Literature Review:

Preliminary Evaluation of a New Microsurgical Robotic System for Head and Neck Surgery

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Presented By:

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Project: Kinematic Simulation, Calibration, and Accuracy Assessment for the Galen Robot

I. Introduction and Background

Ear, nose, and throat (ENT) surgery is an inherently difficult family of procedures due to the risk of damaging fragile anatomical structures and the challenge posed by operating in complex, confined surgical environments. Such constraints are among many prohibitive factors that make current minimally-invasive surgery (MIS) platforms an impractical choice for general ENT surgery [1]. Teleoperated systems, prevalent in both research and commercial spaces, cannot provide the precision necessary for ENT surgery. Furthermore, they suffer from limitations relating to patient accessibility during surgery and are often prohibitively expensive.

In 2012, researchers at the JHU Laboratory for Computational Sensing and Robotics (LCSR) developed the prototype Robotic ENT Microsurgical System (REMS) robot, shown here in Figure 1, to address the clinical need for an effective ENT microsurgery platform. With the help of clinical staff from the Johns Hopkins School of Medicine, LCSR researchers have published a large number of studies validating and verifying the REMS for ENT use cases. Sufficient momentum in research and development led to the founding of Galen Robotics, a start-up company working to build further iterations of the platform. Based in Baltimore, MD and maintaining close ties with the LCSR, the company has developed two further iterations of the REMS system: the Galen Mk. 1 and Mk. 2. The company intends to continue developing the platform and eventually commercialize it.

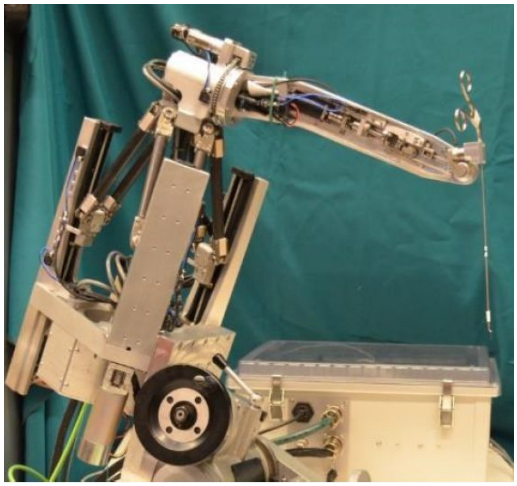

Figure 1: Prototype of the REMS microsurgery robot developed by the LCSR [2]

"Preliminary Evaluation of a New Microsurgical Robotic System for Head and Neck Surgery" by Olds et al. is one of the many studies published in support of the REMS while the platform was purely a research project within the LCSR. This study serves as an initial practical/technical analysis of the prototype REMS robot to validate and verify its use for ear, nose, and throat (ENT) surgery. Researchers conducted two experiments to evaluate the robot's precision, resolution, repeatability, and stiffness, technical specifications that are crucial to the platform's performance during surgery.

II. Project Relevance

Our project, "Kinematic Simulation, Calibration, and Accuracy Assessment for the Galen Robot", will address kinematic calibration of the Galen Mk. 2 robot to improve tool tracking accuracy. Like in many linkage-based robots, sources of mechanical error such as motor

backlash, minimum resolution of movement, and stiffness result in error between the end effector location determined by the robot's forward kinematics and the end effector location measured in the actual workspace. Kinematic calibration is the standard approach for minimizing this error and ensuring that the end effector location is known to the best of our ability. To ensure performance suitable for minimally-invasive ENT surgery, we will perform a rigorous calibration exercise with the Galen Mk. 2. Figure 2 shows the full CAD assembly of the Galen Mk. 2.

Figure 2: Full CAD assembly of the Galen Mk. 2 platform [3]

While the study does not directly address calibration of the REMS, it is significant to our project because it defines technical requirements for the REMS and the need for calibration. The results of the study indicate that the combination of systematic errors and user-generated error induces a worst-case tooltip error that, without correction, is very large and therefore not suitable for ENT surgery. In the discussion section, the authors suggest that future work to improve the robot's design and perform calibration will significantly improve its performance and meet clinical requirements. With the Galen Mk. 2 being the latest iteration of the REMS design, we hope that our calibration will demonstrate the necessary accuracy to bring the REMS to the OR room.

