Sensors and Actuators A 276 (2018) 226–236

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Performance analysis of flexible printed sensors for robotic arm applications

Anindya Nag*, Brendan Menzies, Subhas Chandra Mukhopadhyay

Faculty of Science and Engineering, Macquarie University, Sydney, NSW, Australia

ARTICLE INFO

Article history:
Received 12 February 2018
Received in revised form 17 April 2018
Accepted 18 April 2018
Available online 22 April 2018

Keywords:
Printed sensors
Pressure measurement
Laser cutting
Flexible sensors
Tactile sensing

ABSTRACT

The selection of the type of sensors used for robotic-arm applications holds a pivotal role in the work efficiency of the arms. Flexible sensors have been one of the popular choices for this application due to their dynamic advantages over the rigid ones. Among the different types of flexible sensors available in the market, Flexiforce sensors are one of the prominent ones, due to their low cost and simple operating principle. The dynamic range of pressure differs for the developed patches due to their difference in structure. The sensor developed with Carbon Nanotubes and Polydimethylsiloxane was found to be the most sensitive one, with the sensing pressure ranging between 14 Pa and 1.2 kPa. The outputs of these sensor patches were reproducible and reliable, based on their electrical and mechanical advantages compared to other commercially available sensors. This paper presents a performance analysis for some of the novel printed sensor prototypes with a commonly used commercial flex sensor. All of these sensor prototypes were developed using a laser-cutting technique. The idea behind this analysis is to identify novel flexible sensors for robotic arms for industrial applications with performance better than the existing ones.

1. Introduction

Over the last two decades [1], sensors have been associated with almost every industrial and domestic application [2–4]. The use of sensors for artificial intelligence [5] and robotics [6,7] has been one of the primary applications of sensors in the industrial sector in the past few years. Even though industrial automation has introduced robotics back in the 1970s [8], it has not been till the latter half of the last decade that the industrial robotics industry has started blooming commercially. Today, almost every professional sector, like universities, companies, and industries, have started using the concept of robotics as a tool in serving different sectors [9,10]. Among the different parts of a robot that are utilized for working purposes, the robotic arm [11] has been one of the popular choices for different industrial applications. The robotic arm in simple words can be defined as any mechanical arm which is programmed to perform functions analogous to a human arm. Robotic arms of various characteristics based on their length, degrees of freedom, etc. are available and used depending on their functionality. The performances of the basic tactile tasks like gripping, picking, welding, etc. done by a robotic arm are analyzed by the sensors attached to a specific position on the arm [12]. These are highly sensitive sensors which notify the arm to execute its scheduled function on the proximity of an object.

Tactile or pressure sensors are one type of sensors largely associated with robotic sensing [13,14] due to factors like their simple operation and high sensitivity. Continuous research work has been going on [15–17] to develop the performance of the existing sensors attached to robotic arms. Even though there are tactile or pressure sensors that are commercially used in robotics, some disadvantages limit their usage. Some of the sensors are complicated in structure and operation [18] which increases the fabrication cost as well as makes them cumbersome to replace in the case of any damage occurring to a sensor. Another disadvantage is the drop in the sensitivity of the sensor with time. The performance of the sensor attached to the robotic arm would slowly degrade [19] which would involve glitches, thus causing an error in its functionality. Other than that, even though there are sensors available for force sensing, there are certain disadvantages related to them as well, for which reason there is a need of new sensors. For the embedded MEMS-based strain gauges and piezoresistors, the overall cost of the sensor is high and the stretchability is limited, especially when they are attached to any embedded system. The existing capacitive sensors have complex circuitry, which limits their usage for some applications. There are some piezoelectric sensors developed from different materials like polyvinylidene fluoride (PVDF), but

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* Corresponding author.
E-mail address: anindya1991@gmail.com (A. Nag).

https://doi.org/10.1016/j.sna.2018.04.031

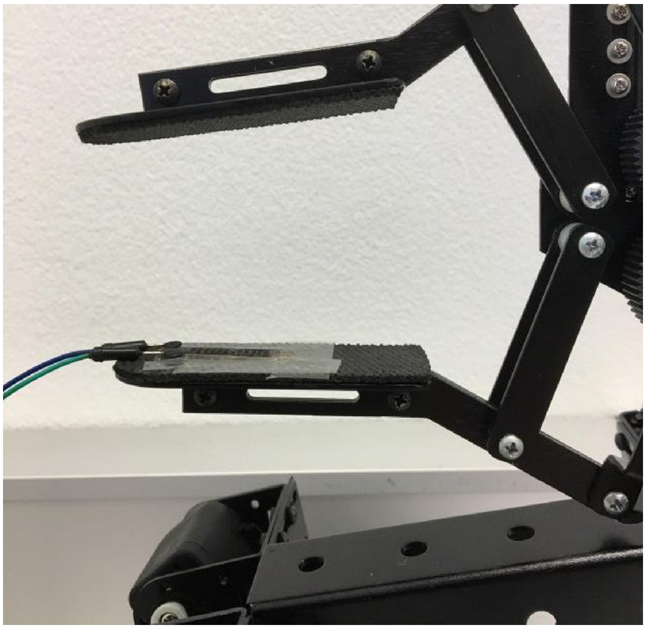

Fig. 1. Representation of the set-up followed during the experimental procedure showing the attachment of the sensor patch to the gripper of the robotic arm.

certain disadvantages like signal alternation and attenuation during bending limit their usage [20]. Another disadvantage related to them is their inability to fit to any surface, which makes it difficult to employ them in industrial uses [21]. Some of the sensors have poor stability and cannot be used for long-term applications [22]. It is thus, the state of the art to develop some sensors that can curb or minimize the above-mentioned disadvantages. This paper presents the fabrication of novel flexible sensor patches and utilizes them to determine their responses towards tactile sensing when connected to a robotic arm. Weighted objects were placed on the sensing area of the patches to analyse the change in the output voltage. The response of the fabricated sensor patches was then analyzed with two of the most commonly used commercial pressure sensors to identify the fabricated sensor patch with the best performance. Fig. 1 depicts the set-up of the sensor patches on the robotic arm followed during experimentation.

