Computer Integrated Surgery II Paper Critique
Group 4: Tool Gravity Compensation for the Galen Microsurgical system
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Project Overview:

Our project involves general performance improvements for the Galen Microsurgical system, including gravity compensation and deflection characterization. Gravity compensation is the process of predicting the force and torque that a tool will exert on the Galen's force sensor and then removing that from the sensor reading. This force will vary if the robot is in motion compared to if it is static, but we intend to implement gravity compensation for both these cases. Deflection is discrepancies between the robot's predicted position and its true position that arise because of forces on the end effector and mechanical give in the system. By characterizing this deflection, we can better predict the true position of the tool.

Papers Selected:

For this presentation, I selected three papers related to our project. The first was "The Robotic ENT microsurgery system: A novel robotics platform for microvascular surgery." This paper was selected because it gave a particular use case that the Galen was more suited for compared to other robotic surgical systems. This shows that the system has both commercial viability and has a place in the operating room. The second paper selected was "Tool Gravity Compensation for Maneuverability Enhancement of interactive robot control for bone fracture system." This paper and the methodology presented was directly related to our static gravity compensation implementation. The last paper chosen was "Gravity Compensation and Compliance Based Force Control for Auxiliarily Easiness in Manipulating Robot Arm." This was another implementation of gravity compensation that used a different method but was selected because it gave us additional insight on the topic.

The Robotic ENT MicroSurgery System:

This paper worked to validate the REMS, an earlier version of the Galen, as a system for microvascular surgery. Microvascular surgery is surgery that needs to conducted under a microscope, on smaller blood vessels. This paper also developed a new scale, called the MTS, for measuring tremors during microvascular surgery, while previous tremor scales were more targeted towards macroscopic surgery.

This study found that naive users had significantly less tremor using the REMS. Naive users also had a slightly lower time to complete using the REMS. They also found that the scale developed had a high inter-rater reliability, which measures how consistent an evaluation of a somewhat subjective measure is between different raters. To validate this, they used a metric called intraclass correlation, and they found this value to be over 0.9.

The paper showed that the REMS add significant potential for use with microvascular surgery. Other surgical systems, such as the DaVinci, are ill suited for microvascular surgery and showed no improvement in surgeon dexterity or operative efficiency. This study, however, found that the REMS was more stable and generally prefered over freehand surgery for naive users. This suggests that the REMS could ease the learning curve associated with microvascular surgery.

For the experiment, 6 naive participants and 1 expert were recruited. The naive participants were fourth year med school students that were applying for residency with a focus in surgery. The participants all performed an anastomosis on a chicken thigh model, which was acquired from a local grocery store. Anastomosis is procedure that involves stitching two tube like objects, such as blood vessels together. The vessel that was chosen on the chicken was roughly 3 mm in diameter. Each participant performed the procedure freehand and with the REMS, as shown in the figure below.

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These trials were recorded for blinded grading of tremors and time to completion by 7 independent microvascular experts using the MTS scale. This scale determines the severity of tremors based on the amplitude of the tool tip movement compared to the vessel width. A table of the scoring system in attached below.

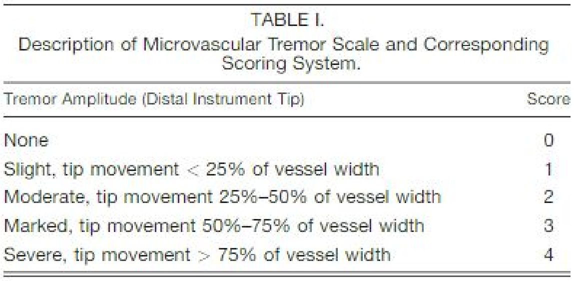

TABLE I.
Description of Microvascular Tremor Scale and Corresponding Scoring System.

Tremor Amplitude (Distal Instrument Tip)	Score
None	0
Slight, tip movement < 25% of vessel width	1
Moderate, tip movement 25%–50% of vessel width	2
Marked, tip movement 50%–75% of vessel width	3
Severe, tip movement > 75% of vessel width	4

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The results showed that for naive users, tremor was significantly reduced and time was slightly reduced. However, for the expert users, tremors and time to completion were very similar. This lead the authors to believe that this system may be more suited as training platform for naive surgeons.

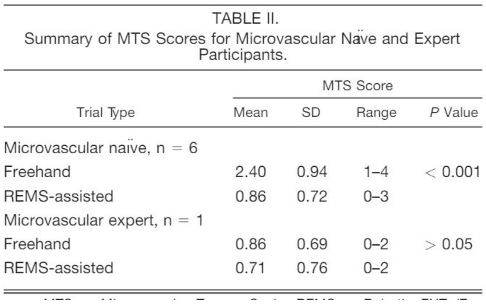

TABLE II.
Summary of MTS Scores for Microvascular Naïve and Expert Participants.

