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Tactile device based on opto-mechanical actuation of liquid crystal elastomers☆

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ABSTRACT

Nematic elastomers are promising materials for the fabrication of actuators due to their ability to reversibly contract and expand during phase transitions triggered by external stimuli. Thus, actuation can be produced on demand, forcing these phase changes. Here, we present a refreshable tactile device based on the opto-mechanical properties of liquid crystalline elastomers (LCE) with the capability to represent Braille characters and simplified graphical information. The actuators designed are based on the use of the stress gradient generated in the elastomer under illumination to exert a force on movable components. Additionally, hardware implementation and a communication software interface were developed to provide end users with a complete solution. Displacements of 0.8 mm with measured forces of up to 40 mN were reached without material degradation, proving not only the viability of the device but also the potential applications of this type of actuator.

1. Introduction

Visual impairment is a serious condition that limits and affects a person's ability to communicate. Thus, blind people depend on tactile and auditory perceptions to receive information. In 1821, Louis Braille standardized a tactile code system named after him [1]. Since then, several types of Braille-based displays have been developed, whose purpose is to improve the quality of daily life for blind people. Examples of commercially available systems range from simple typewriters and printer machines [2] to computer adapted keyboards and assisted devices with voice synthesizers [3,4], as well as complex portable equipment for object recognition [5] that usually combines both tactile and audio stimuli.

All of the systems developed for this purpose should meet some required specifications for Braille representation (i.e., character dimensions, a certain pitch between consecutive dots, etc.). In addition, desirable qualities of such devices include touch-friendly interfaces, fast character detection, and simplicity of use. Despite the latest technological improvements, none of the previously mentioned systems is good enough to completely replace Braille paper books and charts (obtained by embossing-paper printers). Low efficiency, high cost, poor resolution, non-portability and complexity are the most common issues reported.

To solve these problems, some interesting work has been published in the last few years based on the integration of small

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actuators capable of being operated by a wide range of external stimuli, e.g., electromagnetic [6,7], thermoelectric and thermopneumatic [8–11], among others. The most prevalent commercially available solution involves Braille systems based on piezoelectric materials [12]. This type of actuation system allows the fabrication of sturdy actuators that can be rapidly switched between 'on' and 'off' states [13,14], suitable for representing a few Braille characters, thus allowing the fabrication of compact portable devices. However, there are considerable disadvantages to this approach: (i) the actuator dimensions, which restrict its integrability and packaging, (ii) the poor spatial resolution that limits this technology to only Braille representations, (iii) the high price, and (iv) the fact that these actuators do not operate silently, thus making them inconvenient for use as Braille-reading devices in public areas such as libraries, schools and offices.

Soft polymer composites are a new generation of materials that have been of increasing interest in the last few years due to their many attractive and varied characteristics. In addition to their low cost, they are generally lightweight, fracture-tolerant and pliable. Furthermore, they can be molded into almost any conceivable shape, and their properties can be tailored to achieve a broad range of requirements [15]. Their high adaptability and their 'tunability' allow a wide variety of combinations (with other polymers, as well as other types of materials) for the creation of composites that are tailored to the applications for which they are intended. In addition, research into shape-memory and shape-changing polymers (also known as actively moving polymers) has created several materials with the ability to reversibly change shape and size under the application of a wide range of external stimuli, e.g., heat, light, electric and magnetic fields [16]. Polymers, therefore, have considerable potential for a new generation of actuators. So far, preliminary prototypes of Braille devices based on polymer actuators have been reported; most of these feature the exploitation of polymers with electroactive properties [17,18].

Recent improvements in consumer electronics have included the replacement of buttons, switches and keyboards by touch-screens. While this technology has considerable advantages for the average consumer, visually disabled people are unable to use such equipment. The adaptation of Braille to haptic systems and refreshable screens presents considerable challenges: dynamic and refreshable systems are required with lower response times and with Braille elements moved by actuators exerting an optimal force. Ideally, such devices should also be light, portable, and have a reasonable battery life.

A novel technology, intended to reduce some of the existing issues with refreshable Braille devices, has been explored within the framework of an FP7 European project. In this paper, we present the development of a refreshable tactile system based on the opto-mechanical actuation properties of LCE composites [19]. In addition to the design and characterization of the actuators and their components, hardware implementation and a communication software interface have also been developed to provide end users with a complete, fully modular device.

2. Actuators

2.1. Working principle and prerequisites

The working principle of the system is based on the light-induced mechanical actuation of a nematic LCE. Conceptually, the stress gradient generated in an elastomer ribbon, which contracts under illumination, is used to generate a vertical displacement of a pin, which will form the moving Braille component. Thus, material selection becomes a key issue for the actuator performance because the higher and faster the contraction of the material, the larger and quicker the displacement of the pin. This concept can be extended to obtain high-density 2D arrays of actuators, which will lead to the final tactile device.

It is important to mention that the actuators, as well as the whole system, should meet certain requirements for the moving components to be perceptible by a person's sense of touch. Thus, at least 0.3 mm vertical displacements of pins and pushing forces of 15 mN are required for correct tactile perception. Similarly, Braille standards impose spatial restrictions on the actuators' layout, limiting the 'lateral' dimensions of the Braille elements and the pitch between them to 2.5 mm. Compactness and lightness are also requisites of the system for portable devices.

2.2. Material selection

Nematic LCEs, containing liquid crystal units covalently bound to an elastomer polymer network, have been known in the literature for some time. Thin strips of material containing properly aligned LC units can reversibly change their shape and size during a LC phase transition, undergoing a contraction along the alignment direction as the material changes from the nematic to the isotropic state [16,20]. Thus, LCEs can be easily adapted to make actuators producing pulling or pushing forces, as valves in microfluidics [21] and as tweezers [22], among others.

Phase transitions, and hence actuation, in LCEs typically occur with changes in temperature. To operate the elastomers remotely with a controllable speed, it would be desirable for the actuation trigger to be light, rather than heat. Other actuation types, such as electric and magnetic fields [23,24], require higher levels of energy to generate movement. Thus, to obtain similar actuation times and forces, voltages from 1.5 to 25 MV/m and frequencies in the range of 240 kHz to 3 MHz are often used, involving more complex setup configurations and higher power consumptions. Further aspects, such as portability, lightness and safety in handling and testing, make optical actuation the most suitable one for this type of application.

The addition of photo-isomerizable chemical groups, such as azobenzene moieties, to LCE matrices to achieve photo-actuation has been widely discussed [25,26]. However, the actuation phenomenon is limited to the UV range, a fact that becomes a drawback for practical applications. To sensitize LCE material to light in the visible/IR range, we previously reported the dispersion of short segments of carbon nanotubes (CNTs) into the LCE matrix to provide fast local heating once a nanotube absorbs a photon [27,28]. Thus, actuation times can be reduced, and the material can be actuated in a range that is safe for the human eye (visible range). Using this approach, we studied the behavior of LCE-CNT composites under illumination by various types of light sources to obtain their basic physical parameters, which are essential for the engineering of actuators [29,30]. Experimentally measured values of these parameters are summarized in Table 1.

2.3. Sample fabrication

Pyrene main-chain nematic polymer was synthesized and used as a surfactant as described in previous papers [31]. Polymethylhydrosiloxane (PMHS) from Sigma Aldrich, together with MBB

Table 1
Values of the basic LCE-CNT parameters measured [27–30].

Material properties	Values
Young modulus	0.3–0.5 MPa
Poisson's ratio	0.5
Heat capacity	2.6×10^5 J m^{-3} K^{-1}
Thermal conductivity	0.4 W m^{-1} K^{-1}
Yield stress	100 kPa