsurgery. It includes three linear positioning tables with high accuracy (± 1 μm) and a high-stiffness spherical wrist with the last motorized axis coinciding with the instrument axis as shown in figure 5. The instrument tip is placed on the RCM. So in principle, the linear and angular movements are decoupled and the accuracy of the linear tables motion directly determines the accuracy of the instrument tip linear motion.

3.2 Optimization of the wrist geometrical parameters

A dimensional optimization of the wrist was carried out regarding the constraints of workspace (attainable orientations) and avoidance of collisions with the environment close to the anastomosis (the patient and the microscope). The linear actuators were chosen such that their strokes encompass the entire required workspace. This portion of the robot is at a certain distance from the anastomosis and thus only slightly constrained in terms of size.

The spherical wrist topology is defined by 7 parameters as shown in figure 5:

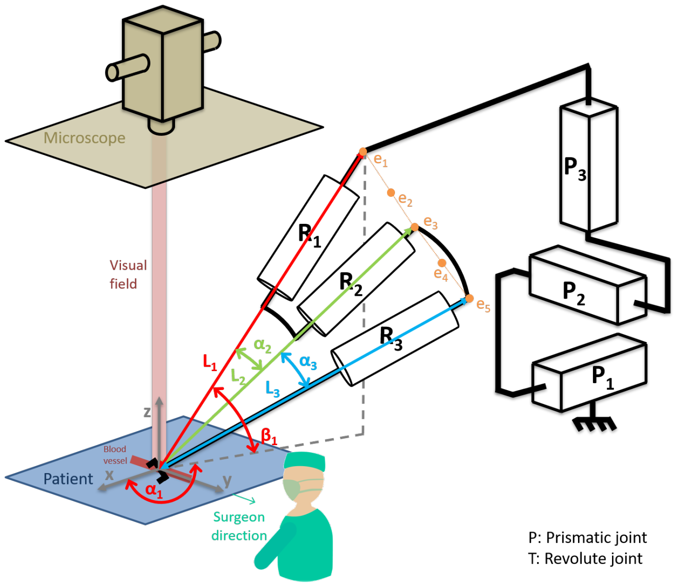

Fig. 5. Robot topology and spherical wrist parameters. The blood vessel is parallel to y axis and the surgeon is in $y > 0$ and $x = 0$. The environment is represented by two planes for the patient and the microscope and one cylinder for the surgeon's visual field. Points e_1, e_2, e_3, e_4 and e_5 form the robot shape. Scale is not respected for scheme readability.

- α_1, β_1 define the orientation of the first wrist axis with respect to the coordinate system aligned with the linear axes;
- α_2 is the angle between the first and the second wrist axis;
- α_3 is the angle between the second and the third wrist axis;
- L_1, L_2 and L_3 are the distances between the instrument tip and the furthest physical points of the robot along its revolute axis (denoted points e_1, e_3 and e_5 respectively). These parameters do not come in play in the wrist geometric model but characterize its maximal physical envelope. In particular, these distances depend on the location of the 3 motors along the wrist axis.

These 7 parameters were optimized according to 3 constraints and 2 objectives:

- Constraints
  - · Reach all the measured workspace;
  - · Do not collide with the environment (microscope, patient and left robot);
  - · Do not pass in the surgeon's visual field.
- Objectives
  - · Maximizing of the dexterity ($dext = \sigma_{min}/\sigma_{max}$ with σ_{min} and σ_{max} the minimum and maximum eigenvalue of the jacobian);
  - · Maximizing of the distance between the robot and the environment (minimum distance between the robot's wrapper (e_1 to e_5) and the microscope, patient and visual field planes and cylinder).

The optimization was based on a systematic exploration of all parameters (cover method). Each parameter range was

Table 1. Parameters discretization during optimization. Come from [Vanthournhout et al. (2015a)].

	First optimization: large range and rough interval			Final optimization: small range and fine interval		
	Min	Step	Max	Min	Step	Max
L_1 [mm]	100	20	220	175	5	230
$\alpha_1[\circ]$	-80	2	80	-68	1	-56
$\beta_1[\circ]$	40	2	80	51	1	61
L_2 [mm]	100	20	220	150	5	230
$\alpha_2[\circ]$	20	2	60	45	1	50
L_3 [mm]	100	20	220	90	5	190
$\alpha_3[\circ]$	20	2	60	42	1	53

restricted by an inferior and a superior value, discretized by small steps and all possible solutions were tested (see table 1). If a candidate did not fulfill the constraints, it was rejected. If it did, it was classified according to the 2 objectives of dexterity and distance to obstacles. Three exploration stages were carried out, starting by a global exploration with large ranges and rough intervals and then by focusing the exploration with smaller ranges surrounding the best candidates of the previous stage and finer intervals. The final parameters are $L_1 = 190$mm, $\alpha_1 = 240°$, $\beta_1 = 58°$, $L_2 = 210$mm, $\alpha_2 = 46°$, $L_3 = 160$mm and $\alpha_3 = 45°$. More pieces of information about this optimization can be found in [Vanthournhout et al. (2015a)].

