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3D Printing of Smart Materials and Actuators

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Abstract. Smart actuators can sense external stimuli and produce controllable mechanical responses, and convert these energies into mechanical energy. They have great applications in the aerospace, electronic circuits, medical and other fields. As a new manufacturing method, the combination of 3D printing and smart actuators had developed rapidly in recent years. In this paper, we summarize the research progress of 3D printing smart actuators and its materials. The smart driver includes water responsive driver, pH responsive driver, temperature responsive driver, light responsive driver and magnetic field responsive driver. The smart driver materials can be divided into shape memory materials, piezoelectric materials, responsive smart hydrogels and electroactive polymers. In addition, their stimulative effect and driving mechanism have been studied emphatically.

Keywords. 3D printing; Smart actuators; Drive materials

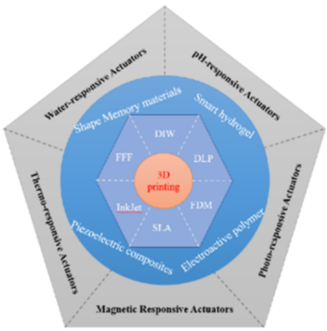

Figure 1. Schematic overview of 3D printing

1. Introduction

Smart actuators can be stimulated by a certain field to convert all kinds of energy into mechanical energy, and then the material undergoes reversible deformation and

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movement [1-6]. Over recent years, the applications of smart actuators in biomimetic robots, bionic robots and sensors. etc. had attracted much attention [7]. However, most smart actuators were processed by traditional methods, such as molding and soft lithography[8]. Although these machining methods have high machining accuracy, but the two-dimensional plane processing ability and machining efficiency are low, so that the materials are only suitable for simple and small-sized structure. With the increasing complexity of smart driving mechanisms, the above-mentioned traditional processing method can no longer meet the current requirements. According to the material morphology and molding principle, it is mainly divided into three categories: extrusion molding, granular material molding and photopolymerization synthesis. Based on this idea that 3D printing can quickly prototype of the target structures, it can avoid the tedious manufacturing process of traditional processing method.

The smart actuators with 3D printing complex structure can realize directional movement through stimulation in special environment. Recently 3D printed smart actuators have great potential value in drug transportation, medical equipment, micro devices, soft robots and so on.

The smart actuator is an actuator, which is an essential part of an automatic control system, and can respond to changes in external stimuli. Thus, it has received wide concern of researchers aiming to enhance their efficiency and agility. Smart actuators include water-responsive actuators, pH-responsive actuators, Thermo-responsive actuators, photo-responsive actuators, magnetic responsive actuators and stimuli responsive actuators.

Smart materials include carbon-based materials, liquid crystalline polymers, biological materials, smart hydrogels, dielectric elastomers, ionic polymer-metal composite. These smart materials respond to external stimuli including water or humidity, pH, temperature, magnetic and electrical fields.

In this study, we present the latest progress in the field of 3D printing smart actuators and their materials. We provide a toolbox for interdisciplinary audiences who are interested in the latest 3D printed smart actuator technology. In particular, we mainly explored the driving methods of 3D printing smart actuators, focusing on the form of motion and its driving effects. The first section discusses the actuating methods of 3D printing smart actuators and explore their functions and the realization of researchers. The materials for 3D printing smart actuators are then discussed.

2. Smart actuators for 3D printing

As one of the main components of robot system, smart actuator has been widely paid attentions by researchers in order to improve its efficiency and flexibility. Recently, researchers have focused on design with smart functions and advanced manufacturing techniques.

Plentiful examples of changes in biological systems can make changes according to their environment in nature. The wide range of stimulus response and different functions provide a good foundation for biological driving system to become smart actuators. In addition, researchers have invested many work into the development of smart actuators. Research in driving mechanism, material selection, 3D printing and creative design realization confirmed the potential of this field[9]. In view of people's interest in 3D printing smart drives, this paper reviews the latest research on smart drives and their biological driving applications, and classifies them according to their driving mechanisms. Here provided the stimulus is water, pH, thermal, optical, magnetic, electric, and the combination of these. These stimulate diagram is shown in figure 2. This paper reviews the latest research on intelligent drives and their biological drive applications, and classifies them according to their driving mechanisms in view of people's interest in 3D printing intelligent drives.

