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Closed-loop 4D-printed soft robots

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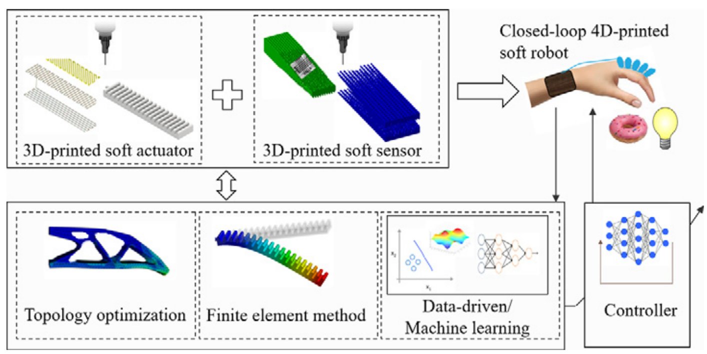
HIGHLIGHTS

- Review of integrated 3D-printed soft sensors and actuators
- Discussions of closed loop 4D printing empowered by machine learning modelling
- Overview of applications of 4D-printed soft robots
- Analysis of control approaches in 3D-printed soft robots

GRAPHICAL ABSTRACT



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ABSTRACT

Soft robotics is a recent and rapidly growing field of research that encompasses emerging advances in functional materials, fabrication, modelling, and performance control with important applications in the manipulation of fragile objects. The incorporation of three-dimensional (3D) printing into the fabrication of soft robots facilitates the customisation of their functions by the strategic placement of functional materials into locations that may be inaccessible by conventional manufacturing methods. Most current 3D-printed soft robots, however, are fabricated without considering their autonomy. In four-dimensional (4D) printing, the functionality of a soft robot is introduced during the printing process. To control this functionality, specific functional materials are embedded in desired locations. Four-dimensional printing and machine learning techniques provide new possibilities for developing stand-alone closed-loop 4D-printed soft robots. This review paper presents the current approaches employed to design and construct 4D-printed soft robots with customised geometrical, functional, and control properties.

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1. Introduction

Three-dimensional (3D)-printed soft robots have considerably attracted the interest of research communities and industry [1–4]. The increasing scope of their applications demands autonomy in their operation so that they can independently function in dynamic environments. A closed-loop four-dimensional (4D)-printed soft robot should be capable of responding to environmental interactions and stimuli without the necessity of accepting any commands from external systems or users. Closed-loop 4D printing integrates 3D-printed sensors, 3D-printed actuators, and control policies not only to optimise the configuration of responsive materials but also to equip them with feedback information and accomplish the functional target over time while interacting with uncertain environments in real-time.

The complexities involved in the modelling and control of 3D-printed soft robots, however, have limited the utilisation of these robots in real-world applications [5]. Although most current soft robots have been 3D printed, modelled, and ultimately controlled, they would not qualify as autonomous. To yield the desired spatio-temporal transformation over time in response to environmental stimuli, four-dimensional printing [6–8] provides new directions and capabilities for the integration of stimului-responsive materials as both sensors and actuators during the manufacturing stage in a programmable and estimable approach. In this study, closed-loop 4D-printed soft robots are developed by integrating 3D-printed sensors, actuators, data-driven/machine learning (ML) model, and dynamic control to handle real-world uncertainties that have not been considered in previous 4D-printing research.

Closed-loop 4D-printed soft robots have potential applications in classification, grasping, and sorting tasks in the food and agricultural industries [9]. For example, these can be used as climbing or crawling agents for monitoring inaccessible environments, pipe inspections, search and rescue missions [10], and hydrogel-based drug delivery devices because of their water-soluble and ingestible properties [1]. Origami-like soft robots can provide variable stiffness with higher efficiency and dexterity required in specific tasks, which conventional robots cannot handle [11]. Closed-loop 4D-printed soft robots may be also used in autonomous surgeries, laparoscopy, and endoscopy [12,13].

To achieve robotic autonomy, sensory feedback control is essential. The addition of sensory feedback information to control a soft robot through the 3D printing of a combined sensor and actuator to provide feedback information is critical. This in itself, however, may not be adequate for the soft robot to make autonomous decisions on the next action to take in an uncertain environment. The high dexterity and flexibility of 4D-printed soft robots lead to extensive interactions with the environment, thus making the autonomous operation inefficient because of limited experimental training data. Finite element methods (FEMs) and dynamic control techniques are therefore necessary to realise closed-loop 4D-printed soft robots. To close the feedback loop and form the aforementioned soft robot, four key components are required (Fig. 1): (1) 3D-printed soft sensors, (2) 3D-printed soft actuators, (3) data-driven/ML model, and (4) controller.