Trial Type	MTS Score			
	Mean	SD	Range	*P* Value
Microvascular naïve, n = 6				
Freehand	2.40	0.94	1–4	< 0.001
REMS-assisted	0.86	0.72	0–3	
Microvascular expert, n = 1				
Freehand	0.86	0.69	0–2	> 0.05
REMS-assisted	0.71	0.76	0–2	

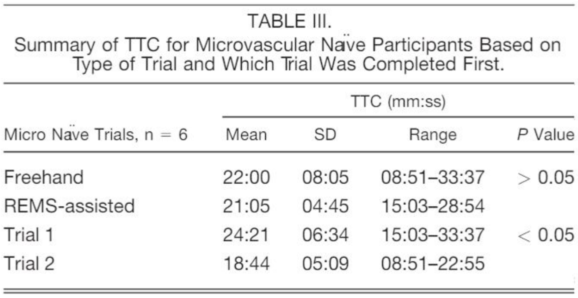

TABLE III.
Summary of TTC for Microvascular Naïve Participants Based on Type of Trial and Which Trial Was Completed First.

	TTC (mm:ss)			
Micro Naïve Trials, n = 6	Mean	SD	Range	*P* Value
Freehand	22:00	08:05	08:51–33:37	> 0.05
REMS-assisted	21:05	04:45	15:03–28:54	
Trial 1	24:21	06:34	15:03–33:37	< 0.05
Trial 2	18:44	05:09	08:51–22:55	

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There are several opportunities for the authors to move towards with this work. It would be interesting to see how intermediate users would differ using the REMS vs freehand. It would also be interesting to see how both expert and novice surgeons would fair if the procedure was on a smaller scale, such a rat model. The system has since been improved and implemented a host of new features, such as path following and virtual fixtures. Seeing how those features could ease this procedure would also be worth pursuing.

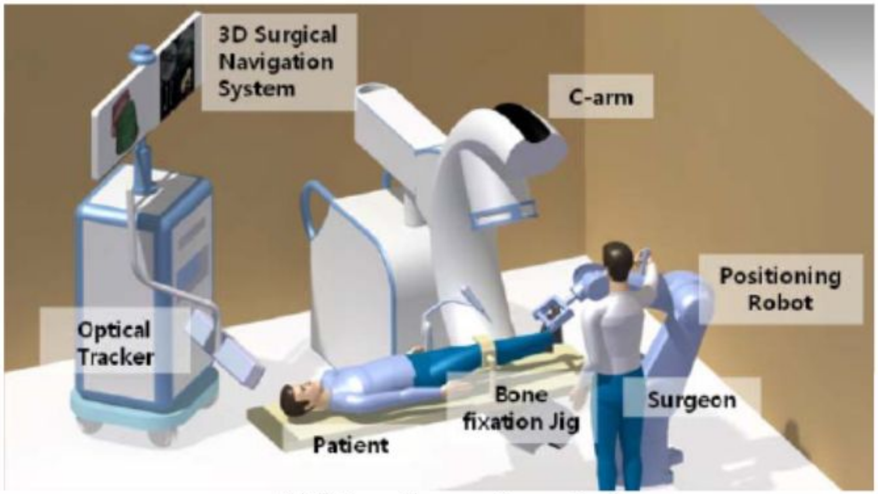
This paper did have a few point that should be taken note of. They mentioned a metric called TTS in the paper but did not describe what that was measuring. They also mentioned that each participant took more time on average on their first trial, whether it was using the REMS or freehand, than the second trial.

Tool Gravity Compensation for Bone Fracture Reduction System:

This paper presented on-going work on a bone fracture reduction robotic system. They show how it was possible to use a 6 degree of freedom force torque sensor to help position their system and developed an analytical approach to tackle gravity compensation. They found that this model was effective at removing gravity based disturbances in the F/T readings.

The system that they were developing was created to address the problems in the bone fracture repair procedure. When long bones, such as the femur or humerus, are fractured, they have to be surgically repaired. During this procedure, several assistant surgeons have to align and support these bones because surrounding muscles are contracted strongly. This is physical straining on these surgeons and also exposes them to additional radiation. These conditions show that this is a perfect procedure for a robotic system to be used.

