 Guest Editorial
Special Issue on Robotic Sense of Touch

I. INTRODUCTION

ROBOTICS has continuously witnessed paradigm shifts ever since robots appeared as “industrial tools.” Over the years, the application domain of robotics has increased manifold, and the wide variety of new generation of robots nowadays include humanoids, rehabilitation and assistive robots, social robots, bio-robots, medical robots, and so on. As humanoids, they simulate the human structure and behavior; as exoskeletons or artificial limbs, they assist humans; as social robots, they enable human–robot interaction; as bio-robots, they help gain insight into the workings of biological systems; and as medical robots, they help carry out surgical interventions more accurately and less invasively. As compared with the human-controlled industrial robots that typically operate in “no humans” working zones, these new-generation robots are characterized by autonomous learning and close interaction with the environment (including humans). To meet these requirements, the robots are nowadays equipped with increasingly sensing components, and accordingly, they are also (to some extent) able to deal with high complexity and dynamics that are from the real world.

Among various sensing modalities that are needed to perceive and react to the dynamics of the real world, the “sense of touch” is particularly important as it allows the assessment of object properties such as size, shape, and texture; manipulation of objects, e.g., rolling an object between fingers without dropping it; development of awareness of the body; and differentiation of “me” from “not me.” Touch sense modality also helps us to understand the rich interaction behaviors of real-world objects that depend on their weight and stiffness, on how their surface feels when touched, how they deform on contact, and how they move when pushed. As conventional methods, such as force-based control that use 3-D intrinsic force sensors and vision sensors, have proved to be insufficient, the need for touch/tactile sensing in robots has often been emphasized.

How can the “sense of touch” be an effective part of future robots, which are expected to work closely and interact safely with humans and real-world objects? Is there any need to revisit the available touch-sensing technology? How can touch information be utilized effectively by robots? To answer these basic questions, it is important to understand at least following four main areas.

1) The technological solutions for touch sensing: The term “sense of touch” in robotics refers to two categories: intrinsic and extrinsic touch sensing. While the former is analogous to the kinesthetic sensing in humans, the latter is closely related to human cutaneous or tactile sensing. A large number of touch sensors (both intrinsic and extrinsic), which explore various modes of transduction, materials, and innovative structures, have been reported over the last two decades and more [1]–[3]. Restricted to fingertips and hands, until the last decade or so, touch sensing schemes, such as electronic skin, that is flexible, conformable, and stretchable and, thus, suitable for the whole body of robots, are nowadays being reported [4]. While intrinsic touch sensing has been in use for a long time, recent research efforts on the whole body skin strive to provide a complete (intrinsic and extrinsic) touch sense modality solution for robots. More is to be done to obtain unique tactile sensing solution similar to complementary metal–oxide semiconductor (CMOS) optical arrays [1], [2]. The role of CMOS optical arrays in advancing the usage of visual data is widely known, and something similar and possibly beyond (at system level) is needed to make tactile sensing an effective part of any robotic system.

2) System integration: Despite the experimentation with a wide spectrum of transduction methods, materials, and innovative designs, touch sensing has not made much headway in robotic applications. Among a mix of technological difficulties, such as wiring complexity, distribution of tactile sensors in 3-D space, handling of large tactile data, etc., the lack of a system approach appears to be the most notable reason for the “sense of touch” not being an effective part of robots. The overall system performance is dictated not only by its individual elements but by the way they are integrated together as well. Therefore, touch sensor design should consider system constraints such as those posed by the presence of other sensors (e.g., vision), by their interplay with the robot controllers, and other important system aspects such as embedding electronics, distributed computing/processing, networking, wiring complexity, power consumption, robustness, manufacturability, and maintainability [1]. For easy integration with the robot’s body, the sensing structure should possess properties such as flexibility, conformability, stretchability, etc. Such design issues are important for the effective usage of the touch sense modality in any robotic system.

