Soft Tactile Sensing for Robotic Manipulation

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Summary

Soft twist sensing is essential for fine motor control in twisting delicate objects, better grasp understanding and better understanding the texture of a surface. This project investigates the response of an electrical impedance tomography (EIT) sensor to a twisting solid cylinder and its use for tactile manipulation. Using experimental measurements and a finite element model the torque response of the hydrogel will be understood and modelled.

1. Background

As soft robots develop, the need for soft sensors grows. Soft sensors allow the robots to maintain their flexibility without losing out on their sensing capabilities. There are many soft sensing technologies, each with unique strengths and weaknesses [1]. One of which, Electrical Impedance Tomography (EIT) [2], enables large-area tactile sensing with minimal interference by placing electronics at the surface edges. EIT injects current between surface points and measures resulting potentials to map conductivity, which reflects the surface's physical state. This allows EIT to measure temperature [3], differentiate materials [4], and detect pressure or damage [5]. Although EIT is capable of multi-area sensing of a variety of conditions, there has been little research into its use for robotic twist manipulation.

Sensing torque and shear forces is vital for accurate robotic manipulation, allowing for precise control through closed loop feedback for twisting tasks, such as: controlled twisting of screws to ensure no under or overtightening, twisting the lid of a jar while ensuring no slippage or for better understanding the texture of a surface. This project aims to model the effect of a stiff rotating cylinder (such as a screwdriver) on the conductivity of a hydrogel and use this model to facilitate more precise manipulation for twisting tasks. EIDORS [6], an open-source finite element simulation software will be combined with an analytical understanding of torque to achieve this goal.

2. Theory

The experiment applies a torque via the twisting of a screwdriver using the experimental setup. This applies a torque along the length of the sensor (Figure 1). This was hypothesised to cause the 'fingertip' to bunch up on one side of the applied force and stretch on the other side, and be uniform in the length. This would mean the material will be most bunched/stretched along the sides of the length, and should reduce towards the edges. No paper was found with an analysis into the effect of a solid roller on an adhesive elastic material, however [7] describes the effect of a ball's lateral movement on a surface, the behaviour on the surface is similar to the expected response stated previously. This is expected to be mirrored and negative on the side in tension. Therefore, the conductivity should also decrease in areas of tension and increase in areas of compression. A first order differential of a Gaussian can be used to model this change in conductivity across the surface of the sensor.

The hypothesised equation for the change in conductivity across the sensor:

$$f(x, y) = -\frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{1}$$

Where x is the displacement from the axis of the screwdriver and y is the displacement perpendicular and σ is the scale factor defining the rate at which the conductivity dies down.

It is hypothesised that the uniformity in the vertical axis suggests that the most efficient setup will require injection parallel to the horizontal axis and readings on pairings of electrode in the vertical axis. It is also hypothesised that due to the conductivity function being odd, only half of the surface needs to be measured to obtain accurate readings.

3. Progress to Date

The first few weeks were used to set-up the experiments and create a framework for simulation. Using the setup, long automated experiments could be run to collect EIT data and torque data for analysis. A pattern for electrode inject patterns was observed.

3.1. Simulation Setup

To understand the effect of the twist on the conductivity of the hydrogel, EIDORS can by utilised to create an FEM of the hydrogel conductivity and calculate expected readings. The conductance is set using the hypothesised equation Equation (1) and the expected readings can be compared to real world measurements.

The first task required setting up a model for the EIT setup. A 2D rectangle is used as the forward model (Figure 1) as the 'fingertips' are cuboids, therefore the conductivity changes across the electrodes are assumed to be equivalent to the conductivity changes across a 2D surface.

