Evaluation of Command Modes of an Assistance Robot for Middle Ear Surgery

Guillaume Kazmitcheff¹, *, Mathieu Miroir¹, Yann Nguyen¹ M.D., Charlotte Célérié¹, Stéphane Mazalaigue³, Evelyne Ferrary¹,² M.D., Olivier Sterkers¹,² M.D. and Alexis Bozorg Grayeli¹,² M.D.

Abstract—RobOtol is a micro-surgical tele operated system designed to assist middle ear surgery. A new prototype, with an improved controller system and mechanical enhancement is presented. Surgeons evaluated the robot by tasks specific to middle ear surgery with two command modes (position-velocity and position-position) and by questionnaires. There was no prevailing command mode. A human robot interface was developed to offer easy and fast intra operative adaptation of the command mode to surgeons’ preferences and specific situations.

INTRODUCTION

The middle ear is composed of the tympanic membrane, the middle ear cleft containing 3 ossicles (malleus, incus, and stapes), and the mastoid (Fig. 1). Lesions involving the middle ear structures lead to a conductive hearing loss accessible to a surgical treatment. In these lesions, surgery consists of restoring the anatomical structures and the sound transmission to the cochlea by tympanic membrane graft and/or ossicular chain replacement with a prosthesis. This surgery which is conducted under operative microscope, requires accurate positioning and movements. Among all procedures, otosclerosis surgery which is the most delicate [1], was chosen as an objective for the development of our robotic system. During this procedure, the stapedial superstructure is cut and removed, the stapes footplate is fenestrated, and an ossicular prosthesis is placed between the incus and the footplate opening [2]. Previous works on robotic tools to perform middle ear surgery have been reported ([3], [4] and [5]).

The first prototype of our robot called RobOtol and dedicated to the middle ear microsurgery [6] was previously presented as a proof of concept. This prototype showed that the choice of kinematic, dimensions, and motorization fulfilled the specifications defined by the surgeons. The entire surgical field could be reached with a well preserved field of vision.

In order to improve the mechanical characteristics, the control and the command of this first version, a second prototype was designed and manufactured. This prototype was evaluated via specific tasks by several otologists and non-otologists. During this evaluation, two different command modes were compared.

ROBOT DESCRIPTION

RobOtol is designed with 2 tool-bearing arms similar to robots dedicated to ophthalmologic surgery [7], each having 6 degrees of freedom and motorized by 3 rotatory and 3 linear motors. The second prototype has only one arm. The command module comprises a haptic interface [8] (Phantom Omni, Wilmington, MA) connected to a command PC controlling all six motors via specific control cards. The robot is controlled under operative microscope placed 400 mm above the surgical field (Fig. 2).

Mechanical characteristics

In the first prototype, the linear actuators were assembled in a step-by-step crossed table (LTM 80P-HSM, OWIS GmbH, Staufen, Germany), and the rotary actuators were DC motors (2342S024CR - IE2 512, Faulhaber GmbH, Germany). To simplify their control, step-by-step actuators...
were replaced by a DC crossed table (LTM 80PHIDS, OWIS GmbH, Staufen, Germany).

In the first version, the two distal rotary axes of the arm were animated via Bowden cables [9]. Evaluation of this mechanism showed that the real position of the axis could deviate from the position of rotary actuators as a consequence of cable sliding on the winding pulleys. Hence, two incremental encoders (2MCA-1024-D-3-09-64-01- S, Scancon, Denmark) were added to the rotatory axes to obtain the real position and also to detect a failure in movement transmission (i.e. broken or jammed cable) and thus to enhance the robot safety (Fig. 3).

The new prototype was built in stainless steel to improve hardness. This change increased the weight and led the robotic arm to have a passive rotation by gravity when the actuators were turned off. An electromagnetic spring-applied brake (BFK 457-01 24V, Intorq GmbH, Germany) was added to the first rotator axis to compensate the effect of gravity. This brake allowed immediate stabilization of the robotic arm in case of power failure. The two other rotator axes were stabilized with the Bowden cable.

