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Design of a flexible tactile sensor for classification of rigid and deformable objects

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ABSTRACT

For both humans and robots, tactile sensing is important for interaction with the environment: it is the core sensing used for exploration and manipulation of objects. In this paper, we present a novel tactile-array sensor based on flexible piezoresistive rubber. We describe the design of the sensor and data acquisition system. We evaluate the sensitivity and robustness of the sensor, and show that it is consistent over time with little relaxation. Furthermore, the sensor has the benefit of being flexible, having a high resolution, it is easy to mount, and simple to manufacture.

We demonstrate the use of the sensor in an active object-classification system. A robotic gripper with two sensors mounted on its fingers performs a palpation procedure on a set of objects. By squeezing an object, the robot actively explores the material properties, and the system acquires tactile information corresponding to the resulting pressure. Based on a k nearest neighbor classifier and using dynamic time warping to calculate the distance between different time series, the system is able to successfully classify objects. Our sensor demonstrates similar classification performance to the Weiss Robotics tactile sensor, while having additional benefits.

1. Introduction

Research in the area of robotic grasping has gradually shifted from structured manufacturing environments toward unstructured everyday environments. Visual feedback has proven to be an important source of sensory information necessary for grasp generation and control, e.g., [1–7]. Although vision provides important information, it is not always enough or trivial to obtain. In addition, the accuracy may be limited, due to imperfect calibration and occlusions. Errors in estimation of object shape are common even for known objects and these errors may cause failures in grasping. Clearly, vision does not provide important information on object properties such as deformability or material texture.

Tactile and finger-force sensors can be used as additional sensors to improve grasping performance during grasp execution [8–10], but are still rather uncommon in practice. Mechanical compliance, for instance, is an important characteristic of an object, and it is essential in grasping fragile items. Furthermore, humans use object properties such as hardness, thermal conductivity, friction and roughness in object manipulation, which could be addressed by robotic grippers as well by using haptic feedback.

In this paper, we propose the design of a novel tactile sensor based on piezoresistive materials and conductive thread electrodes. The sensor has 8 × 8 taxels in an active area of 20 mm × 20 mm and is flexible being based on a piezoresistive rubber material of 0.5 mm thickness. It has high sensitivity capabilities starting from a 10 kPa pressure threshold and it provides a smooth force–resistance characteristic with little relaxation. The sensor is robust to withstand thousands of actuations without any change in its response and is moreover cheap and simple to manufacture. We demonstrate its use in a haptic-based object-classification scenario. We propose a method for classifying rigid and deformable objects using the proposed sensor. These objects cannot be discriminated based on static tactile information. We therefore apply an active exploration procedure, where a robotic gripper, equipped with the sensors, performs palpations on the objects. By squeezing the objects, the robot acquires dynamic information, which is structured through the sensory–motor coordination. This information is used to describe and classify the objects. The complete system is implemented, evaluated, and finally compared to the widely used Weiss Robotics tactile sensor [11].

This paper is organized as follows: Section 2 presents the related work regarding tactile sensors, while Section 3 describes the steps used to manufacture the proposed sensor prototype and the electronics used for data acquisition. Section 4 describes the processing of the tactile images and the data modeling needed for object classification. The experiments are presented and discussed in Section 5. The conclusions and further improvements are outlined in Section 6.

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2. Related work

In this section, we first review the work on the sensor development, followed by work on tactile object classification.

In terms of tactile-array sensors for static stimuli, such as pressure, there are a range of technologies that have been used with various results [12]. There are a few technologies that can be used for manufacturing tactile-array sensors, and the most used are piezoresistive (rubbers or inks), piezocapacitive, piezoelectrical, and optical [13]. In [14], an industrial tactile-array sensor was proposed using a piezoresistive rubber. However, this sensor has a low spatial resolution and does not have any flexible capabilities. A flexible 16 × 16 sensor array with 1 mm spatial resolution was developed for minimally invasive surgery, but the sensor fails to give steady output for static stimuli, and has a high hysteresis and non-linearity [15].

A combination of static and dynamic sensors was developed in [16] to address both pressure profiles and slippage, but the design has only 4 × 7 cells, and a number of wires equal to the number of cells. Flexible sensors based on pressure conductive rubber with 3 × 16 cells were developed using a stitched electrode structure, but the construction method and the leak currents brought high variations in the measurements [17]. A flexible fingertip sensor using pressure conductive rubber was proposed in [18]. The sensor principle is based on measuring resistance of the conductive rubber from one side taking into account both small area contact resistance and the rubber resistance. The underlying layer consists of a flexible PCB, which comprises 36 pairs of gold-plated comb-shaped electrodes resulting in taxels approx. 2 mm × 2 mm.

