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A compact dielectric elastomer tubular actuator for refreshable Braille displays

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ABSTRACT

Electroactive polymer actuators stimulated by appropriate levels of electric field are particularly attractive for human-assist devices such as Braille. The development of a full page refreshable Braille display is very important for the integration of the visually impaired into the new era of communication. In this paper, development of a compact dielectric elastomer actuator suitable for Braille application is reported. The actuators are fabricated from commercially available silicone tubes. The tube has been rendered mechanically anisotropic through asymmetric levels of applied pretension in circumferential and axial directions in order to direct the actuation strain in the axial direction of the actuator. Key performance parameters, such as displacement, force, and response time of the actuator are investigated. The test results demonstrate the potential of the compact, lightweight, and low cost dielectric elastomer as actuators for a refreshable full page Braille display.

1. Introduction

Braille is a means of communication in the form of tactile reading and writing for persons with visual impairments. In Braille, each character is made up of six or eight raised dots in a rectangular array of two columns where each combination of up and down position of the dots produces a specific sensation on the finger tip representing letters of the print alphabet. In a refreshable Braille cell, the dots are formed by independently controlled pins driven by a variety of actuators that are generally controlled by the output of a computer. Refreshable Braille is an electronic tool that enables the visually impaired to independently access information provided through texts, charts, graphs, etc. The importance of such display devices to the visually impaired community cannot be overstated in the context of modern information systems.

Today's commercially available refreshable Braille displays are electromechanical devices that are designed to raise dots through holes on a flat surface and are mostly limited to line displays. According to the National Library Service for the Blind and Physically Handicapped specifications, traditional embossed Braille dots of a base diameter of 1.45 mm should have a nominal height of 0.48 mm with a dot to dot spacing of 2.33 mm [1]. For a refreshable Braille display an ideal device should have the capability to display a full page that requires packing of many small dots of *ca.* 1.65 mm in diameter in close proximity with raised height of 0.5–0.7 mm, and minimum actuation force between 0.05 and 0.15 N [2,3]. A full page (28 cm × 30 cm) display thus requires 6000–8000 dots [2]. For graphical tactile displays a much higher resolution (1 dot/mm^2) is required, resulting in the need of 84,000 dots per page of similar size. Such a display has been dubbed as static because of their slow refresh rate [3]. In a static tactile display of this kind, a full page of information is presented to the reader and it takes a few minutes to explore the entire page, as a result the refreshing times are in the range of 10–15 s [4]. In contrast, in a dynamic refreshable display a small tactile display is mounted on a mouse-like pointing device. As the mouse is moved around a virtual page with a finger resting on the tactile display (on the mouse), the content of the tactile display is refreshed. The recommended refresh rate for this configuration should be in the range of 30–50 Hz [3,5]. Needless to say that the cost associated with such displays could be substantial. According to one estimate, a page with 1 dot/mm^2 resolution with 76,800 dots would cost more than $300,000 [3].

Various mechanisms including electromagnetic [6,7], pneumatic [8], and material-based actuators [9–26] for use in refreshable Braille displays have been investigated over the last three decades. Materials based actuators using shape memory alloys (SMA) [9,10], electrorheological fluids (ERF) [11,12], thermopneumatic actuators using phase change materials [13–15], piezoelectric ceramics [16–18], and various electroactive polymer actuators including conducting polymer actuator [19], piezoelectric polymer [20,21], dielectric elastomers [22–25], and ionic polymer metal composite [26] have been examined with varying success.

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In general, the electromechanical devices are complicated and expensive. In case of pneumatic actuators, in-use sticking (stiction) as well as low tip displacements are problems [8]. SMA actuators change their shape when heated and tend to exhibit hysteresis so they are often used as on–off devices with latching mechanisms [9]. A pair of SMA coils is generally used in an antagonistic fashion; one of the coils is heated for upward movement of the pin, while the other is heated to lower it [9]. While SMAs produce small strains, it is possible to fabricate actuators with large strokes and forces. However, in order to obtain fast response time, cooling may be necessary [10]. Consequently, SMA Braille cells involve high cost, and high power consumption requirements [9]. The electromagnetic Braille cell displays are limited to one line because of the large size of the actuators [6,7]. ERFs are designed to rapidly increase their apparent viscosity when subjected to an electric field as a result ERF based Braille cells respond very fast [11,12]. However, these are dimensionally large and require encapsulation [11]. Thermopneumatic actuators are made of sealed cavities, containing a low boiling point liquid, with a flexible side [13–15]. An in-built resistive heater increases the temperature in the cavity, resulting in increased pressure due to liquid–gas phase transition, and the displacement of the flexible side of the cavity. In the same vein, volumetric expansion of paraffin upon heating has been utilized to generate a stroke [13]. These actuators based on thermal expansion or phase transition are generally slower and have high power consumption. Piezoelectric ceramic actuators seem to be the standard in the current refreshable Braille designs [27]. These actuators are generally very fast, however, due to inherently small strains (<0.05%) produced by the material, these are used in bimorph configuration to attain the required displacement in the Braille application [16–18]. As a result, piezoelectric ceramic actuators are often bulky and too costly to be used in full page displays.