3.3 Geometric and dynamic models

Theoretically, in such a kinematic structure, position of the instrument tip and orientation of the instrument can be controlled in a decoupled manner by the actuators of the linear tables and of the wrist respectively. Therefore the geometric models of the linear tables and of the wrist were derived independently and take the form of a position transformation matrix and of an orientation transformation matrix respectively. By combination, the global geometric model is computed as a transformation matrix R_G:

$$R_G = R_P(x_p, y_p, z_p)\ R_O(\gamma_1, \gamma_2, \gamma_3) \quad (1)$$

With R_P the position transformation matrix, R_O the orientation transformation matrix, (x_p, y_p, z_p) the positions of each linear table and (γ_1,γ_2,γ_3) the angles of each rotation axis in the wrist.

The linear table model is defined directly by

$$R_P = Tr(x, x_p)\ Tr(y, y_p)\ Tr(z, z_p) \quad (2)$$

with $Tr(i, j)$, being the translation transformation matrix along axis i of a distance j. The orientation transformation matrix is:

$$R_O = Rot(z, \pi/2 + \alpha_1)\ Rot(x, -(\pi/2 + \beta_1)\ Rot(z, \gamma_1)$$
$$* \ Rot(x, \alpha_2)\ Rot(z, \gamma_2)\ Rot(x, \alpha_3)\ Rot(z, \gamma_3) \quad (3)$$

with $Rot(i, j)$, being the rotation transformation matrix around axis i of the angle j. R_P and R_O are kept as matrix multiplication for readability.

A dynamic model was developed using Robotran, a symbolic software devoted to multibody systems [Fisette (2017)]. It allowed us to compute the required motor torques. We took into account the motors weights and the required instrument acceleration when the maximum angular acceleration and speed are imposed in all directions, in each point of the angular workspace. We found that the average torque for rotary actuators 1 and 2 must be at least 320 mNm (1130 mNm in peak) and 145 mNm (150 mNm in peak) respectively. The torque for rotary actuator 3 is not significant because the robot instrument is aligned with its axis and has low rotational inertia and external load. As for the linear actuators, they are assigned a minimal force load of 2N corresponding to the force expected at the tool tip.

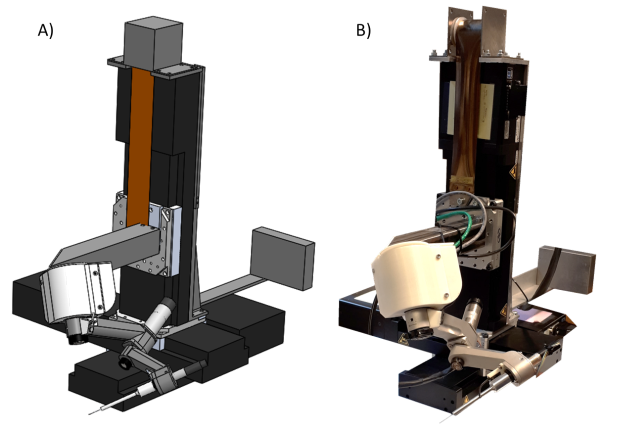

Fig. 6. A) CAD representation of robot. B) Prototype.

3.4 Detailed design

The ASTEMA robot is shown in figure 6. It is composed of three perpendicular linear tables with high resolution followed by a home-made spherical wrist with optimized dimensions.

The linear tables (Newport ILS100-CC) are taken away from the surgical area using a stiff link to the spherical wrist. These linear tables have a range of motion of 100 mm, a movement resolution of 1 μm, a load capacity of 40 N and a maximum speed of 100mm/s. Because the ASTEMA robot will be employed in the teleoperation context, its movement resolution is more important than its accuracy. Besides, the linear tables range of motion is wider than the specified linear workspace and will allow to test several strategies to scale down the movement with a larger workspace. The speed and the load capacity allow to reach the requirements above.

The spherical wrist design is detailed on figure 7. A particular attention was given to alignment between actuators shafts and expected RCM. First, a DC gear-motor (2657W012CR 23:1, Faulhaber, Schönaich, Germany) is mounted perpendicularly to the R_1 axis. The movement is transmitted to the R_1 axis by a helical gear (20:38). A high-resolution encoder (SCA24, 7500 pulses/revolution, Scancon, Hilleroed, Denmark) is mounted on the top of the R_1 axis (in green). Axes R_2 and R_3 (in orange and red in figure 7) are actuated by DC motors with backlash-free planetary gearboxes and with standard encoders (2232R012SR 69.2:1 IE2-1024 and 1224E012S 69.2:1 HEM3-256-W, Faulhaber, Schönaich, Germany).

