# EN.601.654: CIS II Critical Paper Summary: Accuracy Assessment and Kinematic Calibration of the Robotic Endoscopic Microsurgical System

## 1.Introduction

### Project Statement & Paper Selection

The paper under examination in this report is *"Accuracy Assessment and Kinematic Calibration of the Robotic Endoscopic Microsurgical System"[1]* by Lihan Feng, Paul Wilkening, Yunus Sevimli, Marcin Balicki, Kevin C. Olds, and Russell H. Taylor. The paper builds on previous work done on the development of the Robotic Endoscopic Microsurgical System (REMS) by assessing its accuracy and proposing and applying a calibration procedure to improve it. This procedure is what we are following for the second half of our CIS II project to perform kinematic calibration on the Galen robot (Figure 1), which is itself the newest iteration of the REMS system. Therefore, a thorough reading and understanding of this paper is essential to smoothly go through the calibration procedure we intend to complete.

*Figure 1: Galen is the latest iteration of REMS [2]*

### Paper's Contribution and Important Results

For a precise surgical robotic system, high accuracy and precision is needed due to the sensitive nature of surgical operations and the tight tolerances related to working on the human body, particularly on the head and neck where many important anatomic structures are very closely located from each other. Therefore, the accuracy of the system needs to be evaluated and ideally improved upon to meet the needs of different ear-nose-throat surgeries. The authors do exactly so by calibrating REMS using a procedure involving data collected from a Polaris optical tracking system and the utilization of the solutions to the standard hand-eye calibration problem as well as Bernstein polynomials for kinematic pose accuracy. Following this procedure, the authors report an improvement in the tool tip pose accuracy, from 2mm of average absolute error before calibration to 0.14 mm of average absolute error afterwards. The simplicity of the procedure, particularly since it allows for kinematic calibration without requiring the calibration of individual robot links is also among its most important features.

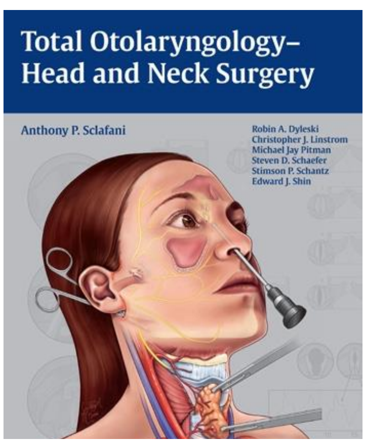


*Figure 2: Tools and important structures concerning ENT surgery [3]*

## 2.Background

### Clinical Background

Head and neck surgery (ENT) procedures have narrow workspace around delicate structures, and require holding fairly long tools with high precision and stability as demonstrated by Figure 2. General robotic systems such as the DaVinci are useful for such stabilization, however they are not optimized for ENT procedures. Therefore, task specific systems have been adapted for particular tasks, and can't be very easily generalized to other procedures.

## Previous Work: Robotic Endoscopic Microsurgical System

To address this generalization and optimize a multi-task robot optimized for ENT procedures, the Johns Hopkins Laboratory for Computational Sensing and Robotics has developed REMS. Designed to be inexpensive, precise, and intuitive to use, it is a collaboratively controlled robot meant to cancel hand tremor by performing the tool movement instead of the surgeon based on their input on to the tool. Such a robot is capable of being used as a surgical navigation system and for implementing virtual fixtures, once a desired level of accuracy is reached. Prior to this paper, REMS' uncalibrated stereotactic accuracy was observed to be good relative to similar systems, but could indeed be improved.

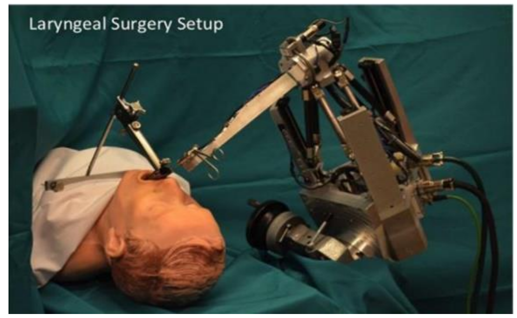


*Figure 3: Robotic ENT Microsurgical System (REMS) [4]*

# 3.Technical Approach: Kinematic Calibration

## Calibration Protocol Overview

For a set of n poses, the optical tracker records pose measurements of the end effector $C_i$, which is treated as the undistorted ground truth. For each pose, the corresponding forward kinematics of the robot $K_i$ is evaluated and recorded. $K_i$ is the "distorted" data that needs to be corrected.