3) Utilizing touch information to improve cognitive skills of robots: In addition to the sensing hardware, the effective utilization of touch sensing depends on understanding the tactile sensing mechanisms and constructing the world model accordingly. This includes knowledge about encoding and transmission of the tactile information. Suitable algorithms are, thus, needed to select and decipher the tactile information that is gathered by the large number of sensors, which are distributed over the robot’s body,
i.e., in a 3-D space. Interaction with real-world objects and the construction of the world model may also require integrating signals from multiple sensory modalities for a robust percept. In humanoids, for example, these signals could come from touch sensors (both extrinsic and intrinsic), vision sensors, audio sensors, or a combination of any of them. In fact, this is true for most daily-life activities. The correct fusion of signals from sensors that belong to a different sensory modality calls for compatibility among sensing hardware.

4) **Bioinspiration for improved robotic sense of touch:** Designing a meaningful robotic tactile sensing system should be guided by a broad, but integrated, knowledge of how tactile information is encoded and transmitted at various stages of interaction via touch sensing. In this context, various studies on humans, monkeys, rats, etc. can be helpful as many of these investigations have addressed problems that are also challenging to roboticists [5]. These include the role of skin mechanics, feature extraction, movements for optimum exploration, active and passive perception, selective attention, sensory guided motor control, etc. [6]–[9]. Such studies also become important due to the absence of any rigorous robotic tactile sensing theory that can help us to specify important system parameters such as sensor density, resolution, location, transmission, and bandwidth. Some of these parameters are also likely to be task or application dependent.

The ways in which biological systems acquire and process the sensory data to the control behavior may not always lead to the best engineering solutions for robots; nevertheless, they provide a comprehensive multilevel conceptual framework that organizes the overall task to design the sensors for robotic systems. The bioinspired approach may bring up new ideas that can help us to increase the level of tactile sensitivity and acuity of robots to the human range. Besides improving the sense of touch in robotics, the tactile sensing systems can be helpful in understanding the functionality of biological systems as well.

The earlier discussion is helpful in understanding various issues related to the (lack of) effective utilization of the sense of touch in robotics. Many works fitting into one or more of the aforementioned four areas have been reported in the literature, as well as in this Special Issue. The challenge is to obtain an effective robotic touch sensing system while consolidating all the knowledge that we have gained in this area. The same has been the aim of this Special Issue, which is also the first Special Issue on the sense of touch in robotics.

From a historical perspective, “sense of touch” has been a component of robotics for roughly as long as the artificial vision and auditory sense modalities. Touch sensing began to develop in the 1970s, albeit at a slower pace, when compared with the development of other sensory modalities. The extent to which the “sense of touch” was utilized largely remained restricted to joint force/torques or simply “intrinsic touch sensing,” which can probably be attributed to the focus largely on the industrial robotics during the initial era of automation. Both from a safety and an operational point of view, intrinsic touch and vision are considered to be more convenient and suitable for an industrial setup. For this reason, until the end of the last decade, research on sensors and sensor-based robotics was biased toward using vision and intrinsic touch sensing. This is evident from large number of articles reported in journals such as IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, the IEEE TRANSACTIONS ON ROBOTICS, and the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and conferences such as the International Conference on Robotics and Automation and the International Conference on Intelligent Robotics and Systems.