III. System Overview: REMS

The REMS is a 5 degree of freedom (DOF), cooperatively-controlled microsurgery robot developed for use in ENT surgery. The X-Y-Z cartesian degrees of freedom are provided by the delta stage and the remaining 2 rotational DOF are provided by the roll and tilt stages. While the robot only provides 5 actuated degrees of freedom, a 6th DOF is achievable in rotating the surgical tool in the tool adapter. Figure 3 shows a labeled CAD assembly of the REMS. Admittance-style control works to eliminate hand tremor and increase movement precision. Furthermore, the design of the delta stage makes the robot exceptionally stiff, therefore also increasing precision.

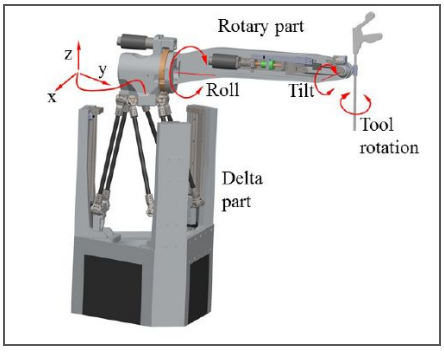

Figure 3: CAD model of prototype REMS platform with labeled delta, roll, and tilt stages [4]

IV. Summary of Experimental Methods and Results

As previously discussed, the experimental methods for this study can be divided into two sections: the experimental methods for a precision augmentation evaluation and the experimental methods for the direct technical evaluation of the robot's resolution, repeatability, and stiffness. The following is a brief summary of each experiment.

A. Precision Augmentation Evaluation

The precision augmentation evaluation is a mock clinical trial modeled to simulate needle insertion for suturing vibratory tissue during endolaryngeal phonosurgery. This task is notoriously difficult given the amplification of hand tremor at the tip of laryngeal forceps and the small diameter of the suturing hole (~1.5 mm) [1]. Figures 4 and 5 on the next page shows the experimental set-up. 3 participants, one laryngeal surgeon, one surgical fellow, and one novice, were instructed to insert a needle into the perforated holes of the aluminum plate and touch the foil underneath it without making contact with the plate itself. The participants used 25 cm. long laryngeal forceps to guide a 0.4 mm. needle into the hole; for the purposes of this experiment, the needle was fixed to the forceps. The participants attempted the simulated needle insertion task 6 times for each size hole with assistance of the REMS and then repeated the exercise with conventional freehand methods. The set-up provided distinct auditory feedback for successful attempts (touching the foil without touching the plate) and failed attempts (touching the plate), which were recorded along with elapsed time for each attempt and force exerted on the robot by the participant.

Figure 4: Surgeon performing REMS-assisted microlaryngeal phonosurgery exercise [1]

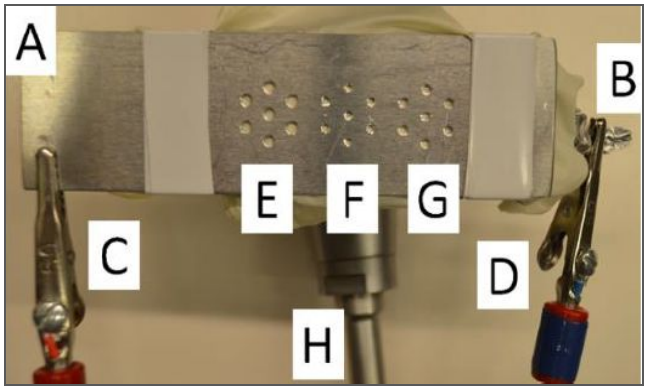

Figure 5: Microlaryngeal phonosurgery testing apparatus; perforated aluminum plate (A), foil sheet (B), failure electrode (C), success electrode (D), 2.0 mm holes (E), 1.2 mm holes (F), 1.5 mm holes (G), passive support stand (H) [1]

The key result of the precision augmentation task was a 91% success rate for needle insertion using the REMS as opposed to 28% using freehand methods. However, the authors note that successful REMS attempts were slightly slower than successful freehand attempts at 9 seconds and 7 seconds, respectively. Furthermore, the skill level of the participant also contributed to the data. The laryngeal surgeon performed the best in all evaluation metrics for all trials with the exception of REMS-assisted success rate, where she was only slightly bested by the surgical fellow.