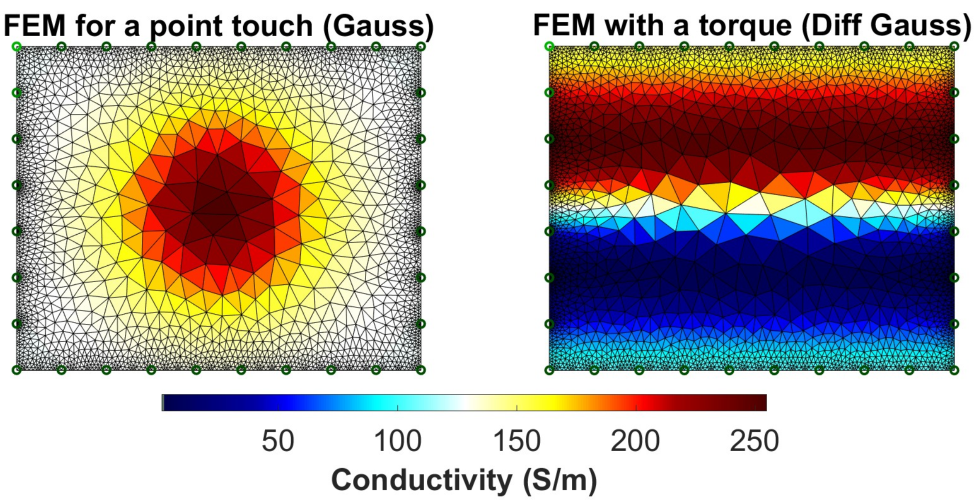
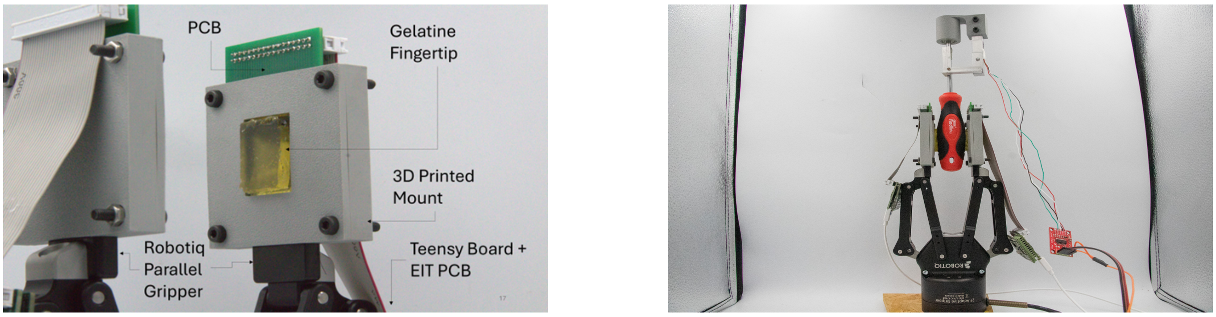


Figure 1: FEM of a point press and a twist respectively

3.2. Physical Setup

In order to validate the hypothesised torque conductivity model. The first thing to establish was an automated repeatable experiment setup. This setup is required, regardless of the overall goal of the research. The setup involves 3D printing a clamp mounted head for the the hydrogel 'fingertips'. These 'fingertips' can be attached to the end of Robotiq Parallel Grippers as shown in Figure 2a. Which in turn is attached to a Universal Robots UR5. This creates a pinching robot with 6 Degrees of freedom. Finally, to provide ground truth values for torque, a simple set up was made with a screwdriver, a metal bar and a load cell. The full setup is as shown in Figure 2b.



(a) Mount on Gripper. This mount is shown clamping the hydrogel 'fingertip' onto a custom PCB with electrode pads connecting to a multiplexer and teensy board. The whole setup is attached to a parallel gripper.

(b) Complete Setup showing the parallel gripper with mounted 'fingertip' EIT sensors. They are shown holding the ground truth measurement setup. The gripper can be attached by the base to the UR5 which can then be used to twist the screwdriver.