The system contains a few different elements. The first is that positioning robotic that holds the fractured bones in place while the surgeon operates. This is the robot that uses the F/T sensor to be easily and intuitively move the robot into position. There is also a drilling robot that used to operate and create the necessary conditions for inserting the plate or rod needed for recovery. Next, there is a 3d surgical navigation system that displays the relative position of the bones. This works by using an optical tracker and pre-operative registration. There is also a C-arm to take periodic x-ray images during the procedure. The tracker itself helps to cut down on the number of x-rays that need to be taken during the procedure.



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Their gravity compensation approach calculated the expected force on the sensor based on the tools center of mass and its orientation compared to the world frame.

The forces/torques that were measured by the sensor were a combination of the force due to gravity and the force exerted by the surgeon, seen below.

$$\mathbf{F}_{\text{measured,unbiased}} = \mathbf{F}_{\text{tool gravity}} + \mathbf{F}_{\text{interaction}}$$

$$\mathbf{M}_{\text{measured ,unbiased}} = \mathbf{M}_{\text{tool gravity}} + \mathbf{M}_{\text{interaction}}$$

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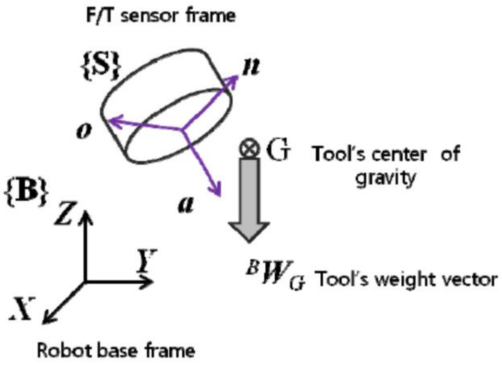
There are 3 frames of interest. The world frame is important because the tool gravity force is always parallel to the z axis of this frame. The sensor frame is relevant because that is where the forces need to be resolved and it helps determine the orientation of the tool compared to the world frame. The tool tip frame is needed to calculate the moment of inertia necessary for torque.



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The force at the force sensor could be calculated using the equation below. R is the rotation matrices between the frames, W is the weight of the Tool, M is the moment and P is a skew symmetric matrix based on displacement of the tool center of mass compared to the sensor.

$$\begin{bmatrix} {}^{S}\mathbf{F}_{\text{tool gravity}} \\ {}^{S}\mathbf{M}_{\text{tool gravity}} \end{bmatrix} = \begin{bmatrix} {}^{S}_{B}\mathbf{R} & 0_{3\times 3} \\ {}^{S}\mathbf{p}_{G}\times {}^{S}_{B}\mathbf{R} & {}^{S}_{B}\mathbf{R} \end{bmatrix} \begin{bmatrix} {}^{B}\mathbf{W}_{G} \\ {}^{B}\mathbf{M}_{G} \end{bmatrix}$$

$${}^{S}\mathbf{p}_{G}\times = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix}$$

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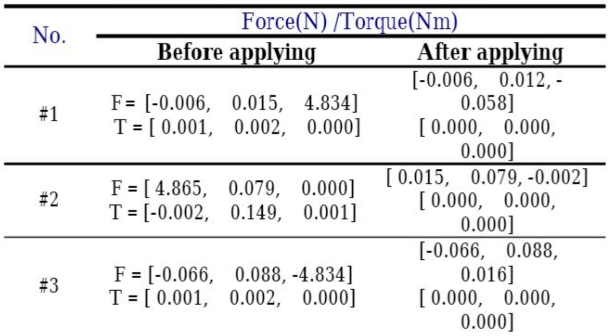
They also ran into a issue with force sensor bias, which is a similar problem to the one that we are facing. When the robot is turned on, the sensor takes the initial readings and subtracts that out to give 0s for each reading initially. The problem that arises here is that there is now a bias force vector that always in the same position with respect to the force sensor, while the force vector due to gravity shifts do the force sensors orientation. The sensor reads the component vector due to these forces. Therefore, the vector we need to compensate for is this one, which can be calculated by adding the predicted force due to the tool to the bias vector.

For our implementation, we broke this down into two parts. The Galen has a tool adaptor that is always attached to the force sensor, so the bias vector is just the forces and torques due to gravity on the adaptor. A tool can then be attached without affecting the bias vector. Therefore, by knowing the center of mass and weight of the adaptor, we can calculate the bias vector, the force vector due to gravity, and then use those components to calculate the expected F/T readings. We can then independently calculate the F/T readings from the tool and add it to this vector.

This was both well written and directly relevant to our project. They used a good empirical evaluation, which can be seen below. The paper, however, did not give many details about their surgical system, leaving out details on the type of equipment used in the actual system. This might be due to the fact that this was a conference paper, which tend to smaller in scope.