As far as tactile sensing (or extrinsic sensing) in robotics is concerned, early surveys show a wide diversity in the types of tactile sensing devices that were developed in the 1980s [10], [11]. Early works on tactile sensing focused on the creation of sensor devices that use new transduction techniques, and a large number of experimental devices and prototypes were built and reported in the literature. Particular attention was given to the development of tactile sensing arrays for object recognition [12]. The creation of multifingered robotic hands during the 1980s increased the interest in tactile sensing for robotic manipulation and, thus, started appearing in works utilizing tactile sensing in real-time control of manipulation [13]–[15]. The new applications demand features such as mechanical flexibility and conformability, and accordingly, new designs and materials for tactile sensing started receiving attention. While the development of tactile sensors for robotic fingers and hands continued, application areas such as motion planning in an unstructured environment brought whole body sensing to the fore. As a result, many sensitive skin design projects were undertaken in the late 1980s and 1990s [16], [17]. Over this period of time, robotics itself has undergone the paradigm shift. In addition to manipulation and exploration tasks, the new-generation robots are also expected to interact safely. As a result, there is an increased interest to develop the large area or whole body tactile sensing structures that allow a robot to carry out a task while maintaining physical contact [18], [19]. The discussion on “sense of touch” in robots is not only restricted to the sensing hardware and related issues. The introduction of whole body skin concept in robotics has also brought up challenging issues related to handling and utilizing the tactile data. Therefore, issues such as the representation of tactile sensors located in 3-D space, the development of suitable models to enhance perception capability of robots, etc. are also getting attention these days [20]–[22].

Topics related to the “sense of touch” in robotics are increasingly being included in the technical programs of various conferences such as the Robotics and Automation Society funded conferences such as ICRA, IROS, the International Conference on Human–Robot Interactions (HRI), International Conference on Humanoid Robotics, the International Workshop on Robot and Human Interactive Communication, the International Conference on Rehabilitation Robotics, the International Conference on Biomedical Robotics and Biomechatronics, etc. Topics that are related to touch sensing technology are also increasingly being included in the technical programs of various conferences such as the IEEE International Conference on Sensors,
as well as and the IEEE International Conference on Solid-State Sensors, Actuators, and Microsystems and IEEE Electron Device Meetings. Touch sensing technology and other related emerging technologies for electronic skin are increasingly occupying spaces in well-known weekly magazines, letters, and journals such as Science, Nature, the Proceedings of National Academy of Sciences, Applied Physics Letters, Advanced Materials and Nano Letters, etc. With many commercial products such as touch panels, cellular phones etc., the “sense of touch” is making waves in the commercial arena too.

II. GUIDE TO THIS SPECIAL ISSUE

This special issue contains 19 regular papers and two short papers, which have been organized into three groups. The first group of papers presents insights into the development of touch sensing hardware and related system level issues. The focus of the papers that are presented in the second and the third groups is on the development and analysis of computational tools to obtain contact information from the data acquired by the sensing hardware during a number of tasks performed by robots.

The first group of papers presents the enabling technologies for robotic tactile sensing. The structures that are suitable for covering large parts of robotic devices are presented in the first two papers. The paper by Schmitz et al. presents a capacitive tactile sensor-based compliant skin system for humanoids. The reported skin system is implemented on flexible printed circuit boards following a modular approach and employing off-the-shelf components. The compact skin system has also been integrated into three different humanoid robots.

Following the modular approach, the paper by Middendorf and Cheng presents multifunctional hexagonal-shaped modules for whole body touch sensation in humanoids. Multiple discrete off-the-shelf sensors are used in each module to detect temperature, acceleration, and light touch. Interacting with objects via tactile sense modality may involve measuring more than one contact parameter, and in this context, having multiple sensing components is helpful. The paper by Ho et al. presents a soft fingertip, which is the size of human thumb, having a microscaled force/torque sensor embedded in soft and compliant polyurethane rubber. With the ability to detect one component of force and two components of moment, the fingertip can be useful for dexterous manipulation. The paper by Tawil et al. presents electrical impedance tomography (IET)-based skin that is possibly stretchable as well. A method for better image reconstruction, with multiple internal electrodes in the EIT-based skin, is also presented. In humans, the receptors are present at various depths in the skin that is viscoelastic and has variable elastic properties. The response of receptors is considered to be affected by these properties of the skin. The materials such as polyurethane rubber have been often employed in robotics to mimic the viscoelastic and compliance properties of the human skin. The paper by Berselli et al. presents fluid-filled visco-elastic contact interfaces. Some insights into engineering such structures have also been presented in this paper. The next two papers in this Special Issue are related to the tactile sensing technology for medical applications and human studies. An optical fiber-based probe that is presented by Liu et al. is able to measure the stiffness distribution of soft tissue. The probe can be helpful in detecting tumors during minimally invasive surgery. The paper by Wierlowski et al. presents a piezoelectric-property-based apparatus that is capable of measuring the tangential interaction force with a high degree of temporal and spatial resolution. The apparatus has been used to study textures perception in humans.