The protocol stars with performing hand-eye calibration to determine the transformation between the end effector and the tool tip $T\_Tip$, and between the robot's base frame and a reference frame $T_B$. An eye-to-hand approach is preferred to an eye-in-hand approach as this is easier and more robust to set up. After solving the hand-eye calibration problem, Bernstein polynomials are fitted to correct the distorted frame to align with the ground truth.

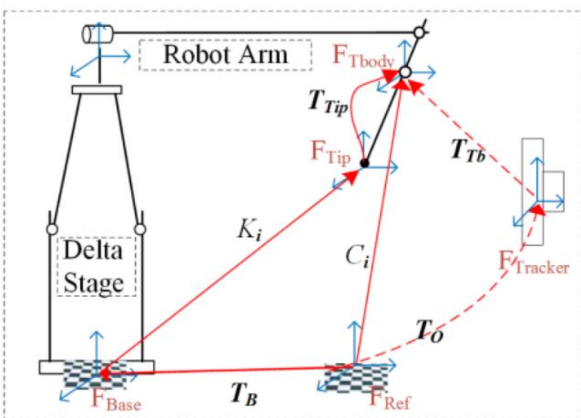


*Figure 4: REMS & Optical Tracker Kinematic Relations [1]*

## Hand-Eye Calibration

From the frame relationship as seen in Figure 4: $T_O \cdot T_{TB} = T_B \cdot K \cdot T_{Tip} = C$ (1)

Where C is calculated by tracker. For the i$^{th}$ measurement: $C_i \cdot T_{Tip}^{-1} = T_B \cdot K_i$ (2). From the initial measurements $C_0$ and $K_0$: $T_{Tip}^{-1} = C_0^{-1} \cdot T_B \cdot K_0$ (3). Substitute (3) in (2): $C_i T_{Tip}^{-1} = C_i C_0^{-1} T_B K_0 = T_B K_i$, we have the expression:

$$(\boldsymbol{C_i C_0^{-1}})\boldsymbol{T_B} = \boldsymbol{T_B}\,(\boldsymbol{K_i K_0^{-1}})$$

An expression for $T_{Tip}$ can be similarly constructed as:

$$(\boldsymbol{C_0^{-1} C_i})\boldsymbol{T_{Tip}^{-1}} = \boldsymbol{T_{Tip}^{-1}}(\boldsymbol{K_0^{-1} K_i})$$

These expressions have the form of the classic AX = XB problem, and the authors use the quaternion method to solve it and obtain $T_{Tip}$ and $T_B$.

## Kinematic Correction

Once $T\_Tip$, and $T_B$ are known, a predicted pose for the **tool tip** is calculated as $\mathrm{K}_{\mathrm{Pre,i}} = T_B^{-1} \cdot C_i \cdot T_{Tip}^{-1}$, and the error between this ideal prediction and the evaluated kinematics is calculated as $\Delta\mathrm{K_i} = K_i^{-1} \cdot \mathrm{K}_{\mathrm{Pre,i}}$. These poses are still frame transformations expressed as matrices, to fit a Bernstein polynomial to them, they are then converted to vector form as seen in Figure 5 with an element for each degree of freedom. It should be noted that the rotation about one of the degrees of freedom, $\omega$, is controlled by the surgeon in this system and hence doesn't need to be included in the calibration procedure and $\rho_i$, the vector representing $K_i$, which makes the training process 5-to-6 dimensional.

$$\left.\begin{array}{l} K_i \\ K_{Pre,i} \end{array}\right\} \xrightarrow{\text{yields}} \left\{\begin{array}{l} \boldsymbol{\rho}_i = \mathrm{Dof}(K_i) = [\boldsymbol{p}_i, (\boldsymbol{\theta}_i, \boldsymbol{\varphi}_i)] \\ \boldsymbol{\eta}_i = \mathrm{Dof}(K_i^{-1} K_{Pre,i}) = [\boldsymbol{\varepsilon}_i, \boldsymbol{\alpha}_i] \end{array}\right.$$

