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Review

Tactile sensing for dexterous in-hand manipulation in robotics—A review

Hanna Yousef[a,*], Mehdi Boukallel[a], Kaspar Althoefer[b]

[a] CEA, LIST, Sensory and Ambient Interfaces Laboratory, 18 route du Panorama, BP6, Fontenay-aux-Roses F-92265, France
[b] King's College London, Department of Informatics, Strand, London WC2R 2LS, United Kingdom

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ABSTRACT

As the field of robotics is expanding from the fixed environment of a production line to complex human environments, robots are required to perform increasingly human-like manipulation tasks, moving the state-of-the-art in robotics from grasping to advanced in-hand manipulation tasks such as regrasping, rotation and translation. To achieve advanced in-hand manipulation tasks, robotic hands are required to be equipped with distributed tactile sensing that can continuously provide information about the magnitude and direction of forces at all contact points between them and the objects they are interacting with. This paper reviews the state-of-the-art in force and tactile sensing technologies that can be suitable within the specific context of dexterous in-hand manipulation. In previous reviews of tactile sensing for robotic manipulation, the specific functional and technical requirements of dexterous in-hand manipulation, as compared to grasping, are in general not taken into account. This paper provides a review of models describing human hand activity and movements, and a set of functional and technical specifications for in-hand manipulation is defined. The paper proceeds to review the current state-of-the-art tactile sensor solutions that fulfil or can fulfil these criteria. An analytical comparison of the reviewed solutions is presented, and the advantages and disadvantages of different sensing technologies are compared.

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* Corresponding author.
E-mail address: hanna.yousef@cea.fr (H. Yousef).

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1. Introduction

"For robots, the final frontier is not space; it is your living room" [1]. The field of robotics today is continuously expanding from the fixed environment of a production line to include more complex environments such as homes, offices, and hospitals. The new application areas require versatile autonomous intelligent robots that can interact with humans and their wide range of tools in real-world environments. To perform increasingly human-like functions, robots are required to be able to perform increasingly human-like manipulation tasks, moving the state-of-the-art in robotics from grasping to advanced manipulation tasks such as in-hand regrasping, rotation and translation.

To intelligently perform in unstructured and changing surroundings, robots will be required to manipulate objects while simultaneously sensing and reasoning about their environment. To achieve this, robots need an interface that can provide information about the forces and positions at all points of contact between them and the objects they are interacting with. A key issue in the robotics community today is therefore the development of artificial skin interfaces with fully distributed tactile sensing.

Tactile sensing in robotics is defined as the continuous sensing of variable contact forces [2]. This information can be used to determine if the robot is in contact with an object, the contact configuration, the stability of the grasp, as well as for force feedback for the control of the robot [3]. Furthermore, tactile information is envisaged to be used to analyse object manipulation to better understand and optimise handling techniques so as to further increase the versatility, skills and performance of the robot [4].

A thorough review of the state of the art in tactile sensing for mechatronics in general is presented by Lee and Nicholls [5]. Different technologies and application areas are reviewed including sensing fingers, industrial grippers and multifingered hands for dexterous manipulation. A more recent review by Saraf and Maheshwari [6] includes an outlook on potential high-performance devices based on recent research in nanostructured materials. In addition to these general reviews, several articles reviewing sensors for specific applications areas are presented such as for 'smart skins' [7], minimally invasive surgery [8], robotics in medicine, prosthetics and the food industry [9], and for robotic dexterous manipulation in [3,10]. In the aforementioned articles, although sensor specifications are discussed for robotics, the functional and technical requirements of dexterous in-hand manipulation, as compared to grasping, are in large not taken into account.

This paper provides a review of the current state-of-the-art in tactile force and pressure sensing within the specific context of dexterous in-hand manipulation. Taking human in-hand manipulation as a basis for understanding the specific requirements for in-hand manipulation, a review of models describing human hand activity and movements is presented and a set of functional and technical specifications on a robotic tactile sensor system is defined. The literature reviewed deals with sensors that fulfil these criteria, as well as sensors that in our opinions can be adapted to fulfil them. An analytical comparison of the reviewed work is presented and the advantages and disadvantages of different sensing technologies are compared.

2. Human in-hand manipulation as a basis for robotic manipulation

As robots are required to perform increasingly human-like manipulation in unstructured environments, the tendency in the robotics community is to look to human movements, as well as the human skin and sense of touch, for inspiration. It is therefore of interest to understand the physiology of the human sense of touch and perception, as well as the ergonomics of human hand activity and movements during grasping and in-hand manipulation of objects. The former has been treated in the robotics community, e.g. as reviewed in [10]. An understanding of the latter in the context of robotics we find is however still lacking.

2.1. Human hand and finger movements

Human in-hand object manipulation consists of a series of actions, each fulfilling a sub-task of the manipulation task. Personal constraints aside, the chosen actions to perform a manipulation task depend on object related parameters such as size, weight, shape and texture, manipulation related parameters such as movement patterns, and performance demands such as speed and accuracy [11]. Hand postures and movements for grasping objects have been widely studied, and a large amount of work on modelling and replication can be found, e.g. [12–17]. In comparison, in-hand manipulation has not been studied to the same extent. This can be attributed to the high complexity and diversity of the tasks, as well as to the limitations of available sensing technologies with regard to sensitivity and spatial resolution.

In-hand manipulation has however been studied within the fields of medicine, developmental psychology, sensory integration therapy and physical therapy [18–22]. Two main systems for classification of hand movements for in-hand manipulation can be found [23,24]. Elliot and Connolly classify in-hand manipulation with regard to the movements of the fingers involved in the manipulation [23]. Here three main classes are identified: (1) simple synergies when all the participating digits move as one unit, bending or extending, e.g. when squeezing a small ball or pipette, (2) reciprocal synergies when the thumb moves independently while the remaining involved digits move as one, e.g. when screwing/unscrewing the lid of a bottle, and (3) sequential patterns when the participating fingers move independently of each other to form movement patterns, e.g. during turning and/or repositioning of a pen in the hand. In addition to the movement of the fingers, the authors introduce a class of movements, palmar combinations, where the manipulated object is immobilised by the palm of the hand while the participating digits manipulate another part of the object, e.g. when screwing/unscrewing the lid of a tube while holding with the same hand.

In Exner's classification system [24], the amount and type of displacement of the object in the hand is taken into account in addition to the movement of the hand. Here, three main categories are identified: (1) translation when an object is moved from the fingertips to the palm of the hand, or from the palm to the fingertips, e.g. picking up multiple small object and storing in the hand, (2) shift when the object is moved linearly along or across one or more fingertips, e.g. when repositioning a pencil for writing, and (3) rotation when an object is turned around in the pads of the fingers and thumb (simple) or when rolling an object or turned from end to end (complex), e.g. when flipping a pen around to reposition for writing.

Pont et al. [25] further develop Exner's classification system to include the complexity of the finger motion required to achieve the manipulation, as well as including a specific focus on the need for stabilisation. In this way, Pont et al. present a system that is consistent with both Exner as well as with Elliot and Connolly. In this system, Exner's "shift" is further divided into simple and complex shifts. Here, simple shifts combine Exner's shift with Elliot and Connolly's simple synergies, and complex shifts combine shift with sequential patterns. Furthermore, the authors discuss that the importance of translation from fingers to palm is mainly to achieve stability.

In the different movements described in the three systems above, it can be seen that the pads of all five fingers at the dis-