In-Grasp Torque Estimation for Visuotactile Sensors with Tactile Dipole Moments

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***Abstract*— Tactile sensing has become a popular sensing modality for robot manipulators. Among the diverse range of information accessible from tactile sensors, torques transmitted from the grasped object to the fingers through extrinsic environmental contact may be particularly important for tasks such as object insertion. In this work, we introduce the notion of the Tactile Dipole Moment, which we use to estimate tilt torques from gel-based visuotactile sensors. This method does not rely on deep learning, sensor-specific mechanical, or optical modeling, and instead takes inspiration from electromechanics to analyze the vector field produced from 2D marker displacements. Despite the simplicity of our technique, we demonstrate its ability to provide accurate torque readings. These results suggest that simple analytical calculations may be sufficient for extracting certain physical quantities from visuotactile sensors. Further details about this work is available in [1].**

I. INTRODUCTION

Visuotactile sensors have gained great interest in recent years for their ability to endow robots with a sense of touch, while maintaining simple construction, high resolution, and ability to leverage techniques from computer vision [2]. We are interested in the problem of using visuotactile sensors to estimate external torques applied to grasped objects.

Zhang et al. [3] proposed to use a technique from flow analysis to relate patterns in the marker motion vector field, namely the diverging, unidirectional, and rotational components, to 3D forces and the 1D in-plane torques applied on the tactile gel. Inspired by this, we measure the remaining 2 dimensions of torque, called the “tilt” torque in [2], using analysis techniques inspired by electrodynamics [4]. The core underlying idea comes from the observation that the marker motion displacement field that results from tilt torques closely resembles the electric fields produced from electric dipole moments, as shown in Fig. 1. Therefore, we propose to use the same calculation used to characterize electric dipole moments to similarly estimate tactile tilt torques, and demonstrate through experiments that this simple calculation can enable successful measurement of tilt torques without relying on deep learning or sensor-specific analytical modeling of mechanical or optical properties.

II. METHOD

We consider the setting shown in Fig. 2, where an object is grasped by a parallel gripper with visuotactile sensors mounted on each finger, and a human applies torques on the grasped object which must be sensed from the visuotactile sensors. As illustrated in Fig. 1, the marker displacement field pattern that results from these torques produces vector field patterns similar to electric fields induced by an electric dipole, which is defined as a charge distribution consisting of equal and opposite charges separated by some distance.

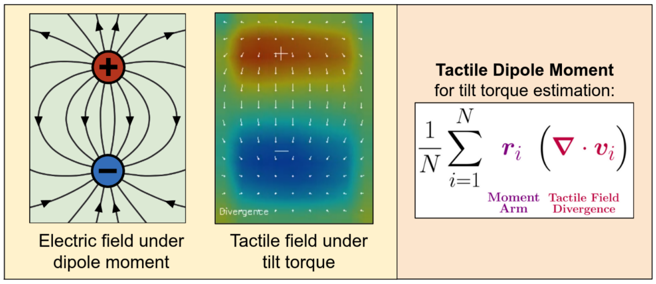

Fig. 1. The core contribution of this work. Left: Similarities between the electric fields produced from a dipole charge distribution, and visuotactile marker motion fields produced from tilt torques. Right: The corresponding equation defining the tactile dipole moment to estimate tilt torques.