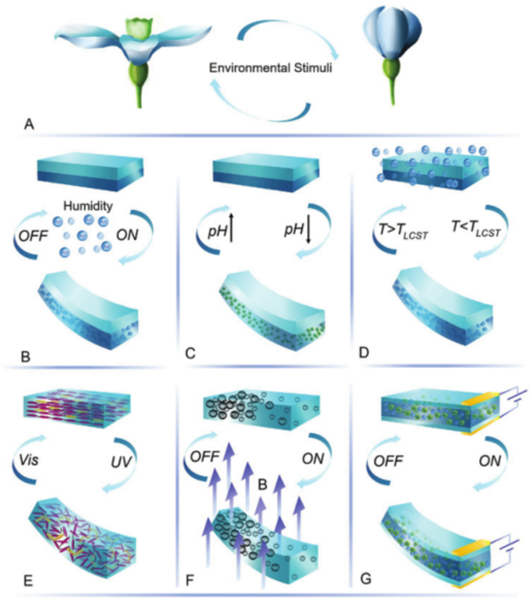

Figure 2. 3D printing smart actuators made of soft smart materials (reproduced from ref. 31 with permission of the John Wiley and Sons)

2.1. Water-responsive Actuators

In nature, many plants with two-layer structure can drive deformation through the change of h content in external water. The anisotropic deformation of the two-layer structure is caused by the different responses of each layer to water stimulation. Therefore, the researchers were prepared a variety of water drive response inspired in nature.

Water-responsive actuators are widely used in human body with the increasing demand of biomedical and sensor applications. The drive behavior is usually manifested by a changing in shape. Over recent years, bilayer composites have been widely used in the design of water responsive actuators. Consists of two layers, with different water absorbing capacity of double layer composite materials can realize response to water drive. Ren et al.[10] constructed a water responsive actuator based on composite membrane shown in Fig. 3. The composite membrane can be converted between two different states, thus showing bidirectional shape memory effect in response to water.

Han[11] et al. prepared skin collagen fiber/polyurethane (SCF/PU) composites with double network structure by paper making method with water as solvent for the first time shown in Fig. 3. SCF/PU composite has completely non-warm water responsive shape memory ability, and has high shape fixation rate (> 95%) and shape recovery rate (> 90%) in repeated memory cycle. In this study that exposure to water can destroy the hydrogen bond in collagen fibers, which makes the flexible elastomer matrix change into the desired shape. In addition, the existence of collagen fiber network makes SCF/PU composite biodegradable and with low cytotoxicity.

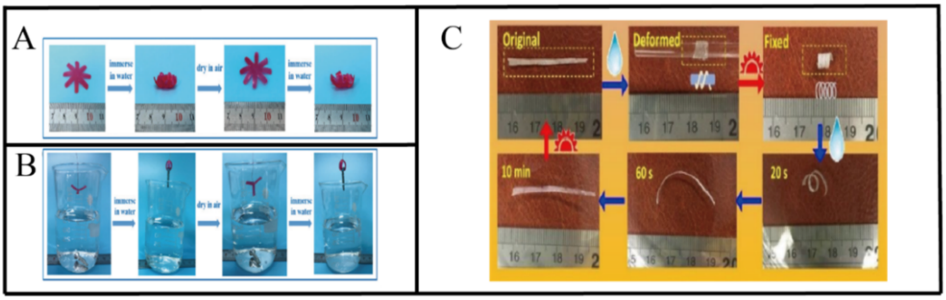

Figure 3. 3D printing water-responsive actuators. A-B) flower-like and claw-like actuators (reproduced from ref. 39 with permission of the Royal Society of Chemistry); C) water responsive shape memory behavior (reproduced from ref. 40 with permission of the Royal Society of Chemistry)

2.2. pH-responsive Actuators

Although the water responsive smart actuators is powerful and adaptable, it is not practical in fluid environment, such as precision mechanical structure and microfluidic application. The materials used in these drives will deform with the change of pH. Researchers found that this feature can be applied to the development of smart actuators. The development of different synthetic polymers has enabled researchers to make pH-responsive drives. Therefore, researchers have developed a number of pH-response smart actuators based on groups of different polymers. The polymers used to prepare pH-responsive actuators can be divided with basic group and acid group.