Figure 2: Physical Setup

3.2.1 Mount

To connect the hydrogel to the electrodes and to the parallel gripper a mount was required. A clamping mount was chosen, to make the setup modular and swap materials based on the needs of the experiment (Figure 6b). It also provides sufficient contact between the hydrogel 'fingertip' and the electrodes on the PCB. A mould was required for the hydrogel 'fingertips' (Figure 6c). Both were designed in Fusion 360 and printed on a Bambu Labs X1 Carbon.

3.2.2 Ground Truth Measurement

To measure ground truth values for the torque, a calibrated load cell and a metal bar attached to a screwdriver in a ball bearing were used. The length of the metal bar was used to convert the force measurement on the load cell to a torque measurement. This allows for accurate torque measurements that are used as the ground truth value used to measure the accuracy of the EIT sensors. This data can then be analysed.

3.3. Results and Analysis

The data recorded from live experiments (over 100 torque readings with 10 different magnitudes, alongside 896 channels (electrode pairings) from the EIT sensor) needed to be analysed to find the channels with the best responses, and therefore the electrodes most in use for an applied torque. This information can be used to verify the hypothesised best electrodes from the theoretical analysis and simulation.

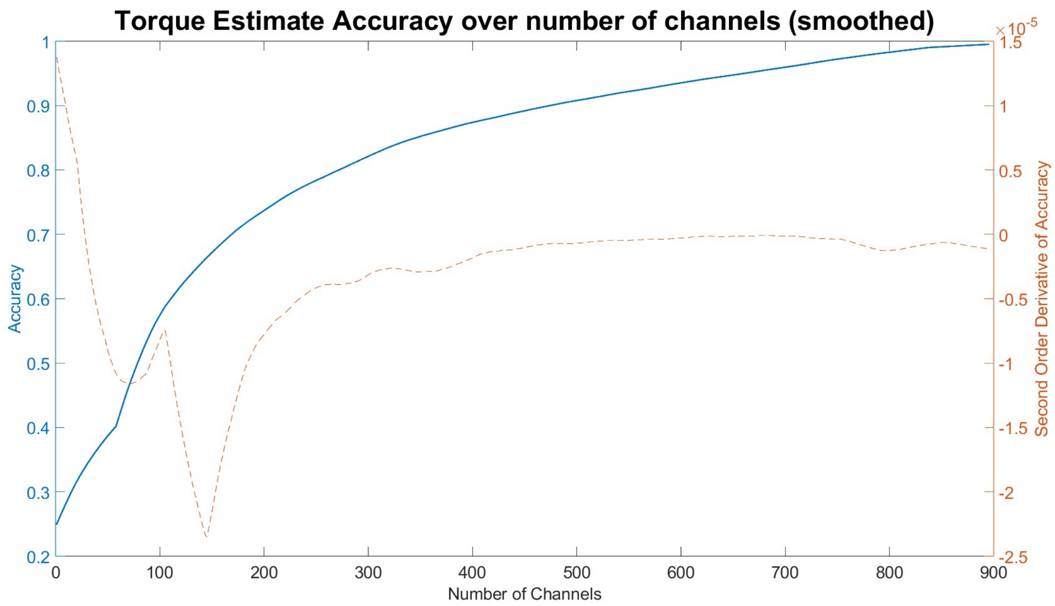


Figure 3: Torque Accuracy and 2nd Derivative of Torque Accuracy over number of channels. The accuracy of the ith channel is defined as $\frac{e^i_{MSE}}{e^{896}_{MSE}}$, where e^i_{MSE} is the mean squared error of the multivariable linear regression fit of the top i channels to the ground truth reading

The methodology used to rank channels was chosen from correlation between channel and ground truth data, a comparison of frequency content between the channel and ground truth data and root mean squared error between the channel and ground truth data. The best of these was found to be correlation. Through ranking the channels based on their absolute correlation values, the error over the number of channels used can be plotted as shown in Figure 3. By also plotting the 2nd order derivative of this data we can determine a point of diminishing returns, which is found to be approximately the top 500 channels. However, we can also see that in the accuracy in the top 122 channels is equal to the accuracy from the top 122 to all channels, therefore it may also be viable to consider a cut off percentage for the accuracy. To get a 70% accuracy we need the top 169 channels, for a 80% accuracy we need the top 272 channels and for a 90% accuracy we need the top 475 channels.