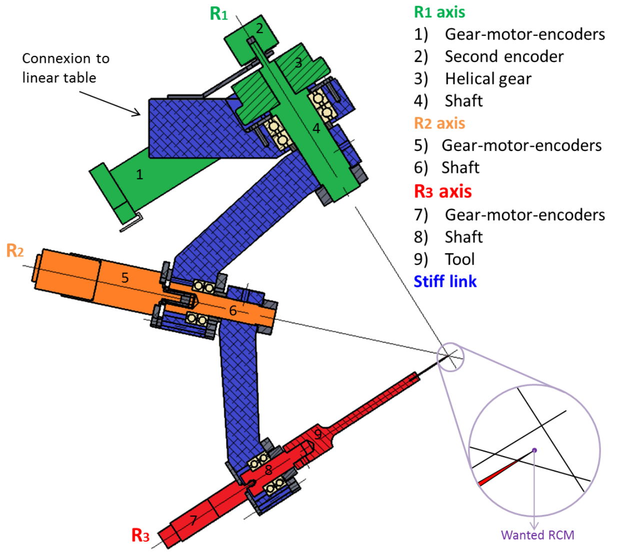

Fig. 7. Spherical wrist cross-section of robot. Real RCM is not reached due to manufacturing tolerance, free-play and flexibility.

The R_1 axis is different from R_2 and R_3 because there is no Faulhaber backlash-free gearboxes allowing enough torque for the R_1 joint. This assembly allows to precisely know the angular position which will be used within the calibration process explained in the following.

The links between joints (in blue in figure 7) are made of stainless steel between the linear tables and R_1 axis, and of aluminium alloy elsewhere, and were machined in one piece. Super-precision angular contact ball bearings (71900, 71901 and 71904 ACD/P4ADGB, SKF, Sweden, Goteborg) are used and the coupling between gears and actuators shafts are rigid. All these precautions lead to a high rigidity and very little amount of mechanical play, minimizing sources of imprecision.

Currently the robot is simply placed on a table as it could be in experimental surgery. In the operating room, it will be attached directly to the microscope. So the ASTEMA could therefore be installed simultaneously with the microscope and easily moved during operation if there are several microsurgery sites on the patient. The robot should also be either decontaminated or wrapped in a sterile cover. Moreover, for a future prototype devoted to the operating room, linear tables could be replaced by smaller- but more expensive ones to be less cumbersome.

3.5 Control

The robot is teleoperated with a six degrees of freedom GeomagicTouch joystick (resolution: 55 μm, see joystick in figure 10) through a computer running on Linux with a C++ code and interfaced with Technosoft control boards for low-level regulation of the actuators. The robot control diagram is shown in figure 8.

For motor control, we use Technosoft control boards (IPOS 3602 SX and IPOS 3604 SY, Technosoft, Neuchâtel, Switzerland) featuring a PVT control mode (Point-Velocity-Time). At each time step, the computer sends to the boards a time, a position and a speed that the actuators must reach. The board stores the data sent in a reception buffer, interpolates the desired positions to order 3 and controls the motors in position. The buffer is emptied as the points are executed. The controller consists of a position loop (PID controller - Proportional, Integral, Derivative) superimposed on a current loop (PI or I controller). Figure 9 shows the internal operation of the control boards.

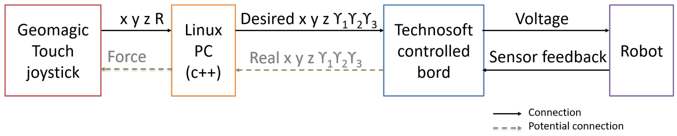

Fig. 8. Robot control diagram. Real position and orientation are used for RCM compensation only. Forces are sent to joystick only to limit the workspace.

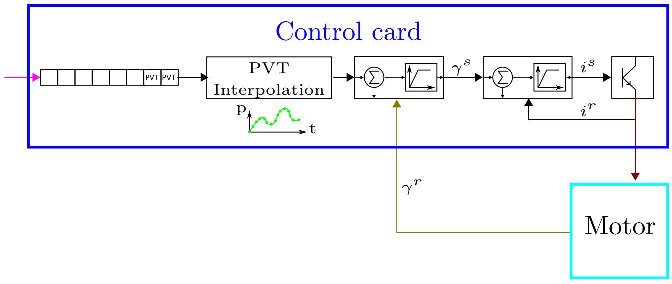

Fig. 9. Internal operations of the control boards.

3.6 Correction of the wrist geometric model

Despite all precautions taken, the actual robot geometric model shows discrepancies with respect to the theoretical model developed in section 3.3, mainly because of machining inaccuracies. In particular, a coupling between instrument rotation and instrument tip displacement appears since the wrist axes are not perfectly aligned with the instrument tip. Practically, when the instrument orientation is modified through actuation of the robot wrist, the tip position moves at the same time.

To highlight these model discrepancies, errors between theoretical and actual instrument tip positions for 30 different desired instrument orientations were measured using a microscope with camcorder and a x40 optical magnification as shown in figure 10. The picture resolution is 6.2 μm/px and a shape recognition algorithm (using the `bwtraceboundary` function of Matlab, based on Moore-Neighbor tracing algorithm) was used to locate the needle tip. The desired angle at each axis to obtain the 30 different instrument orientations were:

$$[\gamma_1\ \gamma_2\ \gamma_3] = \begin{bmatrix} 20 & 90 & 0:30:330 \\ 0:10:90 & 90 & 360 \\ 45 & 90 & 360 \\ 0 & 90:10:150 & 360 \end{bmatrix}^{\circ}$$

The maximum error between desired and obtained positions is 307 μm as shown in figure 11.