2.2.1. Ionization of Acidic Group

Dutta et al[12]. reported a pH-responsive smart hydrogel actuator. The responsive polymer displayed reversible cross-links with fluctuations in pH between pH 2.0 and 7.4 shown in Fig. 4.[12] In another study, Okwuosa et al[13] .recently used 3D dual extrusion FDM printing for the fabrication of the drug release capsules shown in Fig. 4. This 3D printed polymer shell structure has pH response characteristics. The core and shape memory capsule structure are designed using CAD modeling technology, and the best shell thickness is >0.52 mm. Due to the presence of the pH-response characteristic shell structure, its limited solubility under acidic pH protects the effect of the drug in an acidic gastric environment. The control of drug release is achieved by 3D printing with accurate shell thickness. This method can be widely used in the medical field in the future.

2.2.2. Ionization of Basic Groups

A number of basic groups have been used to develop basic polymers, including tertiary amine such as poly(N-(dimethylamino) (PDMA), morpholino such as poly[(2-N-morpholino)ethyl methacrylate] (PMEMA), and pyridine groups such as poly(4vinylpyridine) (P4VP), to name a few. Nadgorny et al[14].. prepared a 3D printing of an actuator using pH-responsive P2VP. When P2VP is blended with ABS, the mechanical strength can be significantly improved, because P2VP has excellent plasticizing properties in the extrusion manufacturing process.

The 3D printing of pH-responsive actuators shows great potential for their applicability in the medical field due to their biodegradation and biocompatibility[13]. However, the applicability of pH-responsive protein smart hydrogels in 3D printing actuators and materials are limited due to the non-physiological pH gel effect. Therefore, this is a problem that many researchers need to solve at present.

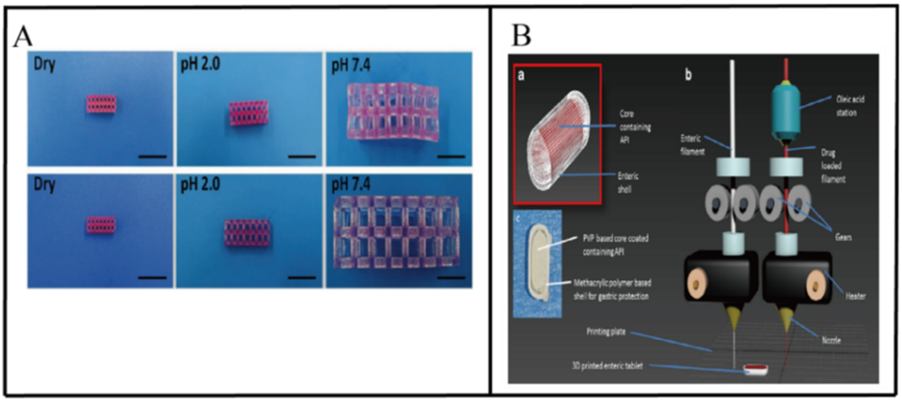

Figure 4. 3D printing water-responsive actuators. A) flower-like and claw-like actuators (reproduced from ref. 44 with permission of the Royal Society of Chemistry); B) water responsive shape memory (reproduced from ref. 45 with permission of the Springer Nature)

2.3. Thermo-responsive Actuators

Although a number of water-responsive and pH-responsive actuators have been developed with excellent features based on 3D printing technology. This has prompted researchers to invest in the development of drives suitable for dry environments. Among these actuators, the advantage of temperature responsive actuators is that they can realize various driving methods, because they can respond to various heating methods. In addition, these actuators are capable of showing large volume and shape changes. Therefore, researchers have developed a number of temperature-sensitive response drivers for 3D printing technology.

Shin[15] and others successfully manufactured a temperature response soft actuator by 3D printing technology, demonstrating its switching function in electrical applications. In another report, thermo-responsive PNIPAm along with polyether-based PU into 3D printed poly (2-hydroxyethylmethacrylate) (PHEMA) has been reported for shape morphing using 3D printing shown in Fig. 5[16] .The thermo-responsive actuator has fast response performance and is manufactured by this method. The thermo-responsive smart hydrogel smart actuator with LCST is limited by the phase change when heated, it has huge application potential.

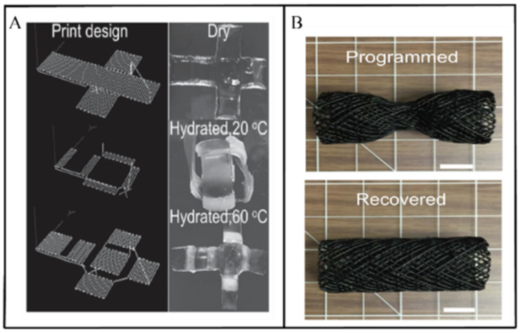

Figure 5. 3D printing Thermo-responsive actuators. (A) Smart hydrogel actuator (reproduced from ref. 54 with permission of the John Wiley&Sons, Inc). (B) Cylindrical support. (reproduced from ref. 55 with permission of the Springer Nature).