Closed-loop 4D-printed soft robots capable of diverse manipulation tasks are an unexploited research domain. The majority of 4D-printed soft robots cannot be adequately described by linear models mainly because they involve many degrees of freedom, material nonlinearities, and time delays. It is therefore an exigent task to formulate a viable model for the robust control of such systems in real-world applications. Machine learning techniques that circumvent the complexities of advanced mathematical models can be employed to realise the feedback control of nonlinear dynamical systems [14–16].

Machine learning indeed contributes to closed-loop 4D printing in two aspects. First, the ML approach can be adopted to develop closed-loop 4D-printed soft robots during manufacturing, where the faster optimisation of 3D printing parameters in the fabrication of 3D-printed soft sensors and actuators are desirable. To achieve maximum printing fidelity, ML algorithms can be utilised to accelerate the optimisation of relevant material properties, such as extrudate viscosity and build orientation for 4D-printed soft robot components. Through the integration of physical models, the ML uses sparse datasets in a statistical learning framework to predict materials and 3D printing processing parameters to increase 3D printing speed and fidelity [17].

Second, the ML is used in conjunction with the FEM to predict a precise actuation signal for the nonlinear dynamics model of 4D-printed soft robots. Certain elements, such as targeted anisotropy, variable stiffness, and spatially heterogeneous mechanical strengths, can therefore be introduced during 3D printing to cope with environmental uncertainties.

The design of a closed-loop soft robot to achieve a target shape appropriate for a practical application is an inverse nonlinear problem that requires ML algorithms and FEM to handle the variable physical responses of incorporated materials [18]. Although analytical models and static controllers are more reliable and accurate for conventional rigid robots in a known environment, data-driven/ML approaches can be more suitable for closed-loop 4D-printed soft robots because of their high dimensionality, dexterity, material anisotropy and nonlinearity, and uncertain dynamics [5,19–22].

Different control strategies can be employed to enable the soft robot to adapt to a dynamic environment [18,23–25]. Open-loop controllers have been commonly used in high-speed trajectory-tracking tasks with minimum control effort [16,26]. The controller's gain, however, is limited by the stiffness requirements of the system [27]. Closed-loop controllers and embedded soft sensors are therefore essential to handle uncertainties originating from dynamic surroundings and variations in the material properties of soft robots while preserving stiffness requirements and robustness. The mechanisms and materials used in the construction of soft robots are similar; hence, the control can be inspired by a learning strategy that deals with high nonlinearity and agility [16,19,28].

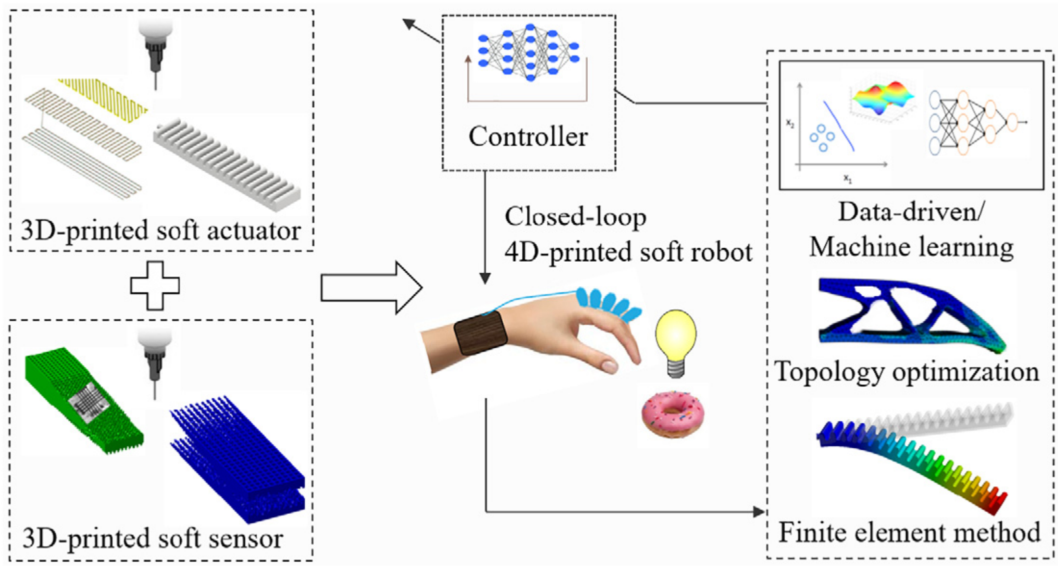

Fig. 1. Diagram of closed-loop 4D-printed soft robot.