In order to compensate for these errors, the following modified wrist geometric model was defined, that includes 15 corrective parameters with constant values to be identified:

$$
\begin{aligned}
R_O = & Rz(\alpha_1 + \pi/2 + p_1) * Rx(-\beta_1 - \pi/2 + p_2) \\
& * Tz(-L_1) * Tx(p_3) * Ty(p_4) * Rz(\gamma_1 + p_5) \\
& * Tz(L_1) * Rx(\alpha_2) * Tz(-L_2) \\
& * Rx(p_6) * Tx(p_7) * Tz(p_8) * Rz(\gamma_2 + p_9) \\
& * Tz(L_2) * Rx(\alpha_3) * Tz(-L_3) \\
& * Rx(p_{10}) * Tx(p_{11}) * Tz(p_{12}) * Rz(\gamma_3 + p_{13}) \\
& * Tz(L_3 + p_{14}) * Tx(p_{15}) \qquad (4)
\end{aligned}
$$

with p_i the corrective parameter number i.

To identify the set of corrective parameters, an optimization program relying on a `lsqnonlin` function of Matlab, based on "trust-region-reflective least squares" algorithm was used. The error to be optimized was calculated as:

$$Error = |P_{microscope} - P_{theoretical}|$$

where $P_{microscope}$ is the position and the angle (projected in 2 dimensions) measured thanks to the microscope and $P_{theoretical}$ is the position and the angle calculated thanks to the new wrist orientation model R_O with different p_i.

The theoretical remaining maximum error after model correction is 18μm and is shown in figure 11. This remaining error may come from measurement inaccuracies and variable plays in the robot joints that can not be identified and were not compensated through the modified model.

The efficiency of the RCM compensation was tested on a real trajectory. Results are shown in figure 12 for γ_1 and γ_2. Before the RCM calibration, the maximum error is 393 μm and after the calibration it is 127 μm. So the precision was increased by a factor of 3. Besides, one can see that error increases as the instrument goes further away from the central axis of the angular workspace. This can be explained by the fact that the identification process reported above was based on a relatively localized set of angular configurations that were chosen near the central axis of the angular workspace, where the angular configurations adopted during an anastomosis are mainly located. In this narrow angular region, the maximum error is 222 μm without RCM compensation and 36 μm with RCM compensation (error reduced by a factor of 6).

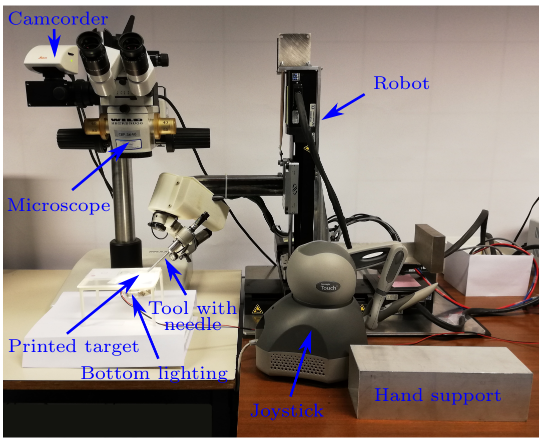

Fig. 10. Calibration and experiment al setup.

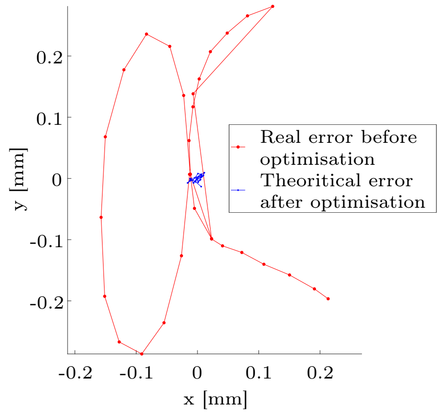

Fig. 11. Error between desired and obtained positions before (maximum error: 307 μm) and after (maximum error: 18 μm) the model optimization.