While a wide variety of materials are capable of producing actuation in response to an external stimulus and apparently capable of meeting the present requirements, electroactive polymers (EAP) seem to offer the most potential. EAPs are lightweight, inexpensive, energy efficient, and generally exhibit fast responses [28]. Examples of EAPs investigated as Braille actuators include a conducting polymer (polypyrolle) based tubular actuator that has reportedly produced 5% strain at a strain rate of 10% s^{-1} [19]. Braille cells based on piezoelectric polymer actuators have also been reported. A spring-loaded rolled actuators of a terpolymer, poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene), has been shown to produce the necessary displacement and force under an electric field of 100 MV/m [18]. More recently, a Braille cell based on multiple PVDF bimorphs with a latching mechanism has been proposed [21]. In this proof-of-concept device four bimorph actuators are attached to a fluid filled cavity. Two of the bimorphs are used to compress the cavity to raise the Braille tip while two other bimorphs are used to manipulate the latching mechanism. The Braille cell produced sufficient displacement (~1 mm) at voltages between 0.5 and 1.0 kV with *ca.* 100 ms response time. Of the various types of EAPs reported in the literature, dielectric elastomers (DE) exhibit one of the highest performances in actuation strain and energy density [29–31].

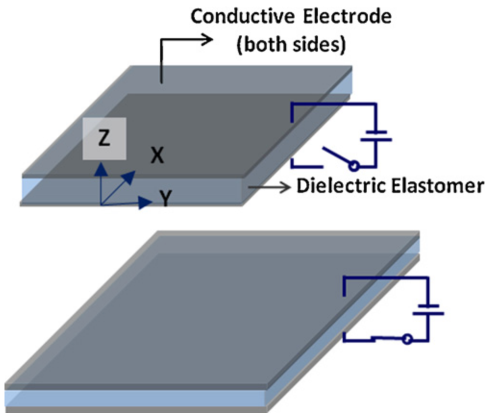

Fig. 1. Schematic illustration of the operational principle of a dielectric EAP before and after actuation. The elastomer film with compliant electrodes on both sides is compressed in thickness direction (z) and expands in area on application of a voltage across the electrodes.

The electromechanical response of DEs is attributed to the development of a Maxwell stress upon application of an external electrical field [29]. In principle DE actuators consist of an elastomeric film coated with compliant electrodes on both sides, see Fig. 1. Upon application of a DC electric field to the electrodes the DE film is squeezed in the thickness direction due to electrostatic attraction between the electrodes. The uniaxial stress (σ_M) acting normal to the film surface serves to compress the film along its thickness direction (z) and stretch the film in plane (x–y), producing constant volume deformation, and is expressed in terms of relative permittivity of the DE material (ε), free space dielectric permittivity (ε_o) and the electric field (E):

$$\sigma_M = \varepsilon\varepsilon_0 E^2 \tag{1}$$

The deformation of the DE film is further increased by repulsive like charges on both film surfaces, as schematically shown in Fig. 1. Three DE materials that show most potential derive from homopolymers and include an acrylic adhesive [29], polyurethane [32] and silicone elastomers [33]. The acrylic adhesives (VHB 4905, 4910) manufactured by 3M Co. (Minneapolis, MN) exhibit the largest actuation strain in this class of materials. More recently, selectively solvated triblock copolymers derived from poly[styrene-*b*-(ethylene-*co*-butylene)-*b*-styrene] (SEBS) have been reported to produce areal actuations as high as 245% and associated coupling efficiencies of 92% at electric fields as low as 22 V/μm [31].

Attempts to use dielectric elastomer based actuators in Braille cells have thus far produced varying degrees of success [22–25]. Many linear and other actuator configurations based on DEs and suitable for Braille application have also been proposed [34–36]. Recently, we reported a simple but compact and efficient cylindrical actuator that can produce axial strains of 10% and higher [34]. Compact actuators of this kind may be ideal for Braille application at a much lower cost. In this paper we explore the tubular actuator further to optimize their electromechanical behavior and propose a design for a refreshable Braille cell.

2. Proposed Braille cell design

The design of the proposed refreshable Braille cell suitable for a full page display is shown in Fig. 2. The key component of the proposed design is the DE tubular actuator (DETA). The DETA, under an optimal level of pretension (*cf.* Section 3), is anchored to the bottom and top plates of the Braille cell. The inactive length of the DETA is meant to work in consort with the active length in storing and releasing energy when required. The Braille pin is attached to the end of the active length of the DETA using an inside spacer and outside clamp to translate any boundary displacement of the DETA to up and down movement of the Braille pin through a hole in the top plate, without any constraint. The bottom end of the DETA is sealed with a conducting plug and is used as a lead to connect the inner electrode of the DETA to the power source.