TABLE I
RESULTS OF TOOL GRAVITY COMPENSATION



No.	Force(N) /Torque(Nm)	
	Before applying	**After applying**
#1	F= [-0.006, 0.015, 4.834] T = [0.001, 0.002, 0.000]	[-0.006, 0.012, -0.058] [0.000, 0.000, 0.000]
#2	F = [4.865, 0.079, 0.000] T = [-0.002, 0.149, 0.001]	[0.015, 0.079, -0.002] [0.000, 0.000, 0.000]
#3	F = [-0.066, 0.088, -4.834] T = [0.001, 0.002, 0.000]	[-0.066, 0.088, 0.016] [0.000, 0.000, 0.000]

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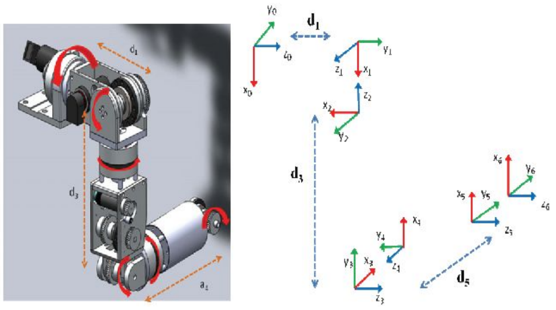
Gravity Compensation and Compliance Based Force Control:

This paper proposed a method to calculate a general solution for gravity compensation at joints of a robotic manipulator using vector projections. They also developed an approach called force counterbalance control to balance external loads while retaining manipulator dexterity. They experimentally found that their methods were successful at retaining ease of use under an external force.

For their implementation, they used a 6 degree of freedom robotic arm connected to a PC. This can be seen below and it is important to note that each joint it revolving around its z-axis.



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Their gravity compensation technique revolved around the use of the Denavit-Hartenberg form, seen below. This allowed them to construct forward kinematics using coordinate transformations between joints. Three values of interest are theta, alpha, and d. Theta is the offset about the z axis at each joint. Alpha is the offset about the common normal of the component z axes. d is the offset along the previous z axis to the common normal.

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_6^0 = T_1^0 \cdot T_2^1 \cdot T_3^2 \cdot T_4^3 \cdot T_5^4 \cdot T_6^5 = \begin{bmatrix} P_6^0 \\ 1 \end{bmatrix}$$

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The overall goal of the system to calculate the torques at each joint due to gravity. This itself requires 3 things. An F force due to gravity, an e unit projection vector all the axes the force is being distributed and an 4 distance between F and e.

$$\tau = \vec{M} \cdot \vec{e} = [\vec{r} \times \vec{F}] \cdot \vec{e}$$

$$\vec{\tau} = \{[\vec{r} \times \vec{F}] \cdot \vec{e}\}\vec{e}$$

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F is found easily below. The r value is found by using the Denavit-Hartenberg equations below. Lastly the e value is found by using some intermediate rotation matrices, which can be calculated by taking values from the Denavit-Hartenberg matrices that were already found.

$$\vec{F}_i = m_i g \vec{i} \qquad T^0_{r_i\;4\times4} = T^0_1 \cdot T^1_2 \cdots T^{i-1}_{r_i}, \vec{r}_i = \begin{bmatrix} T^0_{r_i}(1,4) \\ T^0_{r_i}(2,4) \\ T^0_{r_i}(3,4) \end{bmatrix}$$

$$e_i^0 = R_{\theta_1} \cdot R_{\alpha_1} \cdot R_{\theta_2} \cdot R_{\alpha_2} \cdots R_{\theta_i} \cdot R_{\alpha_i} \cdot \vec{R}, R = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$R_{\theta_i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_{\alpha_i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i \\ 0 & \sin\alpha_i & \cos\alpha_i \end{bmatrix}$$

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They also wrote about another issue they had due to the gear ratio of the robot, which resulted in course movement. They addressed this by adding an additional filter called the auxiliary torque compensator. This essentially worked by allowing them to tune some parameters to affect the inertia of the arm, making movement smoother. Together with the gravity compensation, they called this combined system the force counterbalance control.

This paper overall was riddled with issues. There were grammatical errors throughout this paper. This is somewhat understandable because this is a taiwanese university, however, it made the paper very difficult to read. The paper was also poorly organized and often difficult to understand. I do not believe that they gave sufficient information for their auxiliary torque compensator. They also did not show any empirical evidence that their implementation was functional. They only showed pictures of results, not showing an numerical data or even a link to a video.

Bibliography:

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