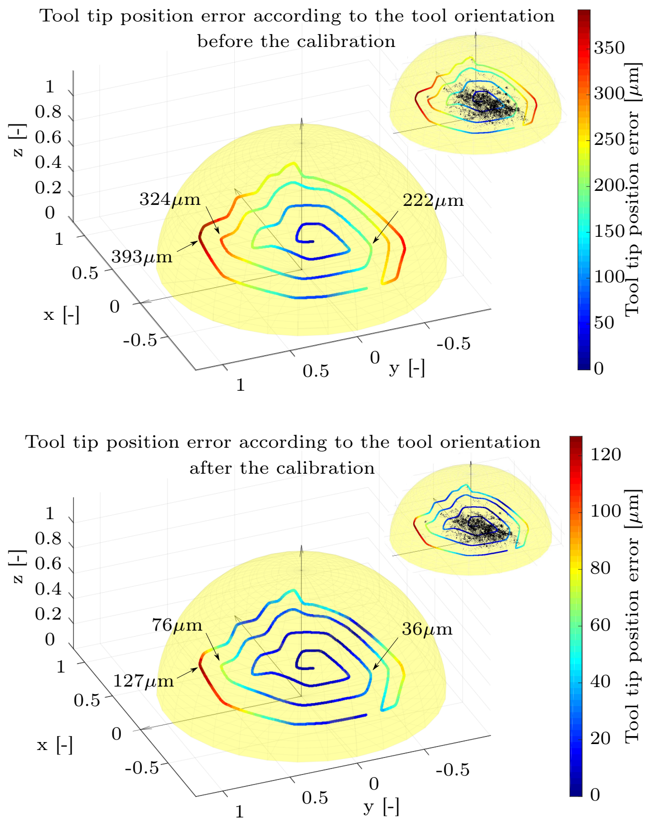

Fig. 12. Instrument tip position error according to the orientation before and after calibration during an angular trajectory which wanders the wanted workspace (γ_1 and γ_2 movement). The angular position is represented by points which correspond to the intersection between the instrument and a sphere center on the instrument tip with a dimensionless radius of 1, as shown in figure 3. In the top right-hand corners, the black point are the orientation measured during a microanastomosis in the needs analysis (see section 2).

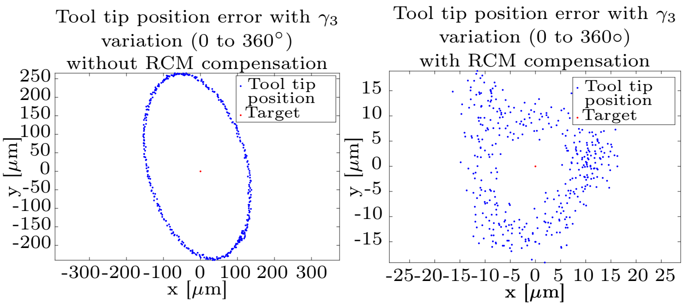

Fig. 13. Instrument tip position error before and after calibration during a self rotation of axis 3 of 360° (γ_3 movement).

Regarding the calibration of axis 3 (γ_3), results are depicted in figure 13. Before and after RCM compensation introduction, the maximum errors are 274 μm and 22 μm respectively. So the error is divided by 12 when the compensation is added.

In the central area of the workspace, when the two independent errors are combined, it gives a total error of 496 μm without RCM compensation and 58 μm with RCM compensation.

4. ROBOT PERFORMANCE ASSESSMENT

This section is dedicated to the ASTEMA performance evaluation. Two experiments were performed to show the ASTEMA performance with and without any operator in the control loop, and to check whether the RCM compensation helps during a teleoperation task. The first experiment allowed to analyse the error with a simple positioning trajectory and the second with a complex angular trajectory.

4.1 Setup

Almost the same setup as for the model correction in section 3.6 was used here. The camcorder recorded a needle attached to the robot instrument at 30 Hz across the microscope with a x40 optical magnification. A trajectory to follow was printed in magenta on white paper with high resolution (1200 dpi) and the light came from the bottom across the paper to avoid shadows as shown in figure 10. This setup allowed to measure the position in two dimensions only. The desired position in z was locked in the robot high-level controller and on the joystick by a physical force imposed by the joystick itself, so as to keep the needle tip in the narrow zone of acceptable sharpness of the microscope. This force was deemed not disturbing by inexperienced subjects during pretests. During the experiments, subjects had to look in the microscope with one eye only to see the trajectory always in the same place. Subjects had to rest their forearm and wrist on a support.

A subject had to follow a desired trajectory with the needle tip while the ASTEMA system was providing a downscaling factor of 30 between the subject gestures and the needle tip linear movements. Because the joystick resolution is 55 μm, the scale factor of 30 leads to a needle-tip linear movement resolution of 1.8 μm.

The printed trajectories are shown in figure 14. In experiment 1, the desired trajectory was a circle of 1 mm

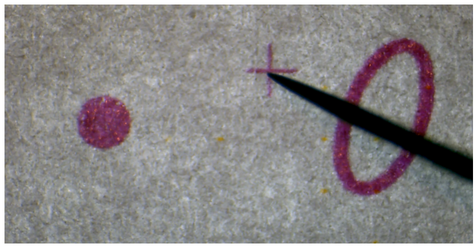

Fig. 14. Trajectory printed and needle. On left: trajectory for experiment 1. On right: trajectory for experiment 2.

diameter to be followed by the needle tip with a free needle orientation. This enabled us to assess the ASTEMA performance when precise tool tip positioning is required. In the experiment 2, the desired trajectory was an angular trajectory with a fixed needle tip position. Our aim here was to measure the ASTEMA performance when a complex angular trajectory is generated with a precise positioning of the needle tip. The angular trajectory was based on a cross mark and an ellipse. Subjects had to maintain the needle tip at the cross center and to move the needle orientation while following the elliptic trajectory with a specific point on the needle shaft. Subjects were asked to focus on the tip positioning precision and not on the execution speed or the orientation precision.