The mechanical characteristics of this new prototype also took into account the future clinical application. To facilitate maintenance, assembly and lower production cost, the design of the second version was slightly changed to improve accessibility to winding pulleys for an easier and faster cable change.

**Controller characteristics**

The controller architecture of the first version was also modified in the second prototype. In the first prototype, each actuator was commanded by different proprietary controllers. Data transfer speed between the linear actuators and their controller limited the command refresh rate to 25 Hz. This low frequency gave the impression of a jittering command and motion under microscope. The new controller architecture was based on an 8-axis PCI controller card (High-performance PCI-bus motion controller, Multiflex MFX-PCI-1802-2, PMC, Carlsbad, CA) and on 4 power supply modules MFX 110 (AXMO precision, Brétigny-sur-Orge, France). The multiflexcard is equipped with 8 pulse-width modulation (PWM) outputs, 8 encoder inputs, 8 analog inputs, and 16 digital outputs and inputs. Each power supply module can command 2 DC motors in PWM (24 V, 1.5 A), manage 4 digital outputs and inputs, and 2 analog inputs. In addition, 2 encoders were implemented in the command architecture. This architecture yielded a command refresh rate of 80 Hz, with a comfortable visual sensation of command. The PWM frequency was set at 17 kHz to generate enough power to the z linear actuator to lift a 500 g load (twice the weight of a standard ear surgery electrical drill with its handpiece) at 3.5 mm.s$^{-1}$. At this frequency, the Faulhaber rotary actuators overheated rapidly because their low inductance (265 $\mu$H).

Indeed, a low PWM converter can lead to overheating as reported by other authors [10]. To circumvent this problem, $\frac{R}{L} \omega_1$ value (R stands for resistance of the motor, L the inductance of the coil, and $\omega_1$ the PWM frequency without overheating) had to be decreased. Thus, the low $\omega_1$ was compensated by a high L value (multiplied by 10 with a toric coil to 2.2 mH) placed serially in the power circuit.

**Command characteristics**

In the first prototype, only a velocity command mode (position-speed command) was implemented. The transmission to rotatory actuators with Bowden cables was not accurate enough to enable a position command. The implementation of 2 distal encoders allowed controlling the robot with a position command (position-position command). The position-velocity command facilitates large movements, whereas position-position command is recommended for the manipulation of small structures and
A dead man’s foot switch (DMFS) was also added to confirm commands. This motion validation was initially insured via the haptic interface buttons, but preliminary trials showed that this solution reduced the ergonomic quality of the haptic pen. DMFS was directly connected to the electromagnetic spring-applied brake and to the analog input of the multiflexcard card. When the surgeon stepped on the DMFS the current of the electromagnetic spring-applied brake was turned off. DMFS enhanced the robot safety and was user-friendly for the surgeons as many other medical devices are already driven by pedals in the operating room.

The previous velocity command was programmed as follows. The surgeon sets the initial position and orientation of the pen and the tool by stepping on the DMFS. A differential computation is performed between the final and the initial pen positions and axes. The result is projected and sent to the robotic arm to perform the motion. Higher amplitudes of stylus movement are coded by a higher speed of the robotic arm. Releasing DMFS or returning the stylus to its initial configuration stops the robot. The haptic pen instruction was divided by a homothety parameter to allow adequate coordination between tool velocity and haptic movement. Moreover, to avoid unwanted rotatory movements, a dead zone around the initial configuration of the stylus registration (2 degrees in each direction) was created.

The position command was programmed similarly to the velocity command and complemented by a position feedback loop. To compute the command, the executed movement was subtracted from the initial command. In this command mode, the motion was automatically stopped when the target position and axis was reached or when the pedal was released by the user. This command allowed the implementation of a homothety between the master and slave arm motions. This is particularly effective in microsurgery where submillimetric gestures are required. In this way, millimetric stylus action can be converted into micrometric movements of the tool tip. More accuracy can be obtained if necessary by reducing the ratio.

