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Development of a bioinspired MEMS based capacitive tactile sensor for a robotic finger

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ABSTRACT

This paper presents the development of a MEMS based capacitive tactile sensor intended to be incorporated into a tactile array as the core element of a biomimetic fingerpad. The use of standard microfabrication technologies in realising the device allowed a cost efficient fabrication involving only a few process steps. A low noise readout electronics system was developed for measuring the sensor response. The performance of both bare and packaged sensors was evaluated by direct probing of individual capacitive sensor units and characterising their response to load–unload indentation cycles.

1. Introduction

There is a growing need for reliable, low cost tactile sensing devices for applications in areas such as robotics, minimal invasive surgery and automation of industrial manufacturing processes [1]. The last thirty years has seen tremendous progress in research on the design and development of tactile sensors. While earlier studies explored various transduction principles and sensor requirements, recent work in the field has involved the development of sensor prototypes that are tailored for specific applications. Biological tactile receptors in the human fingertips, also known as mechanoreceptors, serve as an inspiration for the development of robotic tactile sensors [2–6]. The biological tactile system offers a sophisticated mechanism through which subtle variations in texture can be perceived and this provides a standard for the performance of artificial tactile devices.

When developing sensors for incorporation into a robotic finger, the main challenges arise from the required high spatial and force resolution, and sufficiently small dimensions that allow integration within the space constraints of a finger. For robotic applications, the two main research areas on tactile sensor development are: sensors for enabling the robot to effectively perform lifting and grasping tasks and sensors for giving robots the ability to characterise different surface textures [7,8]. Texture is implemented as protrusions or undulations on the surface of a material that manifests as changes in forces when a sensor is moved across a surface. A brief overview of tactile sensors that have been reported to date for robotic applications and the technologies employed in each case are given in Table 1. Piezoelectric and piezoresistive principles have most commonly been used for the sensing elements. Preceding devices are generally larger than the mechanoreceptors in the human finger pad and lack the spatial resolution of the human finger (approximately 1 mm) [9] and its ability to provide the rich data set of information on spatial distribution of contact forces. To overcome these limitations, a highly dense array of micro tactile elements is needed.

The main objective of this work was to develop and characterise highly sensitive Micro Electro Mechanical Systems (MEMS) based tactile sensors for implementation into a robust microscale sensing array. The elementary sensor units should be individually addressable and provide information on spatial features of contacting stimuli. This would eventually allow for surface characterisation of various textures with the added feature of human finger pad like spatial resolution. In order to facilitate potential incorporation of the device into a robotic finger, it requires compatibility with integration of a layer of elastomeric skin-like material on the surface, mimicking the compliance and conformance of human skin. Thus the system would be able to come into contact with textured stimuli in a biomimetic manner and also be sufficiently sensitive to encode features of texture related attributes such as roughness.

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Table 1
Overview of tactile sensing devices developed to date for robotic applications.

Author (year)	Sensing technology/description	Application	No. of elements	Sensing element size	Array pitch	Force range	Sensitivity
Dario et al. [10]	Piezoelectric polymer: Multilayer structure including an epidermal PVDF layer, a conductive rubber intermediary layer and bottom PVDF dermal layer	Detection of contact pressure, hardness and surface texture	128	–	–	–	740 mV/N
Howe et al. [7]	Accelerometer: Conventional quartz crystal embedded in polyurethane foam and attached to outer 2 mm silicone rubber skin	Slip and texture perception	–	25 mm diameter	–	–	–
Omata et al. [11]	Piezoelectric ceramic: PZT element surrounded by 3 mm diameter hemisphere of silicone	Hardness, softness detection	–	15 mm × 65 mm	–	–	–
Yeung et al. [12]	Piezoresistive polymer: Matrix of Force Sensing Resistors with elastic overlay	Object recognition	16 × 16	–	1.58 mm	–	–
Beebe et al. [13]	MEMS piezoresistive: Silicon sensing diaphragm with load transmitting torlon dome Spatial resolution: 2–4 mm	Force sensing	1	2 mm radius	–	0–100 N	1.4 mV/N
Chu et al. [14]	MEMS capacitive: Silicon diaphragm, glass + polymer substrate, elastomer coating Spatial resolution: 2.2 mm	Robot fingers	3 × 3	0.450 mm radius	–	0–1 g	0.13 pF/g in *z*, 0.32 pF/g in *x* and *y*
Maeno et al. [15]	Strain gauge: 15 phosphor bronze plates embedding strain gauges (thickness 0.1 mm) are incorporated within a silicone rubber body	Detection of slip	15	–	–	–	–
Dargahi et al. [16]	Piezoelectric polymer: PVDF film	Force sensing	3	–	–	0–2 N	57.5 V/N
Mei et al. [17]	MEMS piezoresistive: Square silicon membrane and outer silicone rubber layer	Grip force control, object recognition	4 × 8	4 mm × 4 mm	–	0–50 N	13 mV/N
Leineweber et al. [18]	MEMS capacitive: Polysilicon membrane	Micromanipulation	8	0.24 mm × 0.24 mm	0.240 mm	0–3 bar	1.35 V/bar
Beccai et al. [19]	MEMS piezoresistive: Silicon based flexible sensing structure with four tethers in a cross-shape and centrally integrated force transmitting mesa. 4 piezoresistors implanted in tethers	Biomechanical applications	1	1.5 mm × 1.5 mm × 0.625 mm	–	3 N for normal force 0.5 N for tangential force	0.026 N^{-1} in *z*, 0.054 N^{-1} in *x* and *y*
Hosoda et al. [20]	Randomly distributed strain gauges and PVDF film embedded within an anthropomorphic soft fingertip	Robotic fingers – texture discrimination	24	–	–	–	0.1 V/N
Wettels et al. [3]	Impedance based: Fingertip shaped with rigid central core surrounded by weakly conductive fluid and covered by a silicone elastomeric skin. Spatial resolution: 2 mm	Robotic, prosthetic	–	–	–	–	33.3 kΩ/N
Scheibert et al. [21]	MEMS based piezoresistive device embedded in elastomer film. Cylindrical post attached to a suspended circular Silicon membrane (with 4 embedded piezoresistive gauges)	Fingertip like biomimetic tactile sensor	1	1 mm radius, 0.1 mm thick	–	–	–