Each test was performed under different conditions: with RCM compensation, without RCM compensation, and without ASTEMA (by hand). Besides, the circle test in experiment 1 was also made with and without fixed orientation of the needle. $[\gamma_1\ \gamma_2\ \gamma_3] = [40\ 115\ 20]°$ was selected as fixed orientation to preserve a good vision of the instrument tip. In each case, the joystick orientation remained free. A different order among these conditions was used for each subject (all combinations were tested) and the subjects ignored the condition being tested. A given subject had to perform three paths around the circle and three two-way angular trajectories for each possible condition. One minute training was scheduled before each experiment. This pretest duration was deemed sufficient to take the robot in hand by inexperienced subjects.

Four subjects without link with the ASTEMA project and without any experience in microsurgery took part in these experiments. They were between 25 and 33 year old, with an engineering background. Additionnaly, each experiment was also performed autonomously by the ASTEMA robot without any subject within the control loop. In this case the angular trajectory was chosen after analysis of the angular trajectory of the four subjects, in order to be the closest from their average trajectory.

A statistical study was executed. A linear model followed by a Tukey test was used to highlight differences between the tested modes (significant test if p value $>$ 5 %).

4.2 Results and discussion

Experiment 1: Figure 15 gives examples of circular trajectories followed during the first experiment. Figure 16 shows the mean values of error for all subjects and for the autonomous controller (PC). The statistical study is summarized in table 2. It shows that subjects were

Table 2. Statistical results of experiments.

	Mean comparison between two modes		p-value
Exp. 1	Without robot	Without RCM comp.	<0.001
	Without robot	With fixed ori.	<0.001
	Without robot	With RCM comp.	<0.001
	With RCM comp.	Without RCM comp.	0.51
	With RCM comp.	With fixed ori.	0.84
	With fixed ori.	Without RCM comp.	0.93
Exp. 2	Without robot	Without RCM comp.	<0.001
	Without robot	With RCM comp.	<0.001
	With RCM comp.	Without RCM comp.	0.88

significantly better with the robot than by hand but the tested groups with the robot are not significantly different from each other. A summary of the best performance of subjects with and without the ASTEMA robot is reported in table 3.

As expected, the mean error of the autonomous controller is larger without than with RCM compensation (47 μm vs 9 μm). The mean error even decreases with fixed orientation to 2.5 μm which is under the precision of measure ($\sim$6.4 μm).

In figure 15, the positive effect of the assistance offered by the ASTEMA robot is clearly visible in comparison to the trajectory without the robot help. All subjects performed better with the ASTEMA assistance by a factor of 4 approximately. Currently, the mean precision of the best subject is 14 μm and the robot with an autonomous controller has a precision of 9 μm. It is close to the 10 μm desired precision identified in section 2.2.

So, currently subjects induce errors larger than the autonomous controller alone even when the orientation is fixed and when no error comes from spherical wrist. Indeed, teleoperation induces additional errors due to the limited dexterity of the subject, the manipulability of the joystick or the optical zoom limitation. With higher optical zoom and scale factor, subjects could certainly improve their accuracy if necessary.

On the other hand, without RCM compensation, the mean error is lower for a subject than for the autonomous controller. This is most probably due to the ability of subjects to compensate for unexpected coupled motions thanks to the real-time and high-quality visual feedback from the magnified microscope view. However, special attention should be paid not to increase the surgeon's mental load by relying too heavily on this instinctive compensation.

Additionally, it can be observed that the time taken to cover the trajectory is always shorter by hand than with robotic assistance (between 13 s and 18 s by hand and between 35 s and 70 s with robotic assistance depending on the subject). This can be explained by the fact that the large downscaling of joystick motions significantly reduces instrument tip velocity, thus increasing the time required to follow a defined path.

Experiment 2: Figure 17 gives an example of the instrument tip position during an angular trajectory. Figure 18 shows the mean values of error for all subjects and for a trajectory controlled by PC. The statistical study is summarized in table 2. It shows that subjects are significantly

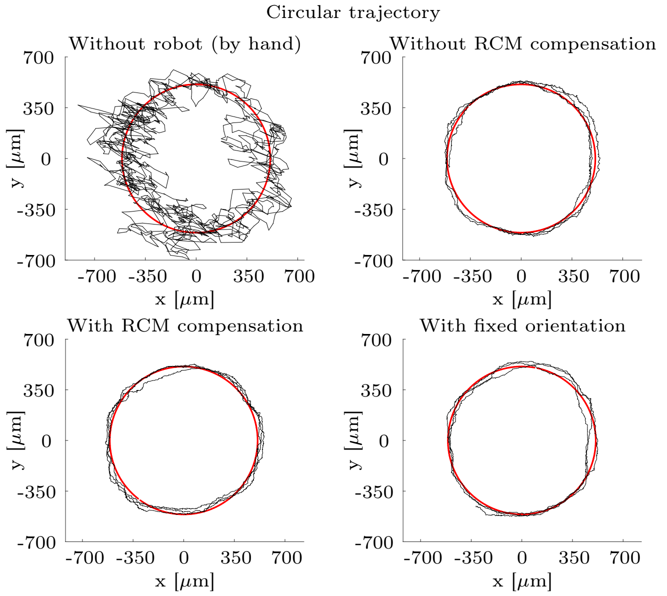

Fig. 15. Instrument tip position of subject 2 when following a circular trajectory of 1 mm diameter. Note that scales are not identical among all sub-figures.

