Soft Robotic Link with Controllable Transparency for Vision-based Tactile and Proximity Sensing

Quan Khanh Luu[1], Dinh Quang Nguyen[2], Nhan Huu Nguyen[3], Nam Phuong Dam[3], and Van Anh Ho[3]
[1]Purdue University, West Lafayette, Indiana 47906, USA
[2]VNU University of Engineering and Technology, Cau Giay District, Ha Noi, Vietnam
[3]Japan Advanced Institute of Science and Technology, Nomi, Ishikawa, Japan
Email: luu15@purdue.edu

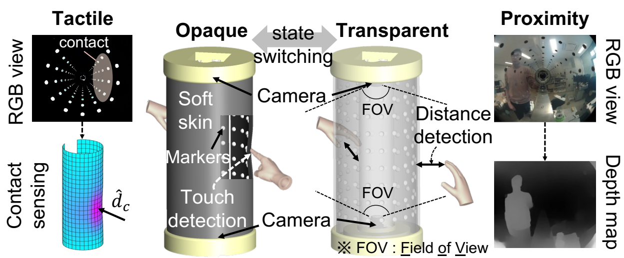


Fig. 1. ***ProTac***. A vision-based proximity-tactile sensing technology with *soft* skin capable of controllable transparency.

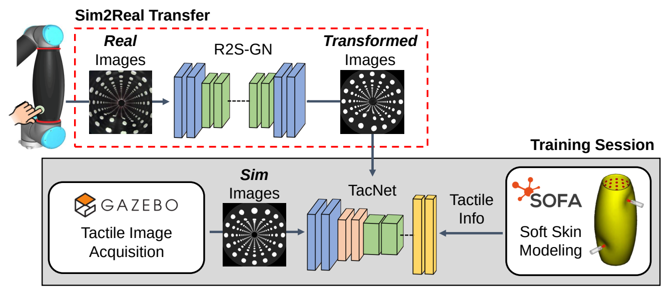


Fig. 2. **Sim2real learning framework for *tactile* mode of the *ProTac* link.** (a) A simulation pipeline, comprised of physics engines SOFA and Gazebo; was constructed to collect a labeled simulation dataset to train the TacNet model, including the information of tactile skin deformation (output) and virtual images (input); and a scheme of sim2real transfer learning was done through a generative network (R2S-GN) of real images into simulation ones.

I. Introduction

Compared with traditional rigid robots, *soft* skin-based robots equipped with multi-modal sensing capabilities offer significant benefits for enhanced human-robot interaction scenarios, such as ensuring safety while providing affectionate and comfortable haptic sensations to humans [1], [2]. Robotic touch offers rich information about physical human-machine interaction. Furthermore, proximity perception could enhance the robot's functionalities by bridging the perception gaps between vision and tactile modalities [3]. Proximity sensing, utilizing various transduction principles (e.g., resistance, capacitance, Time-of-Flight), is often integrated and built with rigid electrical components [4]–[8]. Thus, the simultaneous integration of multi-modal sensing, such as tactile and proximity modalities, into soft artificial skins in an efficient and scalable manner remains challenging due to inherent compatibility issues between soft materials and conventional electronic devices. Recently, vision-based tactile sensors have emerged as an efficient approach to enable an artificial sense of touch by tracking the deformation of soft membranes through visual cues of markers and reflective materials [9]–[15]. With this in mind, this study develops a novel soft sensing technology with intrinsic *tactile* and *proximity* sensing, relying on soft functional skin and vision techniques [16]. We demonstrate this sensing technology for a soft robotic link featuring the tactile-proximity sensing capability. In this study, perceptions for the tactile and proximity modes are enabled through a *sim2real* learning-based technique and a monocular depth estimation model, respectively.

II. Methodology

A. ProTac basic working principle

Figure 1 illustrates the design concept of the soft robotic link that can operate in either tactile or proximity sensing modes (named as *ProTac*). This capability is enabled through internal cameras and a soft functional skin that can actively switch its optical properties between *opaque* and *transparent* state. To achieve this, the skin is made of a layered structure of a soft transparent silicon layer, a polymer-dispersed liquid crystal (PDLC) film, and reflective markers. Thus, the basic working principle of the *ProTac* is:

- *Tactile* mode: As the soft PDLC skin is the the opaque state, the tactile/contact sensing can achieved by processing tactile images capturing markers' movements under contacts, without external light interference.
- *Proximity* mode: When the PDLC skin switches to the transparent state, the internal cameras can see through the skin so that the proximal information of obstacles near the skin can be inferred from see-through camera views.

In the following, we briefly outline approaches to extract the *ProTac* sensing information for each sensing modality.

