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

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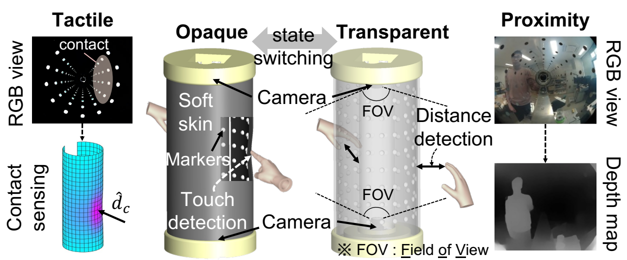


Fig. 1. ***ProTac***. A vision-based proximity-tactile sensing technology with *soft* skin capable of controllable transparency.

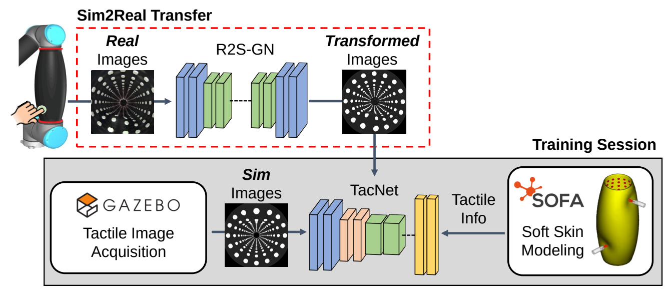


Fig. 2. **Sim2real learning framework for *tactile* mode of the *ProTac* link**. (a) A simulation pipeline, comprised of physics engines SOFA and Gazebo; was constructed to collect a labeled simulation dataset to train the TacNet model, including the information of tactile skin deformation (output) and 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]. 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, which processes the marker-featured tactile images captured

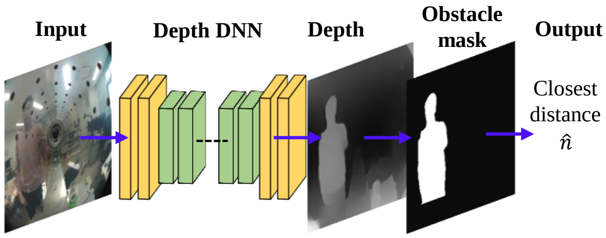


Fig. 3. **Processing pipeline for *proximity* mode of the *ProTac* link**. A monocular depth estimation model is employed to extract proximal information of obstacles near the *ProTac* link, utilizing *see-through* images captured by *ProTac*'s internal camera.

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.

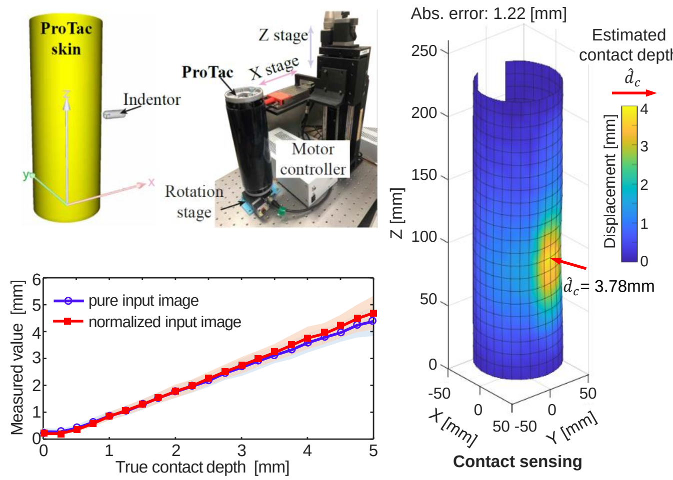
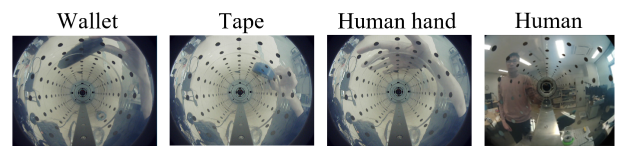
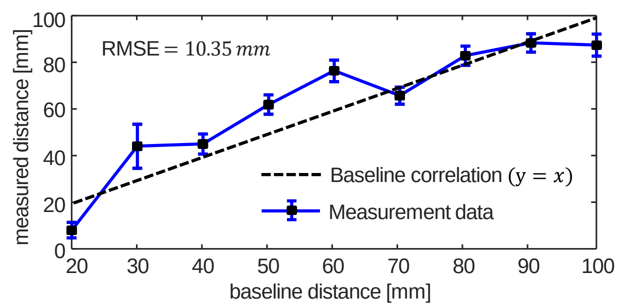


Fig. 4. **Tactile-mode evaluation**. Estimations of contact depth exhibit a high linear correlation with respect to the true values, which demonstrates the effectiveness of *ProTac*'s contact sensing across its large sensing skin.



(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).

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