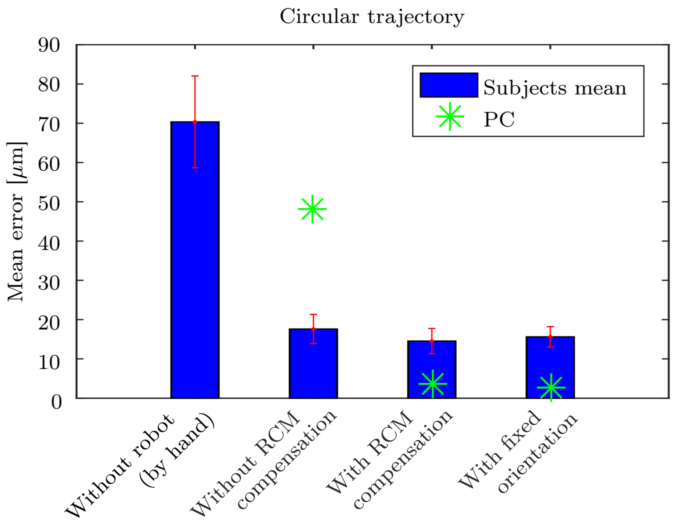

Fig. 16. Average error in instrument tip position during a circular trajectory (experiment 1).

better with the robot than by hand but the tested groups with the robot are not significantly different from each other.

Accuracy is improved by a factor of 4 to 7 from hand execution to teleoperation with the ASTEMA system. In addition, the time required to perform the task is shorter with the robot than by hand (between 13 s and 18 s with robot and between 80 s an 268 s by hand depending on the subject). Maybe a longer training without robot would have decreased this duration for some subjects. Moreover, when the RCM compensation is not implemented, subjects' mean errors with ASTEMA are 2 to 3 times lower than mean error obtained during automatic trajectory execution by the PC. These results confirm the interest

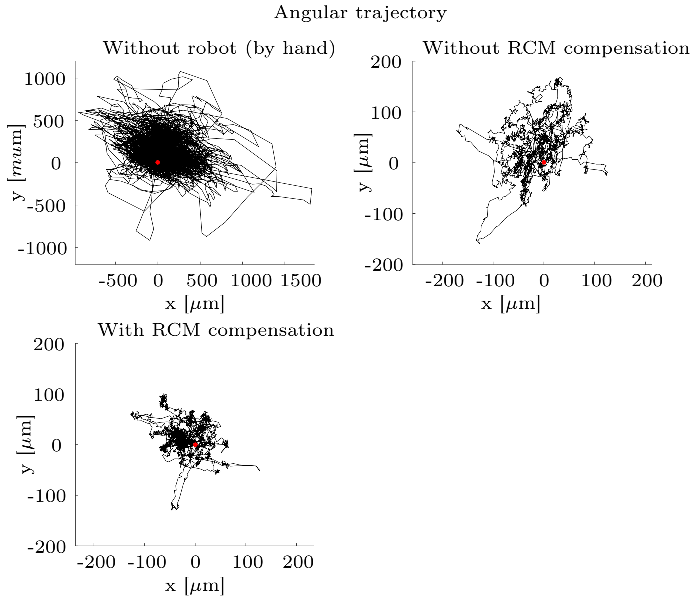

Fig. 17. Instrument tip position of subject 2 when following the angular trajectory and keeping the tip fixed.

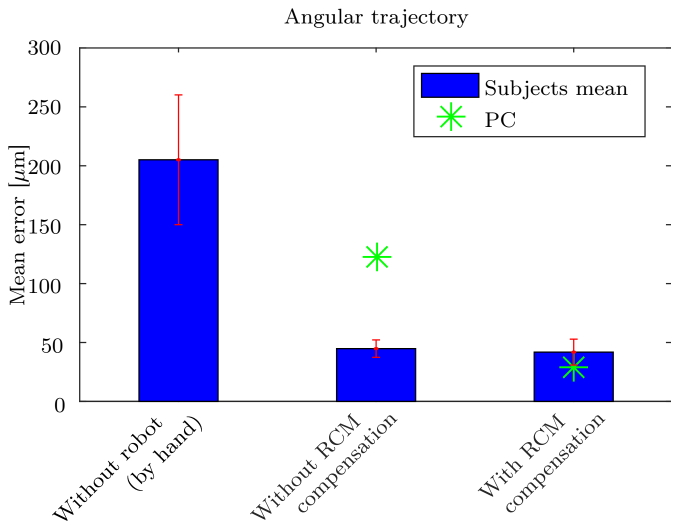

Fig. 18. Average error in instrument tip position during an angular trajectory with a fixed desired position (experiment 2).

of using the ASTEMA teleoperated system for microanastomosis.