**Work hypothesis**

We hypothesized that surgeons are able to perform specific tasks similar to those performed during middle ear surgery by both velocity and position command. We also hypothesized that they prefer and perform better in position command than in velocity, as position command is closer to real surgical gesture.

**Evaluation of command modes**

After a training phase, 4 otologic surgeons and 2 engineers were proposed to accomplish two specific middle ear surgery tasks. Upon completion, their preferences and comments were collected with a satisfaction questionnaire (Likert scale). All tests were carried out under operative microscope with a 400 mm focal lens (Carl Zeiss, Jena, Germany). A supervisor monitored the task via a video camera mounted on the microscope. The master arm was placed under the user’s dominant hand. Homothety (master : slave) ratios were programmed at 7:1 for translations and 2:1 for rotations. A simple proportional controller was implemented and set at 1 in order to have a stabilized motion. With this setting, the velocity mode needed a scale ratio which was set at 28. To avoid confusion between the two modes, the proportional controller was set at 0.25 and the homothety ratio at 7 in the velocity mode similar to the position.

**Training phase**

Ear surgeons are not familiar with surgical robots, since no robot is available for clinical use in this field. Furthermore, multiple control modes require a learning phase. Before evaluation, the two control modes (velocity and position) were explained, and each user was allowed to use the robot during 15 minutes freely under the guidance and advises of a supervisor. After this training period, two tests were performed to validate the training of the operator to move the robot and orient the tool correctly.

The first test (Fig. 4) consisted in guiding the tip of the robotic tool through a slalom path around 7 needles without touching them in less than 3 minutes. The needles formed a set-up of the first training phase.

![Fig. 4.](attachment:image.png)

(a) Set-up of the first training phase. (b) Schematic of the first training task.
a 20 mm diameter circle. This task was performed under the operating microscope. The goal of this first test was to evaluate the user ability to perform simple translations within a narrow space.

A second test was performed to assess the tool orientation aptitude. The user had to orient correctly the robot tool in order to reach the bottom of a plastic tube (diameter: 10 mm, length: 25 mm), fixed on a wood panel with an angle of 15 degrees, in less than 3 minutes. The size and orientation of this tube were similar to the external auditory canal dimensions and surgical orientation. The test was considered as passed if the tool touched the bottom of the tube without hitting the lateral walls during the procedure (Fig. 5).

Evaluation phase

In order to compare different RobOtol command modes, several experiments were designed. The first trial consisted in manipulating an ossicular prosthesis in Teflon (Grace medical, Memphis, TN) with a micro hook inside a glass tube (diameter: 10 mm, length: 25 mm), half filled with water. The goal of this experimentation was to simulate the placement of a prosthetic piston in the stapes footplate after its fenestration in otosclerosis surgery in a wet environment creating surface tensions. A round plastic disc (8 mm diameter) with a 500 µm hole at its center was placed on the water inside the tube to mimic a floating and perforated stapedial footplate. At the beginning of the experiment, an ossicular prosthesis in Teflon (diameter: 400 µm, length: 4.5 mm) was placed through the plastic disc (Fig. 6). With the micro hook, the participant had to pick up the prosthesis, raise it to the top of the tube and replace it through the hole at the center of the plastic disc. A prosthesis fall from the hook was considered as a failure. The experimentation was considered as complete when the participant placed the prosthesis a total of five times in the disc. Each user performed this task with two different modes: velocity or position command. The order of the command modes was randomly assigned by the supervisor. The total duration of the exercise, the time of tool motion (Execution time) and the number of trials were recorded in each mode. A success rate was calculated as the number of successful trials (5) over the number of trials necessary to have 5 success. The distance covered by the tool and the number of time the DMFS was pressed were recorded.