B. Tactile Perception

Tactile information, including contact depth and location, is obtained using a deep neural network (DNN) called TacNet,

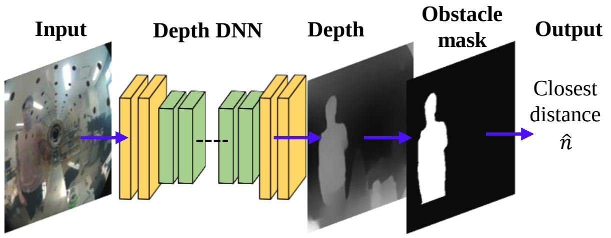


Fig. 3. **Processing pipeline for *proximity* mode of the *ProTac* link**. A monocular depth estimation model is employed to extract proximal information of obstacles near the *ProTac* link, utilizing *see-through* images captured by *ProTac*'s internal camera.

which processes the marker-featured tactile images captured by the *ProTac*'s internal cameras. To facilitate efficient learning of tactile information on such a large-scale skin, we introduced a *sim2real* learning framework to train the TacNet model based on synthetic/simulation datasets obtained from simulation environments [17]. This framework utilizes the *SOFA* physics engine to model complex physical interactions of the soft skin based on finite element method (FEM) to obtain skin deformation states, which serve as labels for the TacNet model (see fig. 2). Additionally, *Gazebo* is used to generate realistic virtual tactile images for the model inputs. Furthermore, a generative network is employed to minimize *sim2real* inaccuracy, preserving the simulation-based tactile sensing performance.

C. Proximity Perception

This section briefly outlines an approach to estimate the proximal distance from *ProTac* skin to the closest obstacle, by processing the *ProTac*'s camera view when the PDLC skin is in the *transparent* state. The processing pipeline is illustrated in Figure 3. Specifically, we leverage a monocular depth estimation model to infer the depth maps of external environments from which the distance to nearby obstacles can be calculated [16]. This method allows for the separate observation of obstacles from different directions using both of the opposing cameras, thereby broadening sensing coverage and improving its suitability for other sensor designs.

III. Result

Tactile mode. The accuracy of contact depth estimated by the TacNet is reported in Figure 4. With respect to the true contact depth of 5 mm, the result shows that the absolute estimation errors averaged over the entire skin were approximately 0.7 mm and 0.6 mm for pure and normalized input tactile images, respectively. Furthermore, Figure 4 demonstrates the visualization of *ProTac*'s contact sensing across its large sensing skin.

Proximity mode. Figure 5b showcases the ability of *ProTac* link to recognize a handful of nearby objects (*e.g.*, wallet, tape, human). These objects were detected from the see-through camera views while the *ProTac* skin was in the transparent state (refer to Fig.5a). Additionally, Figure 5c presents the accuracy of *ProTac* distance measurements within a range of 20 mm to 100 mm along the surface normal of the *ProTac* skin.

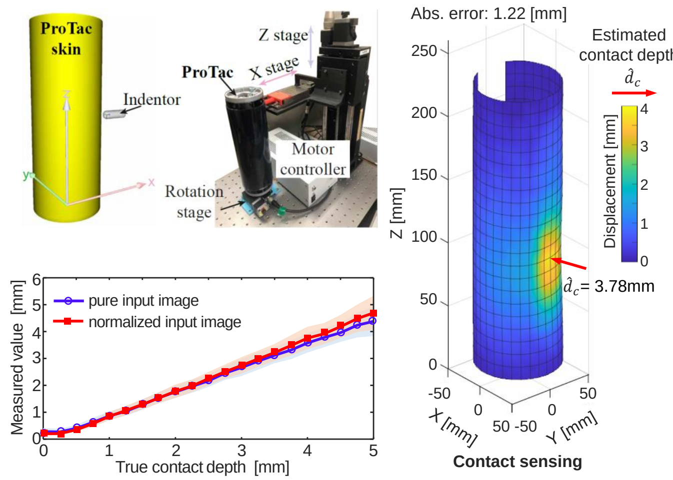
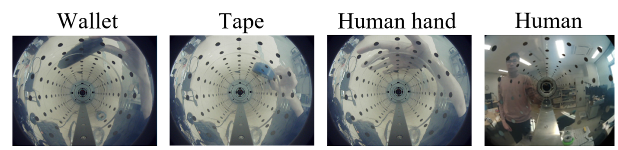
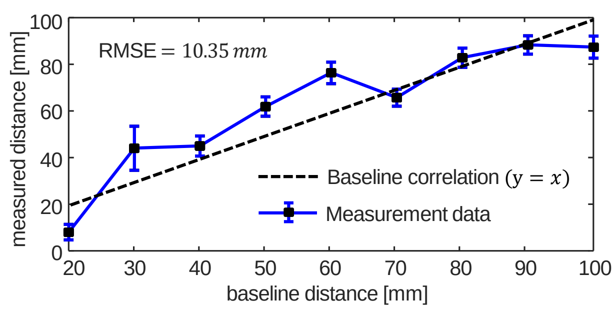


Fig. 4. **Tactile-mode evaluation**. Estimations of contact depth exhibit a high linear correlation with respect to the true values, which demonstrates the effectiveness of *ProTac*'s contact sensing across its large sensing skin.