2.4. Photo-responsive Actuators

Photo-responsive actuators are considered to be one of the most promising smart actuators, because it can realize non-contact driving, selective and precise driving controlled by wavelength and intensity, and high-resolution temporal and spatial control. Different materials and technologies have led to photo-responsive actuators responding to different wavelengths, from ultraviolet to near infrared (NIR), direct (photochemical) or indirect (photothermal).

Rob et al[17]. developed a novel, light responsive thermoplastic actuator with versatility in shape design, reprogramming and multi-mode driving. In addition, this simple preparation method can also be used for the functionalization of other thermoplastic polymers, such as polyimide and polyamide. Due to its outstanding versatility and ease of manufacture, the photo-responsive thermoplastic actuator has established a new toolbox for future smart soft robot equipment, which requires fast and reversible driving, mechanical robustness, as well as activate any geometric shape that is controllable.

2.5. Magnetic Responsive Actuators

Magnetic responsive actuators have great applications including micro-optics systems, electronics, flexible robotics and biomedicine. Magnetic stimulation drives have unique advantages over other drives based on 3D printing technology. These advantages include: 1) non-contact remote control, widely used in various complex environments; 2) Precisely control the actuator; 3) the ability to generate high-frequency AC magnetic fields; 4) tunable ability of the actuators from nano scale to macro scale. However, the disadvantage of magnetic field responsive actuator is that it needs a complex and heavy external device to control the magnetic field and its gradient accurately.

Lee et al.[18] showed 3D printed micro-magnetic actuators with controllable dimensions which can respond to a variety of stimulus. The miniature magnetic actuator can expand and contract reversibly in multiple cycles with temperature, pH and divalent cations. It can expand and contract through narrow passages at designated locations. Their potential to control the occlusion of small capillaries. Furthermore, once the micro-actuator expands, it can only be removed by enzymatic degradation. This kind of micro drive can be widely used in the biomedical field.

3. 3D printing Smart driving materials

3D printing smart driving materials are mainly divided into: 3D printing shape memory materials, 3D printing piezoelectric materials, 3D printing responsive smart hydrogels and 3D printing electroactive polymers. At present, researchers have carried out a lot of work in 3D printing smart materials and demonstrated their applications in the preparation of various kinds of drive devices such as mechanical power generation. Over the past 5 years, researchers have used smart materials, such as shape memory materials, piezoelectric composites, smart smart hydrogel and electroactive polymer to produce smart actuator. These materials have been widely used in medical, health care, aerospace, bio-robot, underwater exploration and auxiliary equipment

3.1. 3D printing shape memory materials

The combination of shape memory material (SMM) and 3D printing technology not only optimizes the material preparation process, but also has the advantages of small mass, small impact and simple structure as smart driving materials compared with mechanical structure driving. At present, great progress has been made in the field of 3D printing SMM, and it has been applied in aerospace, electronic communication, smart robot and other fields. Shen Xinxin et al.[19] used 3D printing method to prepare shape memory carbon fiber composite pod rod, which broke through the limitation of mold in traditional process and effectively reduced the cost. Matt et al. [20] used the general and simple method of 3D printing methacrylate macromonomer to manufacture SMM. The responsive object is used to make soft robots, minimally invasive medical devices, and electronic devices. Sampada et al.[21]developed a composite material composed of SMM PLA and pea, as well as piezoelectric barium titanate nanoparticles by using 3D printing technology, to prepare a robust sensor. The sensor can withstand temperatures from 23 ℃ to 100 ℃ and more than 5000 cycles. However, the performance of 3d printed shape memory materials can not be used in special environment. Therefore, can be widely used in aerospace field of 3D printing shape memory materials received extensive attention of the researchers.

