Optical Tactile Sensing for Multi-Contact Interaction on Aerial Robots

Emanuele Aucone, Carmelo Sferrazza, Manuel Gregor, Raffaello D'Andrea, and Stefano Mintchev

***Summary*: This article introduces an optical tactile sensor tailored for drones, which provides real-world measures of 3D contact locations (mm) and 3D force vectors (N) for multiple contacts interaction.**

I. INTRODUCTION

Tactile sensors have found increasing uses in robotic hands, arms and humanoids for manipulation tasks and interaction with humans [1]–[3], as well as in terrestrial robots for locomotion, navigation and terrain classification [4]–[6]. Despite these advancements, the sense of touch remains surprisingly underutilized in drones. While current solutions often rely on single sensors mounted on end-effectors [7]–[11], the integration of distributed tactile sensing would allow the detection of multiple contacts around the drone's body. This could be highly beneficial to a variety of applications, e.g. to apply multiple forces on surfaces (control task), to track and move objects along a trajectory (non-prehensile manipulation), to estimate the location of the surrounding obstacles (mapping) and their compliance to find a safe path to traverse them (navigation). In this study, we introduce an optical tactile sensor for multi-contact interaction with aerial robots. Differently from previous sensors designed for robotic fingertips [12]–[15] or arms [16], [17], the core of our technological advancement lies in the integration of novel hardware and software solutions. We prove that drones can use distributed feedback, onboard and in real-time, for estimating the compliance of different structures, for decision-making, and for haptic mapping.

II. DESIGN

We propose a large-scale sensor shaped as an arc of a circular ring that partially covers and protects the drone (Fig. 1A). Starting from the design presented in [18], we identify four crucial modifications to tailor the sensor for drones. First, in contrast to previous works that have targeted robotic fingertips, we increase the size of the sensing area to 32 cm by 4 cm (Fig. 1B) for simultaneous measurements on multiple points. This surface is made of soft silicone hosting sparse markers. Second, the choice of a curved surface is motivated by previous works that have demonstrated how the usage of streamlined, sensorized cages - hemispherical [19] or discoid [20] - can be beneficial for drones to safely interact with obstacles. Third, to keep the sensor lightweight, its inner part is hollow, leading to an overall weight reduction by 75% (Fig. 1B). Forth, due to its large and curved profile, we place the light source outside the sensing area and distant from it to illuminate the whole surface homogeneously, in contrast to illumination spread at the contours of the silicone [21] that would not properly allow the light to propagate all over the soft material. Thus, we propose a novel solution based on the combination of UV LEDs and a color filter applied on the optical unit to suppress reflections induced by the distant light source. Finally, the outer faces of the sensor are covered to shield the sensor from external light (Fig. 1C).

III. MULTI-CONTACT SENSING METHOD

We introduce a method (implemented in Python and ROS) to fully retrieve rich tactile information on multiple contact points over the sensing area. An internal camera tracks the motion of the markers embedded in the sensing area, which deforms when in contact with the environment. By segmenting the optical flow obtained from the images, we consider several portions of the sensing area independently, and by exploiting the natural Helmholtz Hodge Decomposition (nHHD) [22] we calculate normal and shear displacements on each subflow (Fig. 1D). Segmentation steps are performed with thresholds that can be tuned to achieve different performance requirements. Lower thresholds can guarantee a smaller minimum detectable force. Having higher thresholds, instead, can be helpful to reject wrong measurements, ensuring robustness to false contacts, which is desired during flight due to vibrations onboard. To compute 3D location (mm) and 3D force (N) at multiple contact points, the sensor is characterized with a small yet representative dataset, collected by applying ground truth forces all over the sensing area, in different contact points and from multiple orientations. This step allows to find the polynomials that map quantities computed from the optical flow (raw displacements, contact location in pixels, potential field) to real-world values (mentioned above).

IV. RESULTS

The performances of the sensor are assessed i) on a testing dataset by computing prediction errors for both contact location and forces and ii) by applying continuous, time-varying forces on the sensing area to validate the correct estimation online and in real-time. The accuracy is 1.5 mm in contact location and 0.17 N in contact forces. Multiple contacts can be detected even when spaced only 2 cm apart.