*Figure 5: Transformation matrices converted into vector form [1]*

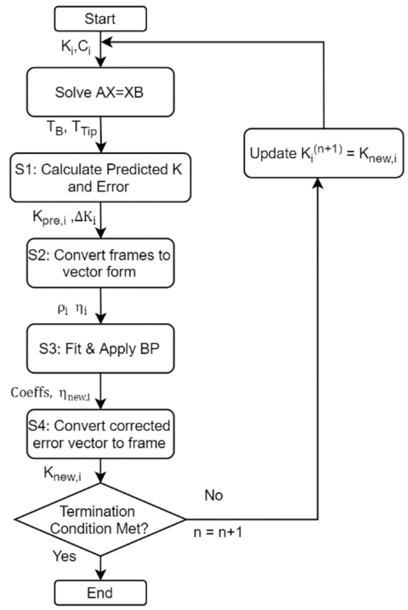


*Figure 6: Kinematic Calibration Workflow including HE Calibration and*

Next, a Bernstein polynomial is fitted to obtain an N dimensional vector of coefficients, which are applied to $\rho_i$ to obtain a corrected error $\eta_{new,i}$ (in vector form). This error is then converted into frame matrix $\Delta\mathrm{K}_{\mathrm{BP,i}}$ and the corrected kinematics are computed as $K_{new,i} = K_i \cdot \Delta K_{BP,i}$. After this corrected kinematics and the ground truth kinematics are compared, if the error between them is greater than desired, another iteration starts where the new "distorted" pose is taken to be $K_i^{j+1} = K_{new,i}$. The workflow for kinematic correction can be seen in Figure 6.

# 4.Calibration Experiment and Results

## Experimental Procedure

Over 5000 kinematic poses across REMS workspace have been collected; 75% of this data being used to fit the Bernstein polynomial and the other 25% being used to test the improved accuracy. Error is defined as the norm of the difference between $K_{new,i}$ *and* $K_{pre,i}$ in vector form. An iteration test is also presented to see how error varies over iterations of this algorithm, showing that the error becomes numerically stable after as few as 5 iterations.

## Accuracy Assessment

A mean absolute error of 0.14 mm for translation and 0.0011 rad for rotation are recorded in a [80, 80, 90] mm workspace when a $5^{th}$ order Bernstein polynomial is used. This fulfills the authors' intention of achieving sub-millimeter accuracy, and is reported to be better than many conventional systems which feature mean absolute error between 0.5-1mm in simulated clinical tests. Furthermore, the error seems to be normally distributed for each calibrated degree of freedom, that any recorded error is likely to be within 3 standard deviations from the mean.

The authors put the worst cases for error under further scrutiny where $E_{tran} \geq 0.4mm\ or\ E_{rot} \geq 0.003\ rad$. A total of 11 points seem to be in this error range for translation and a total of 25 points are within the rotational error range (out of 1250 data points). They examine no pattern for the configurations that result in high $E_{tran}$, however they observe that configurations resulting in high $E_{rot}$ cluster around the boundary of the REMS workspace. It is possible that at the boundary the Delta mechanism slightly rotates and contributes to the rotation of the tool tip, making the assumption of independent translation and rotation invalid at the boundaries.

## 5.Conclusions

The paper presents a simple and relatively easy protocol for calibrating a multiple degree of freedom robotic surgical system, without the need to calibrate each individual joint or link. This protocol is conveyed with mathematical clarity, and results in significant improvement regarding the pose error of the REMS system, reducing it from 2 mm before calibration to 0.14 mm afterwards. However, this simplicity is owed to the assumption that rotational error is independent of translational position. This is a valid assumption for most cases and works for the REMS system particularly because translational error is more significant to its applications, although it becomes invalid at the boundaries at the workspace and causes rather significant rotational errors. Besides this assumption, there are further limitations due a tracker accuracy of only 0.35 mm, and confusing language being used while discussing the results of the calibration experiment.

The authors have already repeated this procedure with a more accuracy Atracsys tracker (with 0.09 mm accuracy), and other possible next steps could include further evaluation of the relationship between translational and rotational error especially at the workspace boundary. Finally, this procedure can be applied to other robotic systems, which is what our CIS II project aims to do. We will follow this procedure on the Galen robot, whose predecessor was REMS, using the Atracsys tracker. We will initially repeat the assumption of rotational and translational error independency to reduce the amount of data we need, and might need to abandon it and adjust our procedure accordingly further down the project pipeline.

## 6.References

[1]: Feng et al: *"Accuracy Assessment and Kinematic Calibration of the Robotic Endoscopic Microsurgical System". 2014*

[2]: Taylor, "The Galen Microsurgery System", 3/21/2019, LCSR Industry Day, Baltimore

[3]: Sclafani et al: "Total Otolarnygology- Head and Neck Surgery", Thieme Medical Publishers, 2015

[4]: K. C. Olds, *Robotic Assistant Systems for Otolaryngology-Head and Neck Surgery*, Ph.D Thesis, The Johns Hopkins University, 2015