(a) *See-through* camera view

(b) Nearby object mask



(c) Accuracy of *ProTac* distance estimation

Fig. 5. **Proximity-mode evaluation**. The results showcase the *ProTac*'s ability for identifying a handful of nearby objects (b), as well as demonstrate the accuracy of the *ProTac*-obstacle distance estimation (c).

References

[1] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing—from humans to humanoids," *IEEE Transactions on Robotics*, vol. 26, no. 1, pp. 1–20, 2010.

[2] T.-H.-L. Le, P. Maiolino, F. Mastrogiovanni, and G. Cannata, "Skinning a robot: Design methodologies for large-scale robot skin," *IEEE Robotics Automation Magazine*, vol. 23, no. 4, pp. 150–159, 2016.

[3] S. E. Navarro, S. Mühlbacher-Karrer, H. Alagi, H. Zangl, K. Koyama, B. Hein, C. Duriez, and J. R. Smith, "Proximity perception in human-centered robotics: A survey on sensing systems and applications," *IEEE Transactions on Robotics*, pp. 1–22, 2021.

[4] P. Mittendorfer and G. Cheng, "Humanoid multimodal tactile-sensing

modules," *IEEE Transactions on Robotics*, vol. 27, no. 3, pp. 401–410, 2011.

[5] V. A. Ho, S. Hirai, and K. Naraki, "Fabric interface with proximity and tactile sensation for human-robot interaction," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2016, pp. 238–245.

[6] J. C. Yang, J. Mun, S. Y. Kwon, S. Park, Z. Bao, and S. Park, "Electronic skin: Recent progress and future prospects for skin-attachable devices for health monitoring, robotics, and prosthetics," *Advanced Materials*, vol. 31, no. 48, p. 1904765, 2019.

[7] G. Pang, G. Yang, and Z. Pang, "Review of robot skin: A potential enabler for safe collaboration, immersive teleoperation, and affective interaction of future collaborative robots," *IEEE Transactions on Medical Robotics and Bionics*, vol. 3, no. 3, pp. 681–700, 2021.

[8] H. Park, K. Park, S. Mo, and J. Kim, "Deep neural network based electrical impedance tomographic sensing methodology for large-area robotic tactile sensing," *IEEE Transactions on Robotics*, vol. 37, no. 5, pp. 1570–1583, 2021.

[9] K. Sato, K. Kamiyama, N. Kawakami, and S. Tachi, "Finger-shaped gelforce: Sensor for measuring surface traction fields for robotic hand," *IEEE Transactions on Haptics*, vol. 3, no. 1, pp. 37–47, 2010.

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

[11] 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*, vol. 5, no. 2, pp. 216–227, 2018.

[12] W. Li, A. Alomainy, I. Vitanov, Y. Noh, P. Qi, and K. Althoefer, "F-touch sensor: Concurrent geometry perception and multi-axis force measurement," *IEEE Sensors Journal*, vol. 21, no. 4, pp. 4300–4309, 2021.

[13] W. K. Do and M. Kennedy, "Densetact: Optical tactile sensor for dense shape reconstruction," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 6188–6194.

[14] Z. Lin, J. Zhuang, Y. Li, X. Wu, S. Luo, D. F. Gomes, F. Huang, and Z. Yang, "Gelfinger: A novel visual-tactile sensor with multi-angle tactile image stitching," *IEEE Robotics and Automation Letters*, vol. 8, no. 9, pp. 5982–5989, 2023.

[15] J. Zhao and E. H. Adelson, "Gelsight svelte: A human finger-shaped single-camera tactile robot finger with large sensing coverage and proprioceptive sensing," in *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2023, pp. 8979–8984.

[16] Q. K. Luu, D. Q. Nguyen, N. H. Nguyen, and V. A. Ho, "Soft robotic link with controllable transparency for vision-based tactile and proximity sensing," in *2023 IEEE International Conference on Soft Robotics (RoboSoft)*, 2023, pp. 1–6.

[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. 39, no. 3, pp. 2003–2019, 2023.