E. Aucone, M. Gregor and S. Mintchev are with the Environmental Robotics Lab, Dept. of Environmental Systems Science, ETH Zürich, Zürich, Switzerland, and with the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland. C. Sferrazza is with the Robot Learning Lab, UC Berkeley, Berkeley, USA. R. D'Andrea is with the Institute for Dynamic Systems and Control, Dept. of Mechanical and Process Engineering, ETH Zürich, Zürich, Switzerland.

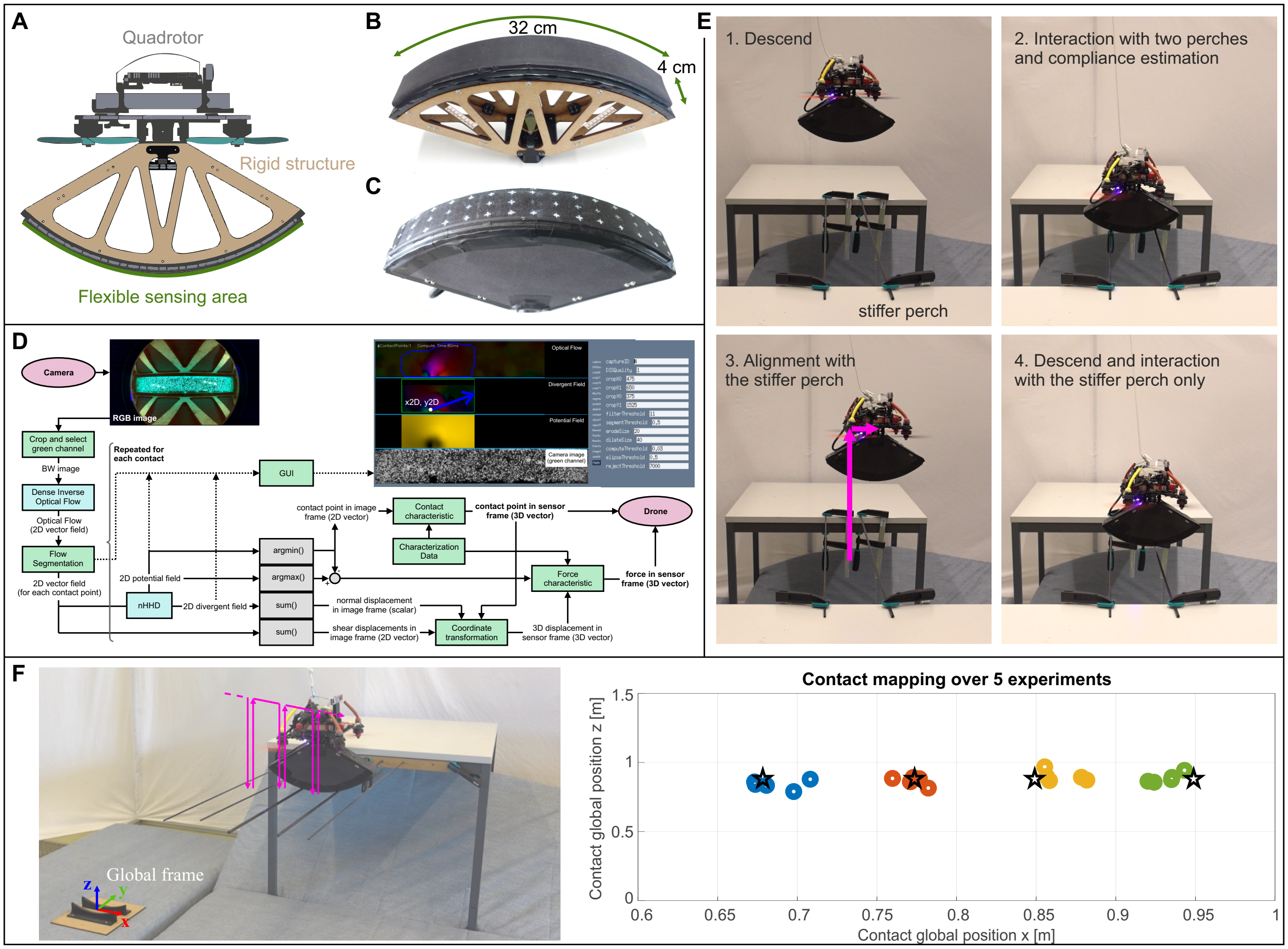

Fig. 1. Optical tactile sensor tailored for drones for multi-contact rich feedback. (A) Prototype of optical tactile sensor shaped as an arc of a circular ring, integrated beneath a quadrotor. (B) Developed sensor (internal view exposed) with a sensing area of 32 cm x 4 cm. (C) Fully assembled sensor with paper shield on the sides. (D) Software pipeline and Graphical User Interface with a window for tuning the sensor performances. (E) Compliance estimation and landing after re-alignment. (F) Location of multiple perches mapped in the global frame, estimated onboard upon physical interaction over 5 experiments.

A. *Demos*

We perform two demos to demonstrate the versatility of the sensor and its use in multi-contact scenarios, by showing how the drone can exploit the sensor readings. The first demo relates to the estimation of the compliance of two perches, re-alignment above and landing onto the stiffer one (Fig. 1E). For instance, information on the compliance can be useful to identify a more stable location where to rest, as drones can get a better support on stiffer perches, both in terms of stability and energy consumption [19]. We prove that upon contact the tactile feedback allows the drone to distinguish which perch is stiffer and where it is located; thus, knowing the compliance of the perches allows to decide in which direction to fly, whereas the information on the location of the stiffer perch defines how much it has to move to be aligned above it and then land. The second demo involves the detection and mapping of sparse obstacles by direct physical interaction (Fig. 1F). This can be useful when navigating in very dense regions, as drones are able to distinguish empty or traversable spaces from cluttered ones. We place multiple rods of different diameter in the scene, and showcase the simultaneous estimation of the obstacles' location in a global frame, in order to map the environment.

