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Review

Evolution of 3D printed soft actuators

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ABSTRACT

Developing soft actuators and sensors by means of 3D printing has become an exciting research area. Compared to conventional methods, 3D printing enables rapid prototyping, custom design, and single-step fabrication of actuators and sensors that have complex structure and high resolution. While 3D printed sensors have been widely reviewed in the literature, 3D printed actuators, on the other hand, have not been adequately reviewed thus far. This paper presents a comprehensive review of the existing 3D printed actuators. First, the common processes used in 3D printing of actuators are reviewed. Next, the existing mechanisms used for stimulating the printed actuators are described. In addition, the materials used to print the actuators are compared. Then, the applications of the printed actuators including soft-manipulation of tissues and organs in biomedicine and fragile agricultural products, regenerative design, smart valves, microfluidic systems, electromechanical switches, smart textiles, and minimally invasive surgical instruments are explained. After that, the reviewed 3D printed actuators are discussed in terms of their advantages and disadvantages considering power density, elasticity, strain, stress, operation voltage, weight, size, response time, controllability, and biocompatibility. Finally, the future directions of 3D printed actuators are discussed.

Contents

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1. Introduction

Soft robots are being developed to tackle the shortcomings of conventional robots in interacting with humans and fragile biological objects. They consist of a collection of subsystems such as sensors, actuators, and controllers that together form a robot that can safely handle fragile and sensitive matters. Focusing on the key component of soft robots, actuators, since conventional rigid actuators are unsuitable for use in soft robots, soft actuators are being developed to safely manipulate delicate objects. Therefore, developing soft actuators to satisfy both mechanical and control properties of soft robots has become a key target of many researchers.

Unlike conventional actuators, soft actuators produce flexible motion due to the integration of microscopic changes at the molecular level into a macroscopic deformation of the actuator material [1]. This can manifest as deflection or volumetric change. Soft actuators can be classified into several subgroups such as thermo-driven [2], electro-driven [3], pH-driven [4], light-driven [5], and magneto-driven [6]. Also, different materials like polymers [7], hydrogels [8], and elastomers [9], have been used for construction of soft actuators. Moreover, majority of the existing soft actuators are fabricated using multistep low yield process such as micro-moulding [10] and [11], solid freeform fabrication [12], and mask lithography [13]. However, these methods require manual fabrication of devices, post processing/assembly, and lengthy iterations until maturity in the fabrication is achieved.

To avoid the tedious and time-consuming aspects of the current fabrication processes, researchers are exploring an appropriate manufacturing approach for effective fabrication of soft actuators. Therefore, special soft systems that can be fabricated in a single-step by rapid prototyping methods, such as 3D printing, are being investigated. Such methods narrow the gap between the design and implementation of soft actuators, making the process faster, less expensive, and simpler [14] and [15]. They also enable incorporation of all actuator components into a single structure eliminating the need to use external joints, adhesives, and fasteners. These result in a decrease in the number of discrete parts, post-processing steps, and fabrication time. In addition, soft actuators with sub-millimetre features can be produced with high accuracy. Whilst the 3D printing approach has been widely applied to the fabrication of sensor devices [16] and [17], the use of this approach for production of soft actuators is a growing field of research. The soft actuators that are produced by the 3D printing method are referred to as 3D printed actuators.

This paper for the first time provides a comprehensive review of the emerging field of 3D printed soft actuators. It describes different methods: for fabrication of the actuators using 3D printers, and discusses their actuation mechanism, power density, reversibility, strain, stress, operation voltage, weight, size, response time, controllability, and biocompatibility.

The paper is organised as follows. Section 2 describes the technical process of printing soft actuators using the 3D printing techniques, and gives a classification of the existing 3D printers. Section 3 categorises the current 3D printed soft actuators into two groups: semi 3D printed and 3D printed soft actuators. Section 4 presents the applications of the 3D printed soft actuators. Section 5 gives a comparison of the current 3D printed soft actuators followed by a discussion of their and advantages and disadvantages. Finally, Section 6 provides the concluding remarks and the future directions of this research field.

2. Fabrication processes of 3D printed soft actuators

Producing any 3D printed soft actuator requires 4 steps, the first being the definition of the problem that is the clarification of the need for using a 3D printer for constructing the actuator. Secondly, the advantages of using 3D printer over conventional manufacturing techniques should be justified. Thirdly, the appropriate materials that can accomplish the desired characteristics of the final product should be selected meticulously. Finally, the method of printing should be decided according to the material properties, size of structure, and vertical movement of nozzle and the thickness of layers. The primary procedure of 3D printing starts from CAD design where the desired model is envisaged and drawn in a CAD software. Then, the 3D designed model is divided into multiple 2D stack layers piled up by means of printer jet nozzle depending on the precision of 3D printer in z axis (Fig. 1) [18].

Thus far, 3D printers have used various technologies for constructing the 3D products. In one common type of 3D printing known as spray forming, liquid moulding materials are sprayed using nozzle jet to form the layers of structure [19]. A similar 3D printer technique called spraying moulding with adhesive, utilizes adhesive materials that are sprayed on a layer of powder material in order to form strong bonds between two successive vertical layers [20]. In selective laser melting (SLM), structures are built up layer by layer by depositing a thin layer of metal powder, followed by selectively lasing to achieve the pattern needed in that section. The lasing causes a phase transition in metals; the particles are completely melted for just a fraction of a second during which they bind to the existing structure below [21]. Further, laser technology is applied instead of adhesive materials to fuse the powder materials by means of heat generated by the laser beam known as laser powder sintering moulding [22]. Stereolithography (SLA) is another technique that relies on a photosensitive monomer resin. A polymer is formed and then solidified when exposed to ultraviolet (UV) light while all these processes occur near the surface of the product [23]. Photosensitive polymer curing is another technique where light sources are adopted for 3D printers that use photosensitive polymers. In these printers, the photosensitive polymers are melted using light sources and then solidified rapidly [24]. In order to make 3D structures using polymeric materials, some 3D printers input polymers as filament using the extrusion technique under the pressure and heat to pile up the 3D structure layer by layer which is called material extrusion moulding [25]. Fused deposition Modelling (FDM) uses extrusion to lay down thin lines of a thermoplastic material in the shape of the object being manufactured [26]. Direct metal laser sintering is based on the principles of atomic diffusion at low speed and low temperature [27].

The materials commonly used in extrusion based 3D printers are acrylonitrile butadiene styrene (ABS), nylon, silicon and other thermoplastics [28]. In sinter/melt processing based printers aluminium, stainless steel, and titanium are the most common materials in use [29] and [30]. Also, 3D bio-printers can fabricate stents and heart valve replacements using Teflon, hydrogels and