A 32 × 32 tactile sensing array that is able to measure not only normal applied forces but also temperature has been presented in [19]. Pressure conductive rubber is employed as the tactile sensing material, and discrete temperature sensor chips are used as the temperature sensing cells. Small disks of pressure conductive rubber are bonded on predefined inter-digital copper electrode pairs which are patterned on a flexible copper–polyimide substrate, fabricated by micro-machining techniques. An approach that uses a thin film of conductive polymer instead of the conductive rubber was proposed in [20]. The material is a conductive water-based ink of a polymer that is deposited by spin-coating on a flexible plastic sheet and the electrodes were based on flex PCB or screen printing directly over the piezoresistive layer with a silver based ink.

The tactile-array sensor that we propose in this paper combines a number of benefits. The sensor, based on piezoresistive technology is flexible, which makes it easy to mount. It has furthermore high sensitivity capabilities and gives consistent measurements over time. The resolution of the sensor is high, without complex wiring. The sensor is moreover simple to produce.

Using tactile sensors for material and object recognition or classification, has become rather popular recently, as is, for instance, reflected in [21]. Different methods have been proposed to classify materials based on their texture. In [22], for instance, a learning method was proposed based on a soft anthropomorphic fingertip containing 24 randomly distributed receptors of two different kinds; strain gauges and polyvinylidene fluoride (PVDF) films. The fingertip was used to rub and push objects of different materials, like wood, paper, cork and vinyl. Based on the averages given by the strain gauges and the variance over time in the signal given by the PVDF sensors, they showed good discrimination capabilities among the considered materials.

A similar approach was employed by in [23] where the Fourier coefficients based on the dynamic measurements given by the PVDF elements and the averages from each strain gauge were used as the input for multiple classifiers. The exploration procedure involved dragging the finger across a textured surface. They showed recognition rates over 90% for eight different natural textures.

Other methods deal with object recognition and classification. In [24] the sensor presented in [22] was used and applied to a finger and the palm of a robot hand. The exploratory procedure here involved squeezing and tapping a range of seven small objects made of different materials such as cloth, paper or plastic. In their squeezing procedure, a constant pressure was applied and the average output of the strain gauges was used to classify the objects using a Kohonen self-organizing map. The method that we propose, on the other hand, uses a palpation procedure where we increase and decrease the pressure. In [25], tactile information was used to estimate whether cans and bottles are open or closed and whether they are filled. To do the classification, they designed a small number of dynamic features. In [26], multiple grasps were performed on a set of household objects in order to classify them. An unsupervised clustering method was used to learn a vocabulary from tactile observations and classification was done using a bag-of-words approach. The approach takes into consideration only tactile information at the points of contact with the considered objects. In contrast with the above method, our object classification procedure takes advantage of the complete time series, which allows more elaborate discrimination of objects.

In some studies, grasp generation is based on visual input and tactile sensing is used for closed-loop control once in contact with the object. For example, the use of tactile sensors has been proposed to maximize the contact surface for removing a book from a bookshelf [27]. The application of force, visual, and tactile feedback to open a sliding door has been proposed in [28]. Tactile information can be also used to reconstruct the shape of unknown explored objects as proposed in [29].

One of the issues often faced in household scenarios is deformable objects. Planning grasps for these types of object is not at all as well studied as rigid objects. Examples can be found in the literature, such as [30], where the deformation properties of objects are learned in order to apply suitable grasping forces for the associated objects.

Our work considers a tactile-array sensor based on piezoresistive technology. For classification, we look at the time series that the sensor provides during a full palpation procedure. Based on this dynamic information, different objects can be classified based on their tactile properties.

3. The tactile sensor

In order to construct a tactile-array sensor, we take inspiration from biology, especially in the characteristics of the human skin. Therefore, we are mainly interested in: (1) dynamic range and sensitivity, (2) size of taxels similar to the mechanoreceptor in the human hand, (3) large array size without too much wiring complexity, robustness – to withstand repeated impacts – and (4) flexibility — so that we could apply the sensor to any kind of robotic grippers very much similar to an artificial skin. Other characteristics that we are aiming for are (5) a good sensor output, (6) low complexity and simple processing circuitry, (7) ease of manufacture, and a (8) a low price. The novel tactile sensor that we propose largely achieves these goals.

3.1. Material properties

After an early investigation and testing of different technologies and methods for building tactile sensors, presented in [31], we have chosen the piezoresistive material as the most suited to build a flexible tactile-array sensor. The CSA material has shown good performance in some research works related to finger pads