V. CONCLUSIONS

The implementation of our distributed tactile sensor represents a significant step towards attaining the full potential of drones as versatile robots capable of interacting with and navigating within complex environments. The current design suggests the potential adaptation of its shape, to allow for interaction detection from all directions, and the application of a low-friction coating, to facilitate dynamic tasks like sliding along surfaces. We further envision the exploration of the sensor output for novel multi-contact, multi-purpose control strategies.

REFERENCES

[1] H. Yousef, M. Boukallel, and K. Althoefer, "Tactile sensing for dexterous in-hand manipulation in robotics—a review," *Sensors and Actuators*

A: Physical, vol. 167, no. 2, pp. 171–187, 2011, solid-State Sensors, Actuators and Microsystems Workshop.

[2] R. S. Dahiya, P. Mittendorfer, M. Valle, G. Cheng, and V. J. Lumelsky, "Directions toward effective utilization of tactile skin: A review," *IEEE Sensors Journal*, vol. 13, no. 11, pp. 4121–4138, 2013.

[3] C. Bartolozzi, L. Natale, F. Nori, and G. Metta, "Robots with a sense of touch," *Nature Materials*, vol. 15, pp. 921–925, 2016.

[4] C. Fox, M. Evans, M. Pearson, and T. Prescott, "Tactile slam with a biomimetic whiskered robot," in *2012 IEEE International Conference on Robotics and Automation*, 2012, pp. 4925–4930.

[5] H. Kolvenbach, C. Bärtschi, L. Wellhausen, R. Grandia, and M. Hutter, "Haptic inspection of planetary soils with legged robots," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 1626–1632, 2019.

[6] A. Vangen, T. Barnwal, J. A. Olsen, and K. Alexis, "Terrain recognition and contact force estimation through a sensorized paw for legged robots," 2023.

[7] T. Bartelds, A. Capra, S. Hamaza, S. Stramigioli, and M. Fumagalli, "Compliant aerial manipulators: Toward a new generation of aerial robotic workers," *IEEE Robotics and Automation Letters*, vol. 1, no. 1, pp. 477–483, Jan. 2016.