The aim of the last experiment was to evaluate the robot ability to come into contact with several anatomical structures in human temporal bones and to compare the velocity and position command. A human temporal bone was fixed into a rigid resin mounted on a six-axis sensors (Nano 17, ATI industrial automation, Apex, NC). Data from the six-axis sensors were recorded and saved by an in-house software running on a PC. A black dot was placed with a surgical pen on 3 anatomical targets in the specimen (anterior rim of sulcus tympani, stapedial head, round window niche, Fig. 7). The target anatomical structures and their order were shown to each user before the test by the supervisor. The user had to move the robotic tool tip from...
one target to another and then move back to the first target 3 times consecutively in each control mode. A task failed the anatomical structure was damaged or all targets were not reached in less than 4 minutes. A supervisor monitored the task by video and real-time force sensor data. The duration, the distance covered by the tool and the number of times that DMFS was stepped on were noted.

Satisfaction questionnaire

A self questionnaire assessed the user’s precision, fatigability and visual field preservation on a Likert scale for each mode and each trial of the evaluation phase. The sensation of ease and speed to complete the task was also noted. Free comments were also collected on the homothety ratio values.

![Image](image.png)

Fig. 7. Anatomical targets trial: The user had to move the robotic tool tip from the anterior part of the sulcus tympani, to the stapedia l head and the round window niche 3 times consecutively.

RESULTS

First training test: Slalom

All users were able to complete this test at their first trial in position and velocity mode. Mean duration to follow the path were 80 ± 34.2 s (mean ± SD, n=6) in position mode and 83 ± 40.4 s (n=6) in velocity mode (not significant, paired t-test).

Second training test: Orientation in the tube

All users were able to complete this test at their first trial in position and velocity mode. The mean duration of perform the task were 40 ± 24.2 s in position mode and 34 ± 16.3 s in velocity mode (not significant, paired t-test).

First evaluation test: Prosthesis insertion

The test consisted in placing a prosthetic piston in a target hole and to take it out. All users were able to complete this exercise in both velocity and position modes. Collected data are reported on Table I. Results are expressed as mean ± standard deviation (n=6). No significant difference could be observed in different evaluation parameters between velocity and position modes (not significant, paired t-test). DMFS: Dead man’s foot switch.

<table>
<thead>
<tr>
<th>Position</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success (%)</td>
<td>90</td>
</tr>
<tr>
<td>Total time (s)</td>
<td>56 ±20.4</td>
</tr>
<tr>
<td>Execution time (s)</td>
<td>40 ±17.6</td>
</tr>
<tr>
<td>Distance (mm)</td>
<td>57 ±3.4</td>
</tr>
<tr>
<td>Rotary distance (rad)</td>
<td>2 ±0.75</td>
</tr>
<tr>
<td>Number of DMFS pressed</td>
<td>7 ±3.5</td>
</tr>
</tbody>
</table>

Second evaluation test: Navigation between anatomical targets

All users were able to complete this exercise in both velocity and position mode. No significant difference was observed for this task between velocity or position modes (Table II).

<table>
<thead>
<tr>
<th>Position</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success (%)</td>
<td>100</td>
</tr>
<tr>
<td>Total time (s)</td>
<td>125 ±35.0</td>
</tr>
<tr>
<td>Execution time (s)</td>
<td>80 ±21.6</td>
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<td>Distance (mm)</td>
<td>65 ±4.9</td>
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<tr>
<td>Rotary distance (rad)</td>
<td>5.7 ±1.5</td>
</tr>
<tr>
<td>Number of DMFS pressed</td>
<td>19.9 ±8.9</td>
</tr>
</tbody>
</table>

Satisfaction questionnaire

Four users preferred the position command, one the velocity command, and one had no preference. The scores on the Likert scale assessing the manipulability and ergonomics of the system are reported on Fig. 8.

Free comments on the homothety settings showed the need for a customization of the gain value. Five users out of six would have preferred different gain values (higher or lower) for rotation and translation in both modes. Difficulties to orient the tip of the hook without translation or alteration of instrument axis (pure z axis rotation) were also reported.