3.2. 3D printed piezoelectric composites

Piezoelectric materials are important parts of a series of devices such as transducers, sensors and actuators. Their functions are usually realized by a single brittle ceramic chip. In order to control the size and shape of piezoelectric materials, mechanical chips or saws are usually used. With the current cutting technology, it is almost impossible to mold brittle piezoelectric materials into more precise structures, which cause many hazards on precise sensor design, efficient transducers and diagnostic equipment. Kanguk et al.[22] used 3D printing technology to optically print efficient piezoelectric nano particle polymer composites into 3D microstructure. By doping barium titanate nanoparticles into light curable polymer solutions and exposing them to a dynamically changing digital optical mask, a user-defined three-dimensional microstructure was generated, and a piezoelectric polymer was prepared. Cui et al.[23]proposed a method to design electromechanical coupling anisotropy and orientation effect, and produced high response piezoelectric materials by 3D printing technology. This creates the freedom to design arbitrary piezoelectric tensors in reverse design, including symmetry and failure characteristics, and goes beyond the common coupling modes observed in piezoelectric monolithic and foam. With this material, the user can design, amplify or suppress any operating mode (DNM) for the target application.

3.3. 3D printing smart hydrogel

Smart hydrogel is a kind of hydrophilic polymer material with three-dimensional network structure, and its three-dimensional polymer network is filled with a large amount of bound water, interface water and free water, showing dual characteristics of quasi-solid and quasi-fluid. Due to its unique physical and chemical properties such as softness, smoothness, stimulus response, biological compatibility and material transport and exchange, smart hydrogel has attracted extensive attention in the construction of functional devices and mechanical equipment in the fields of sensing, flexible electronics, drive, coating, optics and water collection. In addition, smart hydrogels are widely used in biomedical research, including tissue engineering, medical regeneration, drug delivery and biological mechanisms, due to their physiological characteristics similar to those of tissues and organs. However, in order to ensure that smart hydrogel and its derived devices have good controllability and practicability, smart hydrogel materials are required to have intrinsically excellent mechanical properties and rich functional characteristics in practical application exploration. Ji et al.[24] introduced secondary microstructures on the sides of the smart hydrogel strips, which resulted in bending or distortion due to asymmetric expansion. With the advantages of free-form design and manufacturing, various smart hydrogel structures are constructed through 3D printing based on stereolithographic printing, which achieve complex and controllable shape deformation through programmed microstructures on characteristic surfaces. It is worth mentioning that various response smart hydrogels are compatible with this method, which can stimulate reversible shape deformation. At the same time, a set of electric response smart hydrogel flexible driving grippers was manufactured by using 3D printing technology. Zhu et al.[25] prepared a complex structure of PIC smart hydrogel using 3D printing technology. The PIC smart hydrogel has different ionic bonding strength in a variety of parameters of 3D printing. In concentrated brine solution, PIC formed a viscous solution, which can be directly extruded from the nozzle into the water, and the salts and counterions are dialyzed, resulting in the sol gel transition, forming a PIC gel with complex structure and tough physical properties.

In recent years, with the rapid development of high strength and toughness smart hydrogel and adhesive smart hydrogel material system and the continuous innovation of smart hydrogel processing and manufacturing technology, functional smart hydrogel has become one of the important materials of the next generation of intelligent machinery, especially soft machinery. Naturally, smart hydrogel machinery was established and developed rapidly as a new concept. Core purpose is to explore in the field of the smart hydrogel as an important part of intelligent devices and machinery, according to actual needs and conditions of application of the traditional hard materials (metals, ceramics, plastics, etc.) of parts to replace or supplement, expand the smart hydrogel machinery in biomedicine, software robots, flexible electronics, energy and environment and other important practical applications.

3.4. 3D printing electroactive polymer

Electroactive polymer are materials that can adjust its volume mechanically in response to electrical stimulation. However, the manufacturing process of electroactive polymer is very complex. The size or shape of electroactive polymer changes under the stimulation of electric field. David et al.[26] designed a novel 3D printing flexible dielectric material and characterized its application as an electroactive polymer (deap) actuators. The expansion area of the actuator is 5.48% under 4.3kv applied voltage, and the initial prestrain applied to the dielectric material is 63.21%.

4. Application of 3D printing smart driving materials

4.1. Application of 3D printing smart driving materials in soft robot field

The smart response of natural creatures have always been the source for researchers to design soft robots. With the research of natural molluscs, such as elephant nose, earthworm body, octopus tentacle, a variety of biomimetic soft robots have been widely applied. The contact part of traditional rigid robot is composed of rigid materials, which is easy to damage soft objects. In terms of human-computer interaction, medical operations, item grabbing, grab sorting, underwater exploration etc., the rigid robots rely on sensor control to achieve safe interaction, which not only brings manufacturing difficulties, but also makes the complete set of equipment more expensive and is not conducive to the popularization and application. Therefore, the rapid manufacture of mechanical grippers with a variety of functions has been widely concerned by researcher. The actuators use the gas produced by chemical reaction to drive by air pressure, which realizes the movement of crawling and swimming.