[8] M. A. Trujillo, J. R. Martínez-de Dios, C. Martín, A. Viguria, and A. Ollero, "Novel aerial manipulator for accurate and robust industrial ndt contact inspection: A new tool for the oil and gas inspection industry," *Sensors*, vol. 19, no. 6, 2019.

[9] G. Nava, Q. Sablé, M. Tognon, D. Pucci, and A. Franchi, "Direct force feedback control and online multi-task optimization for aerial manipulators," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 331–338, Apr. 2020.

[10] K. Bodie, M. Brunner, M. Pantic, S. Walser, P. Pfändler, U. Angst, R. Siegwart, and J. Nieto, "Active interaction force control for contact-based inspection with a fully actuated aerial vehicle," *IEEE Transactions on Robotics*, vol. 37, no. 3, pp. 709–722, 2021.

[11] F. Benzi, M. Brunner, M. Tognon, C. Secchi, and R. Siegwart, "Adaptive tank-based control for aerial physical interaction with uncertain dynamic environments using energy-task estimation," *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 9129–9136, 2022.

[12] E. Donlon, S. Dong, M. Liu, J. Li, E. Adelson, and A. Rodriguez, "Gelslim: A high-resolution, compact, robust, and calibrated tactile-sensing finger," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Madrid, Spain: IEEE, oct 2018, pp. 1927–1934.

[13] B. Ward-Cherrier, N. Pestell, L. Cramphorn, B. Winstone, M. E. Giannaccini, J. Rossiter, , and N. F. Lepora, "The tactip family: Soft optical tactile sensors with 3d-printed biomimetic morphologies," *Soft Robotics*, pp. 3216–227, 2018.

[14] S. Luo, W. Yuan, E. Adelson, A. G. Cohn, and R. Fuentes, "Vitac: Feature sharing between vision and tactile sensing for cloth texture recognition," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, 2018, pp. 2722–2727.

[15] M. Lambeta, P.-W. Chou, S. Tian, B. Yang, B. Maloon, V. R. Most, D. Stroud, R. Santos, A. Byagowi, G. Kammerer, D. Jayaraman, and R. Calandra, "Digit: A novel design for a low-cost compact high-resolution tactile sensor with application to in-hand manipulation," *IEEE Robotics and Automation Letters*, vol. 5, pp. 3838–3845, 2020.

[16] L. Van Duong and V. A. Ho, "Large-scale vision-based tactile sensing for robot links: Design, modeling, and evaluation," *IEEE Transactions on Robotics*, vol. 37, no. 2, pp. 390–403, 2021.

[17] Q. K. Luu, N. H. Nguyen, and V. A. Ho, "Simulation, learning, and application of vision-based tactile sensing at large scale," *IEEE Transactions on Robotics*, vol. PP, pp. 1–17, 2023.

[18] C. Sferrazza and R. D'Andrea, "Design, motivation and evaluation of a full-resolution optical tactile sensor," *Sensors*, vol. 19, no. 4, p. 928, Feb. 2019.

[19] E. Aucone, S. Kirchgeorg, A. Valentini, L. Pellissier, K. Deiner, and S. Mintchev, "Drone-assisted collection of environmental dna from tree branches for biodiversity monitoring," *Science Robotics*, vol. 8, no. 74, p. eadd5762, 2023.

[20] E. Aucone, C. Geckeler, D. Morra, L. Pallottino, and S. Mintchev, "Synergistic morphology and feedback control for traversal of unknown compliant obstacles with aerial robots," *Accepted on Nature Communications.*

[21] A. Breuss, C. Sferrazza, J. Pleisch, R. D'Andrea, and R. Riener, "Unobtrusive sleep position classification using a novel optical tactile sensor," in *2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, 2023, pp. 1–5.

[22] H. Bhatia, V. Pascucci, and P.-T. Bremer, "The natural helmholtz-hodge decomposition for open-boundary flow analysis," *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, pp. 1566–1578, 2014.