B. Technical Evaluation

The technical evaluation tested the resolution, repeatability, and stiffness of the REMS against specifications defined in previous publications [5, 6]. Resolution was tested by commanding the robot to move in all DOF against the micron-resolution dial indicator in decreasing number of encoder counts until the dial indicator stopped changing. The smallest incremental distance observed before the dial indicator stopped changing was recorded. Repeatability was determined with the same testing configuration, however the robot was commanded to move in oscillatory motions against the dial indicator to compare "rehomed" positions. Stiffness was tested with a similar set-up, however instead of commanding the robot to move against the dial indicator, a 500 gram weight was applied to a mock tool in the X, Y, and Z directions and the resulting linear deflections were recorded. Figure 6 shows the resolution/repeatability set-up and the stiffness set-up, respectively.

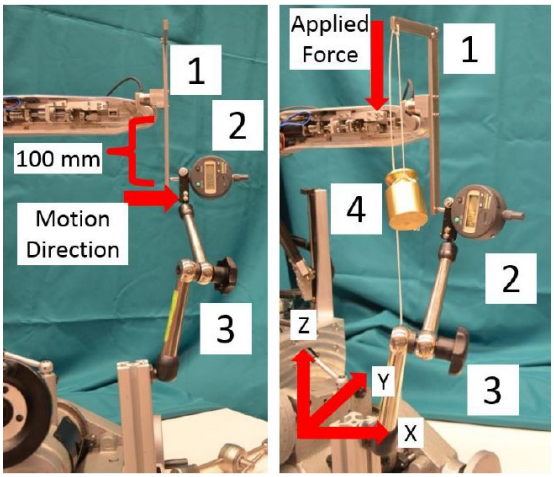

Figure 6: Experimental set-ups for resolution and repeatability tests (left) and stiffness test (right); tool fixture (1), micron resolution dial indicator (2), dial indicator support arm (3), weight for stiffness testing (4) [1]

The results of the technical evaluation showed that the REMS satisfied each individual technical specification, but demonstrated an error of 1.167 mm. under worst-case experimental conditions. The authors explain that this error is quite significant, but ultimately correctable through calibration.

V. Limitations

Before addressing the study's limitations, it is important to note that the authors make many assumptions to simplify the experiments and acknowledge the impacts on the results.

One limitation of the precision augmentation task is the small number of participants involved in the study. Though the authors were able to recruit a participant to represent each of the desired skill levels, the inclusion of more participants within each group is necessary to prevent single participants from defining an entire experimental demographic. Another limitation of the precision augmentation task is the participants' lack of familiarity with the REMS. Although REMS-assisted trials already demonstrated better overall performance without prior user experience, proper instruction/training with the robot could further improve performance and demonstrate the full potential of the system. Average time per successful attempt, for instance, is one performance method used in this experiment that could greatly improve. With average times for REMS-assisted trials nearly matching those of manual trials already, prior instruction could possibly demonstrate comparable, if not shorter, times. Lastly, the precision augmentation task suffered from setbacks in its representation of real-world OR conditions. As shown in Figure 4, the study was conducted on a table as opposed to an OR table. Furthermore, fixing the needle to the laryngeal forceps allowed the participants to perform the task without worrying about the needle slipping out of the forcep grippers.

The technical evaluation also suffered from some significant limitations. Evaluating stiffness with the REMS in the home position, for instance, was not representative of worst-case use. When the REMS is "homed", the delta legs are positioned with equivalent interior angles to the lead screw rails (centered in the delta), providing one of the most stable delta configurations possible. Another limitation is the evaluation method for the resolution and repeatability tasks. Since all delta legs must move in order for the REMS to move purely in any one DOF, one cannot judge resolution from a single motor's encoder counts. However, this could be a misinterpretation on my part.

VI. Conclusion

This preliminary study effectively demonstrates improved precision using the REMS for a simulated ENT use case and resolution, repeatability, and stiffness satisfying the criteria set in [5, 6]. Furthermore, the analysis of worst-case error demonstrates that calibration and design changes are necessary to minimize tool tracking error in the workspace and validate/verify the REMS design for ENT use cases. Now that six years have passed since this paper was written, I am fortunate to note that much of this work has already been done. Not only did the LCSR publish a study documenting the calibration methods for the REMS, but the Galen Mk. 1 and Mk. 2 have since demonstrated significant improvements towards clinical integration.

Though [1] is a rather straightforward, simple publication, it reminds us that calibrating the Galen Mk. 2 is a crucial step towards clinical use. Having now read through the history of the REMS, Can and I are excited to contribute directly towards this goal.

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