Figure 4 shows there is a pattern for the electrode pairings where the read and inject pairings are loosely perpendicular (this matches the hypothesis we had). The read pairings are roughly perpendicular to the direction of the twist, beginning in the top quarter of the surface. This matches the hypothesis that the torque should be symmetrical and only half the surface needs to be measured. Additionally the perpendicularity to the direction of the twist is as initially hypothesised. The top 169 electrode pairs (Figure 4) are more centred as we use the absolute correlation metric which should include both sides of the surface. It maintains the perpendicularity between the injection and read pairings. The injection pairings are always centred as the measurement pattern uses opposite electrodes. The analyse of the recordings agrees with the hypothesised conductivity equation (Equation (1)) and demonstrate how fewer electrodes can be used for an increased temporal resolution and increasing the control stability of the system. This increased stability can allow for more precise control of twisting manipulation.

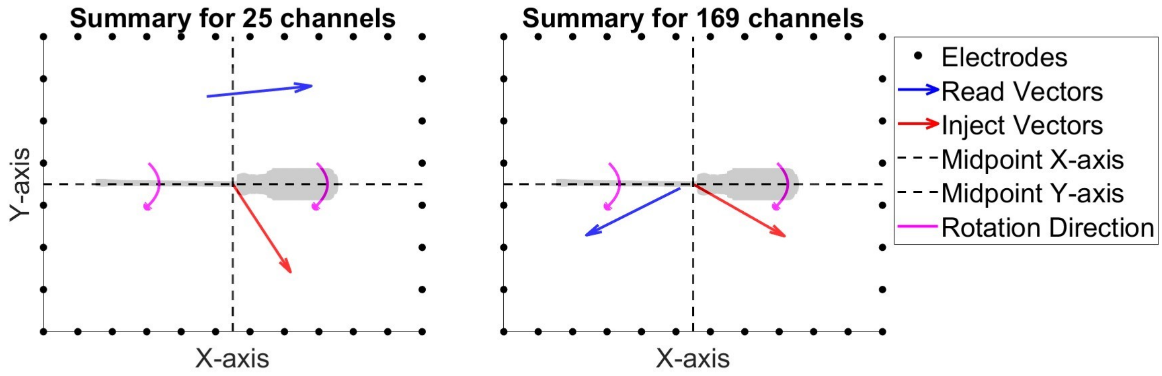


Figure 4: Inject and Read Vectors for the top 25 and 169 Channels during torque prediction respectively. The vectors starting point is the mean midpoint for the top pairings and the direction is the mean direction of the pairings.

Key Achievements	**Challenges**
Automated, adjustable, and repeatable setup	Accurately simulating the point press experiment due to unknown hydrogel conductivity
Preliminary hypothesis for EIT optimizations	Collecting accurate data from EIT sensors and ground truth with differing data rates
Simulation for predicting EIT electrode readings	Data had to be collected separately and post-processed to time sync for accuracy
Experiment analysis compared with hypotheses	
Insights on relationships in prevalent channels	

Table 1: Achievements and Challenges Thus Far

4. Future Work

The future work can be split into 3 key areas: Physical, Simulation and Analysis. Tasks can then also be given priorities. The key focus in Lent will be analysis and simulation development.

Future work will focus on validating the model with further experiments. Using the reduced electrode configuration testing will be done to validate models. Constructing a silicone mould for hydrogel fingertips will enable the use of higher-quality materials. In simulation, efforts will focus on improving simulation accuracy via matching simulation conductance to real fingertip properties. This improved accuracy will then allow for better comparison for the torque hypothesis. Analytical work will focus on using know material theory to create a better model for the conductivity. With all work leading to the closed loop control twisting manipulation.