The second group of papers of this Special Issue are about utilizing tactile sensing modality and machine learning tools in various exploratory tasks. Combining the object recognition from tactile appearance with the purposeful haptic exploration of unknown objects, Pezzementi et al. investigate the connection between sensor-based perception and exploration in context with haptic object identification. Sinapov et al. employ machine learning tools for surface recognition and categorization from the data obtained by letting a robot scratch different surfaces. The robot’s fingernail in this case is equipped with a triaxial accelerometer. Self-organizing maps (SOMs) are employed by Johasson and Balkenius in their paper to extract features from sensory data. The objects are distinguished according to shape and size, and properties such as texture and hardness have been extracted from the explored materials. Machine learning algorithms such as Bayes trees are used in the paper by Jamali and Sammut to distinguish different materials that are based on their surface texture. The tactile data in this paper are collected with polyvinylidene fluoride (PVDF)-based biologically inspired fingers. Oddo et al. present a microelectromechanical systems (MEMS)-based microsensor with a biomimetic fingerprint encasing. The microsensor has been used to actively explore and discriminate the surfaces by encoding the roughness.

The paper by Giguere and Dudek presents a tactile probe for surface identification in the context of all-terrain low-velocity mobile robotics. The surface identification is based on analyzing the acceleration patterns that are obtained by dragging the tactile probe along the surface. An artificial neural network has been used for classification of the tactile data. Kroemer et al. present another machine learning approach to infer lower dimensional representation of tactile data and classify materials following a weak pairing of tactile and visual information. Combining vision and tactile information to improve the performance of dynamic tactile sensors is an interesting development. Humans often use sensory information from multiple sensory modalities to obtain a robust percept.

The third group of papers of this Special Issue are about utilizing tactile sensing modality and machine learning tools in various manipulation tasks. Chitta et al. present the tactile perception strategy and the switching velocity–force controller that are useful during manipulating or for safely grasping an object for measuring a generic set of tactile features such as deformation, the internal state of the object, etc. Petrovskaya and Khatib present the problem of global localization via touch.

A Bayesian approach, termed the “Scaling Series,” is presented as a solution for the full global 6-degree of freedom localization problem. By the use of multimodal sensory inputs, Platt et al. present an approach to localize the features embedded in flexible materials during robot manipulation. The proprioceptive and
load-based tactile information have been used in their work. It is shown that during localization, the proprioceptive and tactile data contain complementary information. Interaction with the flexible materials is quite challenging. Becedas et al. present work on flexible manipulators with a force feedback. A GPI controller is also included to acquire high-control accuracy. The proposed system has been shown to manipulate both rigid and flexible objects in an industrial environment by controlling the applied contact torque. Bekiroglu et al. present work on grasp stability by the use of haptic data and machine learning methods. The effect of different sensory streams to grasp stability have been studied. This includes object information such as shape, grasp information such as approach vectors, tactile measurements from fingertips, and the joint configuration from the hand. A probabilistic learning framework has been presented to assess grasp stability, and it is shown that the knowledge about grasp stability can be inferred from the information from tactile sensors.

The two short papers at the end of this Special Issue also belong to the second group of papers. The paper by Meier et al. presents a probabilistic spatial approach to build 3-D representations of unknown objects that are probed by a tactile probe. The paper by Decherchi presents a comparative analysis of three computational intelligence tools for the problem of contact object material classification.

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REFERENCES