This review introduces the fabrication and integration of 3D-printed soft sensors and actuators by tailoring ML approaches for the modelling and control of 4D-printed soft robots. Other components, such as 3D-printed soft actuators, batteries, and flexible electronics as peripheral parts of closed-loop 4D-printed soft robots have already been reported in existing publications [4,29–33].

The rapid growth of 3D printing technology has enabled the capability of embedding multilayer electronic circuit boards within the structures of soft robots. Soft conductive materials that have both conductivity and stretchability could be used within insulated interface networks in developing flexible electronics parts of closed-loop 4D-printed soft robots [34]. The 3D printing of stretchable networks made from conductive fillers or ionic electrolytes has allowed the 3D printing of silicon-based electronic circuit components (resistors, capacitors, and antennas) to incorporate embedded systems inside 4D-printed soft robot systems [29]. Moreover, passive filters, including low and high-pass filters with varying cut-off frequencies, have been developed by constructing twistable wires and circuit components, such as stretchable and flexible 3D-printed capacitors and resistors [35]. To process sensor outputs and control the actuator, integrated miniature microcontroller units (MCUs) are the other imperative parts of closed-loop 4D-printed soft robots. These MCUs are fabricated in sophisticated chip foundries because they cannot be fabricated by current 3D printers. Three-dimensional printing, however, enables the spatial embedding of MCUs in different layers and orientations with mechanical and electrical design flexibilities as parts of 4D-printed soft robots [35]. In order to closed-loop 4D-printed soft robots exhibit an autonomous behaviour, they require power sources with a high power density and flexible electrodes that could be built through the recent advancement in 3D-printed batteries [29–31,33]. The 3D printing of a stacked-array and self-supporting solid electrolyte [33] or lithium-ion [36] batteries in micrometre-scale using conformal ink makes the foregoing feasible.

The rest of this paper is structured as follows. In Section 2, 3D-printed soft sensors are reviewed. In Section 3, the investigation of the integration of 3D-printed soft sensors and actuators is elaborated. In Section 4, the control strategies for closed-loop 4D-printed soft robots are discussed. Finally, in Section 5, the current limitations and future directions of this field of research are presented.

2. 3D-printed sensors

The first components that are required for closing the control loop of 4D-printed autonomous soft robots are 3D-printed embedded sensors. The current advancements in 3D printing technology and functional materials provide an opportunity for the development of 3D-printed soft sensors with customised geometry and functionality to be embedded in soft robots for specific applications. The typical conductive inks used for the fabrication of 3D-printed soft sensors are based on conductive polymers, nanofillers, and liquid metals [37–39]. In this section, the investigation of 3D-printed sensors based on various sensing principles for potential applications in 4D-printed soft robots is elaborated. Thus far, most 3D-printed sensors are developed based on resistive and/or capacitive principles with applications in tactile, mechanical loading, temperature, and humidity measurements.

Each of the several approaches used for the 3D printing of embedded sensors have pros and cons. The 3D-printed sensors in soft robotic applications can be characterised based on the material properties of printing ink and geometrical dimensions to produce a detectable response signal. One of the early techniques is a semi-3D printing approach where conductive parts are embedded into the 3D-printed substrate [40]. Despite its early success because of the abundance of highly conductive materials, this method is disputed because it is not recognised as a full 3D printing method for free-form deposition/extrusion of wiring conductors. As a result, the infusion method in which conductive and nonconductive materials are infused together as printing filaments or dissolved as printing inks is subsequently proposed [41]. Although this method enables the full 3D printing of sensors, difficulties are encountered in achieving the uniform dispersion of conductive particles and voids in the structure, thus leading to the formation of cracks in 3D-printed tracks. Through commercialisation combined with the progress in printable conductive materials, the availability of fused deposition modelling (FDM) and co-extrusion 3D printers has increased. As a result, multi-material 3D printing has become the most preferred printing method although it has low spatial conductivity (Fig. 2(a)) [42,43]. Different 3D printing technologies that are employed for developing sensors as well as their advantages and drawbacks are extensively discussed in earlier papers [2,44]. It has been reported that both geometry and material specifications perform a function in defining the characteristics of 3D-printed embedded sensors with various sensing principles and applications in soft robotics. Here, 3D-printed sensors with specific applications in 3D-printed soft robots (Table 1) are classified; a more detailed information on general sensors in 3D printing can be found in related review papers [2,44–46].