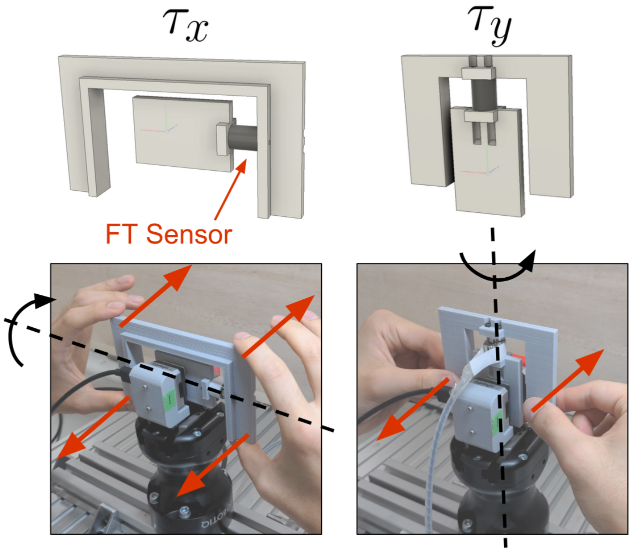

Fig. 2. The experimental setup for our main calibration and evaluation experiments, showing the 3D printed jig to enable direct measurement of the torques applied to a grasped object (top), and the way in which a human manually applies the torque (bottom).

This is becase, in electrodynamics, the diverging component of the electric field relates to the charge distribution that induces it, through Gauss’s Law

$$\boldsymbol{\nabla}\cdot\boldsymbol{E} = \frac{1}{\epsilon_0}\rho. \tag{1}$$

Here, $\boldsymbol{E}$ is the *electric field*, which we draw analogies to the *tactile marker displacement field*, ρ is a position-dependent *electric charge distribution*, which we relate to the *normal force distribution* on the tactile gel, and ϵ_0 is a constant

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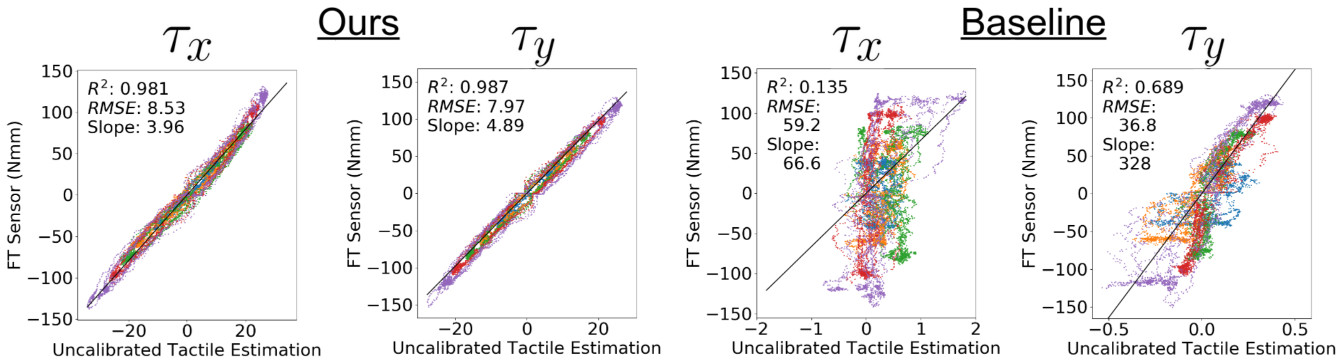

Fig. 3. The main result of this work, showing the linear relationship between our method to estimate tilt torques, and the ground truth provided by the FT sensor (Left). This is compared against the method proposed in [5], which also estimates tilt torques without the use of deep learning (right). The colors correspond to different experiments, each involving different maximum applied torques. Units for RMSE and Slope are in Nmm.

known as the permittivity of free space [4]. Analogously to the electric dipole moment, in the mechanical system of the tactile gel deformation under tilt torques, there are normal forces applied into and out of the gel surface in equal and opposite directions with the opposing regions separated by some distance. As per [3], normal forces are related to the marker motion field divergence similarly to electric charge distributions relating to electric field divergence.