The substrates of the fabricated flexible sensors were developed with some of the commonly used polymers like Polydimethylsiloxane (PDMS) [23], Polyethylene Terephthalate (PET) [24] and Polyimide (PI) [25]. Low cost, easy availability, high mechanical flexibility and the ease of processing these materials are some of the reasons for choosing these polymers. Some of the biggest advantages of using these polymers and conductive materials together to develop the sensor patches lie in their combined advantages of the individual processed material. For example, the biggest advantage of using CNTs with PMDS lies in the formation of a conductive network at a low percolation threshold of the nano-fillers in the polymer matrix as a result. Due to the low Young's modulus of PDMS, they can form sensors with highly flexible nature. This allows the usage of the MWCNTs in the polymer matrix to form nanocomposites having non-isotropic mechanical properties [26]. Another example with be the involvement of graphene electrodes on Polyimide to have enhanced mechanical properties and high electrical conductivity as a result of high charge carrier mobility. One of the major advantages of the fabricated sensor patches is their resilience towards the change of their responses with the changes in changes in temperature and humidity. For example, the Al-PET sensor can be operated at very high temperatures due to the capability of PET to withstand temperatures ranging from −70 °C to 150 °C. Also, MWCNTs can withstand relative humidity conditions ranging between 25% and 95%, thus making it available for a lot of applications [27]. Due to these high resistance capabilities of the developed sensor patches towards extreme operating conditions, these developed patches would be highly favorable to be used in hydraulic and pneumatic industries. The materials considered to develop the electrode part of the patches were Carbon Nanotubes (CNTs) [28], Aluminum (Al) [29] and Graphene [30]. High electrical conductivity, high flexibility, high aspect ratio are some of the reasons to opt for the mentioned conductive materials to develop the sensor patches. All the sensor prototypes were developed with the laser cutting technique [31]. This technique was chosen over other standard techniques like photolithography [32], screen printing [33], or 3-D integration [34] because of the ease of sample preparation, while obtaining very small and thin samples. This paper has been divided into five sub-sections. Following the introduction given in section one, a detailed explanation of the fabrication processes of the sensor prototypes that are used for experimentation is given in Section two. Section three briefly shows the working principle of the fabricated sensor patches. Sections four and five give the experimental results and a discussion of the results. The conclusion is given in the final section of the paper.

2. Sensors used for experimentation

Three different types of sensor prototypes were designed and developed before their usage on the robotic arm. The fabrication of the sensor patches was done in the laboratory environment at fixed temperature (22 °C) and humidity (RH 45%) conditions. The fabrication steps for the first sensor prototype are shown in Fig. 2. PDMS was used to develop the substrate of the sensor patch whereas the electrodes were fabricated from a nanocomposite (NC) layer formed with multi-walled carbon nanotubes (MWCNTs) and PDMS. Poly (methyl methacrylate) (PMMA) was employed as the template to develop the sensor patches due to its nonreactive nature and proper adherence to the cured PDMS. Initially, after the PDMS (SYLGARD ® 184, Silicon Elastomer Base) was cast on the template at a ratio of 10:1 between the base elastomer (pre-polymer) and curing agent (cross-linker), its height was adjusted using a casting knife (SHEEN, 1117/1000 mm). The final height of the PDMS was 1000 microns. This was followed by desiccation of the uncured PDMS substrate for 2 h for the removal of any trapped air bubbles, after which the sample was cured at 80 °C for 8 h. Then a layer of NC was cast on the cured PDMS to develop the electrodes for the sensor patch. The NC was formed by mixing –COOH functionalized Multi-Walled Carbon Nanotubes (MWCNTs) (Aldrich, 773840-100G) with PDMS at a specific concentration. Samples with different wt. % of MWCNTs mixed with PDMS were prepared to study the trade-off between the conductivity and the flexibility of the NC. After a series of trials, a value of 4 wt. % of MWCNTs was found to be the optimum value to fabricate the NC-based electrodes. The white regions in the image represent the PDMS, whereas the black spots are MWCNTs. There are some black spots in the image where the MWCNTs look agglomerated, but the effect of these spots on the conductivity of the electrodes was negligible. The mixture was then cast on the cured PDMS and its height adjusted to 600 microns with the casting knife. Then the sample was cured again at 80 °C for 8 h. The final process step was completed with laser cutting (Universal Laser Systems, Model: OLS 6.75 CO_2 laser system, laser spot diameter: 150 microns) of the top layer of the sample, i.e., the NC layer, to pattern the electrodes. The laser system had a free-standing glass-covered platform having a surface area of 0.37 m^2. The input voltage was 220 V with a current raging of 5 A. The maximum weightage capability that the system can bear is around 147 Kg. made of steel on which the substrates were engraved subsequent to their attach-