4.2. Application of 3D printing smart driving materials in medical field

Custom implants can be made for a fraction of the initial cost because of the specificity of 3D printing. Although the automotive, art and aerospace sectors have benefited a lot of the medical devices sector accounts for a huge market in the 3D printing industry. Therefore, customized devices and implants need to be manufactured. In the biomedical field, 3D printing is often used to manufacture biocompatible implants, artificial tissues and organs. In recent years, researchers have successfully designed and manufactured heart valves and knee meniscus through 3D printing.3D printing rib cage is designed for patients who have lost their ribs due to accidents and other circumstances. Oral cavity or oral cavity includes maxilla (maxilla), mandible (mandible), 32 teeth (16 teeth per mandible), muscles, nerves and blood vessels. 3D printing plays an important role in creating complex biocompatible devices to replace these damaged tissues. Therefore, whether in industrial production or daily life, the medical industry related to 3D printed intelligent devices is in a good stage of development and has become a hot industry for research and development. In this context, it is of great significance and value to develop 3D printing intelligent devices with excellent performance. In the future, the research and application of 3D printed intelligent drivers will use the cutting-edge achievements of many disciplines to achieve high flexibility, versatility, high affinity and other performance characteristics, so as to be widely used in various medical, aerospace, military and other fields.

5. Conclusions

3D printing smart actuators is one of the important directions of the development of modern high-tech materials. As a new manufacturing method that intelligent actuators using 3D printing technology has developed rapidly in recent years. The smart driving materials include shape memory materials, piezoelectric composites, smart smart hydrogels, electroactive polymers, etc. The fields involved include aerospace, soft robots, etc. The research and application of 3D printing smart actuators is far beyond these. In the future, the research and application of 3D printing smart actuators would make use of the cutting-edge achievements of many disciplines to achieve high flexibility, versatility, high affinity and other performance characteristics, so as to be widely used in various medical, aerospace, military and other fields.

The key factors to for the applications of 3D printing smart actuator include the usability of external stimuli, drive efficiency and mechanical performance requirements. Therefore, it can create a tradeoff between performance and material printability due to limitations.

The latest development of 3D printing technology has achieved multi-smart material printing, embedded smart material printing, and the use of magnetic fields and particles to calibrate filling materials. The combination with smart actuator materials means that this technology may become a viable to the next generation of intelligent technology. Many reports discuss the proof that the entire review focused on concepts and potential applications. However, with the continuous advancement of 3D printing smart drive technology and materials, these concepts may soon be realized in the near future.

References

[1] Deng J, Li J, Chen P, et al. Tunable Photothermal Actuators Based on a Pre-programmed Aligned Nanostructure. Journal of the American Chemical Society. 2016; 138(1): pp 225-230.
[2] Liu L, Jiang S, Sun Y, et al. Giving Direction to Motion and Surface with Ultra-Fast Speed Using Oriented Smart hydrogel Fibers. Advanced Functional Materials, 2016; 26(7): pp 1021-1027.
[3] Shahsavan H, Salili SM, Jakli A, et al. Thermally Active Liquid Crystal Network Gripper Mimicking the Self-Peeling of Gecko Toe Pads. Advanced Materials, 2017; 29(3).
[4] Sotiriou GA, Blattmann CO, Pratsinis SE. Flexible, Multifunctional, Magnetically Actuated Nanocomposite Films. Advanced Functional Materials. 2013; 23(1): pp 34-41.
[5] Terasawa N, Asaka K. High-Performance PEDOT:PSS/Single-Walled Carbon Nanotube/Ionic Liquid Actuators Combining Electrostatic Double-Layer and Faradaic Capacitors. Langmuir. 2016; 32(28): pp 7210-7218.
[6] Wang F, Jeon J-H, Kim S-J, et al. An eco-friendly ultra-high performance ionic artificial muscle based on poly(2-acrylamido-2-methyl-1-propanesulfonic acid) and carboxylated bacterial cellulose. Journal of Materials Chemistry B. 2016; 4(29): pp 5015-5024.
[7] Ban J, Mu L, Yang J, et al. New stimulus-responsive shape-memory polyurethanes capable of UV light-triggered deformation, hydrogen bond-mediated fixation, and thermal-induced recovery. Journal of Materials Chemistry A. 2017; 5(28): pp 14514-14518.
[8] Zhang YF, Ng C JX, Chen Z, et al. Miniature Pneumatic Actuators for Soft Robots by High-Resolution Multimaterial 3D Printing. Advanced Materials Technologies. 2019; p 4(10).
[9] Ilami M, Bagheri H, Ahmed R, et al. Materials, Actuators, and Sensors for Soft Bioinspired Robots. Advanced Materials, 2020.