Therefore, we characterize the tilt torques applied on the gel surface using the same calculation used to characterize electric dipoles–the dipole moment $\boldsymbol{p}$, defined as

$$\boldsymbol{p} = \iiint \boldsymbol{r} \rho \, dx \, dy \, dz, \tag{2}$$

where $\boldsymbol{r}$ is the distance vector from some predefined point in space to the infinitesimal volume element for integration [4]. We can additionally substitute Gauss's Law (1) to obtain the dipole moment in terms of the electric field

$$\boldsymbol{p} = \epsilon_0 \iiint \boldsymbol{r} \Big(\boldsymbol{\nabla} \cdot \boldsymbol{E} \Big) \, dx \, dy \, dz. \tag{3}$$

Transferring this calculation to the domain of tactile tilt torque estimation, we define the **tactile dipole moment** as

$$\boldsymbol{p}_{tilt} = \frac{1}{N} \sum_{i=1}^{N} \boldsymbol{r}_i \Big(\boldsymbol{\nabla} \cdot \boldsymbol{v}_i \Big) \tag{4}$$

$$= \frac{1}{N} \sum_{i=1}^{N} \begin{bmatrix} (r_i)_x \\ (r_i)_y \end{bmatrix} \left(\frac{d(v_i)_x}{dx} + \frac{d(v_i)_y}{dy} \right), \tag{5}$$

where we replaced the volume integral with a summation over vectors $\boldsymbol{v}_i$ representing a discretized vector field indexed by $i \in [1, \dots, N]$, and $\boldsymbol{r}_i$ is the moment arm vector. Since the dipole moment is dependent on the origin from which to define $\boldsymbol{r}_i$ in the general case where the net charge is nonzero [4], we take the integral from the midpoint between the centroids of the positive and negative divergence regions to approximate the point about which the planar gel surface rotates in reaction to tilt torques.

Finally, since the dipole moment points from negative to positive charges, the torque $\boldsymbol{\tau}_{tilt}$ points in a direction perpendicular to this dipole moment and is scaled by constant calibration factors c_x, c_y,

$$\boldsymbol{\tau}_{tilt} = \Big[c_x (p_{tilt})_y, -c_y (p_{tilt})_x \Big]^T. \tag{6}$$

III. EXPERIMENTS

We used the Gelsight Mini [6] to evaluate the accuracy of our estimation technique under ideal conditions. Fig. 3 shows a comparison between tilt torques estimated by our approach with that measured from a small and high-resolution FT sensor (Nippon Liniax Corp., TFS12A-25), which we use as ground truth wrench measurements. This is compared to the method given in [5], as a baseline that also estimates tilt torques from 2D visuotactile data without deep learning. Our method demonstrates higher estimation accuracy from the improved distributed normal force measurement via vector divergence over the vector norm. We additionally observed that this linearity was maintained whenever torques along x and y axes were coupled.

IV. CONCLUSION AND FUTURE WORK

In this paper, we introduce the Tactile Dipole Moment as a technique to estimate tilt torque from visuotactile sensors. Our results demonstrate the effectiveness of vector calculus techniques for analyzing visuotactile data. Future work could involve automatic tactile object insertion with feedback control using our torque estimation method as sensory inputs.

REFERENCES

[1] Y. Fuchioka and M. Hamaya, "An electromagnetism-inspired method for estimating in-grasp torque from visuotactile sensors," *arXiv preprint arXiv:2404.15626*, 2024.

[2] W. Yuan, S. Dong, and E. H. Adelson, "Gelsight: High-resolution robot tactile sensors for estimating geometry and force," *Sensors*, vol. 17, no. 12, p. 2762, 2017.

[3] Y. Zhang, Z. Kan, Y. Yang, Y. A. Tse, and M. Y. Wang, "Effective estimation of contact force and torque for vision-based tactile sensors with helmholtz–hodge decomposition," *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 4094–4101, 2019.

[4] D. J. Griffiths, *Introduction to electrodynamics*. American Association of Physics Teachers, 2005.

[5] A. Yamaguchi and C. G. Atkeson, "Tactile behaviors with the vision-based tactile sensor fingervision," *International Journal of Humanoid Robotics*, vol. 16, no. 03, p. 1940002, 2019.

[6] "Gelsight mini," https://www.gelsight.com/gelsightmini/, accessed: 2023-09-03.