4.1. Risk Assessment

To prevent electrical hazards, test equipment, inspect cables, and follow instructions. Conduct a COSHH assessment for hazardous substances like silicone. Use ventilation for soldering. Only authorized personnel may operate robotics under safety protocols. Mechanical hazards are negligible; for lifting, use trolleys, team lifting, and training. Turn off idle equipment, minimize storage, and keep escape routes clear.

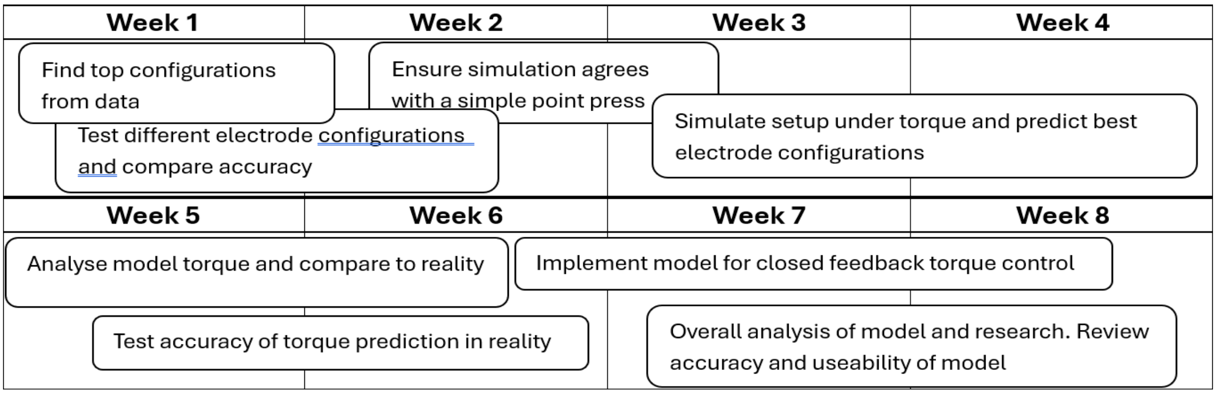


Figure 5: Plan for future work, Easter term will be used for report writing

References

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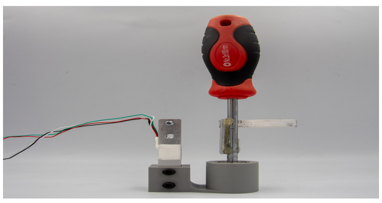
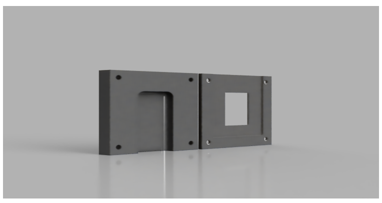
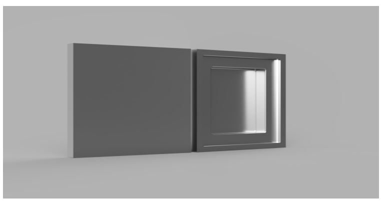


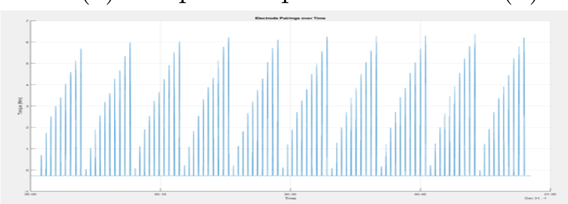
(a) Torque Setup



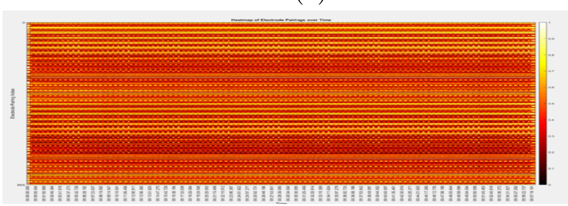
(b) Mount CAD



(c) Mould CAD



(d) Ground Truth Data



(e) EIT Data

Figure 6: Additional Figures.