DISCUSSION

In the second prototype, we built a more robust robotic arm with a simplified controller architecture. A higher command refresh rate was implemented. The second prototype enhancements allowed users with a short training (< 30 minutes) to perform tasks with a high accuracy. The weight increase was counterbalanced by an increased PWM power and required the addition of an electromagnetic
Fig. 8. Likert scale results in position and velocity command modes (mean ± standard deviation, n=6). There was no difference between position and velocity command modes (Mann-Whitney U or paired t-test, n=6).

brake. Evaluation trials with in vitro models and human temporal bones were chosen to reproduce the critical steps of the otosclerosis surgical procedure. Velocity or position command modes were compared by users with different surgical experiences. Our initial hypothesis was that the position command would be easier for surgeons to control the robot. Results showed that surgical tasks could be accomplished in both command modes, and the performances did not depend on the command mode. Satisfaction questionnaires were in accordance with recorded performances showing no prevailing command mode. Therefore, there was a necessity of an interface to switch easily and rapidly from one command mode to another, and to change the homothety gain values. A human machine interface (HMI) was developed in response to these needs.

HUMAN MACHINE INTERFACE

Since users preferred different command strategies, it seemed relevant to offer the possibility of setting command parameters to the users.

A human machine interface (HMI, Fig. 9) was developed to allow the operator to adjust several parameters. This interface was based on a software developed from open-source libraries (OpenGL, Chai3D [13]) and a hardware component represented by a pedalboard with 7 switches (Fig. 10).

The software displays a virtual representation of the robot and a control panel for a selected number of parameters in a limited range. This virtual representation has a refresh rate of 60 Hz (frames per second, fps) and is independent from the robot control. It is based on its 3D geometrical model updated by encoders feedbacks. The user can control the correspondence between the real and the virtual robot configurations displayed on the HMI. In case of mismatch, the user has to perform a robot initialization procedure. This procedure resets the encoders' value and improves safety.

Several users expressed different preferences of command type (velocity or position) and used different strategies to perform the tests. The questionnaire showed that users performing a series of small movements (between two pedal steps) preferred a larger homothety master : slave ratio. In contrast, those performing long motions between 2 DMFS steps preferred a low ratio in order to be accurate during the continuous tool movement.

Users also reported difficulties to orientate the tool while keeping the tool position unchanged or to perform a pure translation without rotation. Hence, the possibility to uncouple the translation and the rotation of the tool was added to the HMI.

HMI screen is divided into a command panel on the left, and the graphic panel representing a 3D view of the robot on the right (Fig. 9). On the command panel, the surgeon can select the movement type (translation, rotation or both), the homothety ratio for translation and rotation, the type of command (position-velocity or position-position) and several sets of camera positions for the virtual representation of the robot. The right panel contains encoders’ data of the linear motors (real motor positions and their total course), the refresh rate (fps) and the elapsed time in second. The user can also translate, rotate and zoom the cameras with the mouse to change the point of view.

A command pedalboard (Fig. 10) was designed to allow the user to set different parameters from the command panel in combination with haptic pen buttons without using the mouse. For example: Turning on the "Translation scale" enabled the modification of the homothety by the two haptic buttons. This pedalboard was designed to avoid
manipulation of the mouse by the surgeon and to improve ergonomics. All functions on the pedalboard can be accessed through the HMI and the mouse by the surgeon’s assistant. Pedalboard data can be recovered through the analog input of the multiflexcard card.

**CONCLUSION**

RobOtol’s second prototype includes improved mechanical components (stainless steel arm, rotatory encoders and inductance coil). The controller architecture is also simplified. These improvements allowed the programming of two command modes (position-velocity and position-position). Evaluation of these command modes by surgeons showed no prevailing mode for middle ear surgery tasks. After a short training, all users were able to move the robot in a human temporal bone without damaging the anatomical structures. The development of the human machine interface offers parameter settings and real-time monitoring of the robot configuration. Further data on surgeons’ performances are needed in both command modes to further improve RobOtol ergonomics.

**REFERENCES**