[10] Ren S, Feng J. Water-responsive actuators based on the solution casted PVA/epoxidized-SBS two-way shape memory bilayer composite film. Journal of Materials Chemistry C, 2020; 8(42): pp 14826-14833.

[11] Han Y, Hu J, Chen X. A skin inspired bio-smart composite with water responsive shape memory ability. Materials Chemistry Frontiers. 2019; 3(6): pp 1128-1138.

[12] Dutta S, Cohn D. Temperature and pH responsive 3D printed scaffolds. Journal of Materials Chemistry B, 2017, 5(48): pp 9514-9521.

[13] Okwuosa T C, Pereira B C, Arafat B, et al. Fabricating a Shell-Core Delayed Release Tablet Using Dual FDM 3D Printing for Patient-Centred Therapy. Pharmaceutical Research. 2017; 34(2): pp 427-437.

[14] Symes MD, Kitson PJ, Yan J, et al. Integrated 3D-printed reactionware for chemical synthesis and analysis. Nature Chemistry. 2012; 4(5): pp 349-354.

[15] Shin S, So H. Time-dependent motion of 3D-printed soft thermal actuators for switch application in electric circuits. Additive Manufacturing, 2021, 39.

[16] Naficy S, Gately R, Gorkin R, Iii, et al. 4D Printing of Reversible Shape Morphing Smart hydrogel Structures. Macromolecular Materials and Engineering. 2017; 302(1).

[17] Verpaalen RCP, Da Cunha MP, Engels TP, et al. Liquid Crystal Networks on Thermoplastics: Reprogrammable Photo-Responsive Actuators. Angewandte Chemie-International Edition. 2020; 59(11): pp 4532-4536.

[18] Lee YW, Ceylan H, Yasa IC, et al. 3D-Printed Multi-Stimuli-Responsive Mobile Micromachines. Acs Applied Materials & Interfaces. 2021; 13(11): pp 12759-12766.

[19] Shen X, Jia B, Zhao H, et al. Study on 3D printing process of continuous carbon fiber reinforced shape memory polymer composites, 2019 International Conference on Advanced Electronic Materials, Computers and Materials Engineering. 2019.

[20] Zarek M, Layani M, Cooperstein I, et al. 3D Printing: 3D Printing of Shape Memory Polymers for Flexible Electronic Devices (Adv. Mater. 22/2016). Advanced materials (Deerfield Beach, Fla.), 2016; 28(22): 4166-4166.

[21] Bodkhe S, Ermanni P. 3D printing of multifunctional materials for sensing and actuation: Merging piezoelectricity with shape memory. European Polymer Journal, 2020, 132.

[22] Kim K, Zhu W, Qu X, et al. 3D Optical Printing of Piezoelectric Nanoparticle - Polymer Composite Materials. Acs Nano. 2014; 8(10): pp 9799-9806.

[23] Cui H, Hensleigh R, Yao D, et al. Three-dimensional printing of piezoelectric materials with designed anisotropy and directional response. Nature Materials. 2019; 18(3): p 234.

[24] Ji Z, Yan C, Yu B, et al. 3D Printing of Smart hydrogel Architectures with Complex and Controllable Shape Deformation. Advanced Materials Technologies. 2019; 4(4).

[25] Zhu F, Cheng L, Yin J, et al. 3D Printing of Ultratough Polyion Complex Smart hydrogels[J]. Acs Applied Materials & Interfaces. 2016; 8(45): pp 31304-31310.

[26] Gonzalez D, Garcia J, Newell B. Electromechanical characterization of a 3D printed dielectric material for dielectric electroactive polymer actuators. Sensors and Actuators a-Physical. 2019; 297.