Unlike experiment 1, subjects were faster with the robot than by hand. This is certainly due to the fact that there is no angular scaling so it does not slow down the user. Moreover, since the task is complex, it is very difficult to carry it out by hand without tremor. The robot allows to carry out the task more easily and therefore more quickly.

When the RCM compensation is applied, the mean error of autonomous controller is significantly reduced (23 μm compared to 222 μm). This proves again the effectiveness of the RCM compensation. However, the RCM compensation seems to have no visible effect on the average precision of subjects (75 μm without compensation, compared to 62 μm with compensation). This tends to show again that subjects compensate by themselves a large part of the error due to coupling between position and orientation when an imperfect RCM is implemented.

Table 3. ASTEMA performance during experiments: best results among all subjects and for the robot alone for each task.

Mean error [μm]	Without robot (by hand)	Without RCM compensation	With RCM compensation	With fixed orientation
Subjects' best tool tip traj.	75	18.5	14	18
Autonomous tool tip traj.	N.A.	46	9	2.5
Subjects' best angular traj.	271	59.5	45	N.A.
Autonomous angular traj.	N.A.	222	22.5	N.A.

When following the trajectory prescribed in this experiment, the instrument makes an angular diplacement of more than 65°. This trajectory thus evolves in the outer portion of the angular workspace identified in section 2.1. With an average accuracy of 45 μm for the best subject, the accuracy specification of 100 μm established in section 2.2 for large angulations is therefore fulfilled.

5. CONCLUSION AND PERSPECTIVE

Microanastomosis is a complex task that requires precision and dexterity. Under 1 mm diameter, only experienced surgeons can perform this gesture safely. We designed and built a novel telerobotic assistant, called ASTEMA. It has a resolution under 1 μm, a precision of 9 μm along a trajectory under autonomous control, and an average error of 14 μm during a circular trajectory controlled by a subject. According to these first experimental results, our system will eventually increase the precision of the surgeon and allow to move from microsurgery to supermicrosurgery. The gap between the modes with and without robot should be smaller with microsurgeons because they have a better accuracy by hand. But it should remain present because with robot, even an inexperienced subject has a better precision than the surgeons' average precision found in experience of Fig 2 (76µm). Further experiments with microsurgeons will be carried out to verify this hypothesis.

Table 4 allows to compare the ASTEMA with the requirements defined in section 2 and with some of the most relevant and sufficiently documented robots of the state of the art. ASTEMA meets the needs of microanastomosis particularly well in terms of precision, workspace and speed. When compared to other robots, one can see that it has a higher or equal accuracy and this especially compared to the da Vinci which is the main marketed telesurgery system for microanastomosis. This is due to its kinematics which is intrinsically accurate because it directly transfers the high resolution of the linear tables to the tip of the tool. Besides, unlike the other surgical robots, ASTEMA was designed to produce the same speed of motion than a human operator. This should greatly contribute to limit the operation time during microanastomosis.

Yet, these first experiments also highlighted a trend to slow down instruments motions through teleoperation, due to the high downscaling factor used. The next step will consist in trying to solve this common speed/accuracy

Table 4. Comparative between ASTEMA, the need and robots the most pertinent and sufficiently documented in reconstructive microsurgery.

	Accuracy [μm]	Workspace [cm^3]	Speed [mm/s]	Volume	University/company	Reference
ASTEMA	9-22	1000	100	++	Université catholique de Louvain	Vanthournhout et al. (2014) Vanthournhout et al. (2015b) Vanthournhout et al. (2016)
Da Vinci	<1000	6250		- - -	Intuitive Surgical	Katz et al. (2005) Huart et al. (2012) Liverneaux et al. (2013) Saleh et al. (2015) Willems et al. (2016)
RAMS	10-25	400		++	JPL-Caltech	Schenker (1995) Charles et al. (1997) Saraf (2008)
MUSA	30-40	6.3	10	+	Eindhoven University of Technology Microsure	Cau et al. (2014) van Mulken et al. (2018b) van Mulken et al. (2018a)
MM-3	44	3400	50	- -	University of Tokyo	Morita et al. (2005) Mitsuishi et al. (2013)
Besoin	10-100	100	100	++		

trade-off which all existing telesurgery systems are currently facing. Adaptive downscaling strategies are being envisioned and implemented, based for instance on the instrument position with respect to the microanastomosis site or regarding the velocity of the master joystick [Conti and Khatib (2005); Dubey et al. (2001); Munoz et al. (2011); Ko et al. (2017)]. Indeed, anastomosis seems to be particularly adapted to these strategies because it requires to perform small, slow and precise gestures (e.g. insert the needle in the vessel), as well as big, quick, not too precise gestures (e.g. make a knot or pull on the thread). An experimental comparison of several adaptive strategies is being carried out with surgeons, in order to identify the most suitable strategy in terms of usability, accuracy when/where needed and task duration.

Finally, a motorised instrument and a mirror robot for the left instrument are currently being built. With a fully operational bi-manual device, we will be able to move on to more realistic experiments involving actual microanastomosis gestures.

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