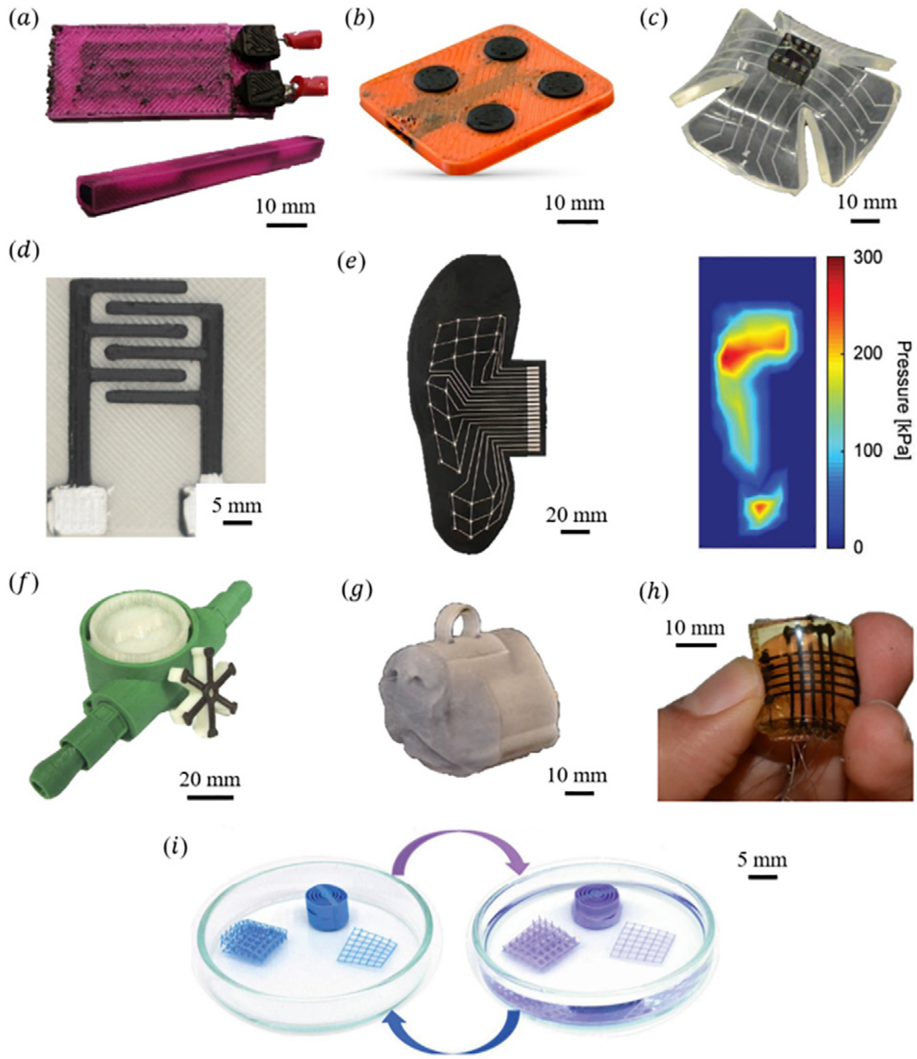

Fig. 2. 3D-printed sensors with applications in 4D-printed soft robots. (a) 3D-printed integrated strain sensor (reproduced with permission from Copernicus Publications on behalf of AMA [42]); (b) 3D-printed sEMG electrodes (reproduced with permission from Copernicus Publications on behalf of AMA [42]); (c) 3D-printed piezoelectric sensor in jellyfish soft robot (reproduced with permission from SPIE [67]); (d) 3D-printed e-tongue sensor (reproduced with permission from Frontiers [110]); (e) 3D-printed pressure sensors (reproduced with permission from John Willey and Sons [71]); (f) 3D-printed fluid flow rate sensor (reproduced with permission from IOP Publishing [98]). (g) 3D-printed dog nose for gas detection (reproduced with permission from Nature Publishing Group [109]); (h) 3D-printed flexible tactile sensor (reproduced with permission from Springer [58]); (i) 3D-printed thermochromic and solvatochromic sensors (reproduced with permission from John Wiley and Sons [100]).

2.1. 3D-printed strain sensors

Strain sensors can be used in 3D-printed soft robots to measure mechanical deformation. Most 3D-printed strain gauge sensors can be developed based on the piezo-resistive property and geometry changes of printed constructs under mechanical deformations. Three-dimensional printing could be readily used for these sensors by strategically placing printed strands on appropriate locations based on the expected mechanical loadings. A planar series of stretchable strain sensors is successfully 3D-printed into an elastomeric material. This array of 3D-printed soft sensors exhibits a resistance variation in response to cyclic loadings, and the technique is shown to be promising for the 3D printing of planar and 3D geometries of strain gauge sensors in soft programmable structures [47]. Reference [48] reports the fabrication of a 3D-printed tactile piezo-resistive sensor by using FDM and thermoplastic polyurethane (TPU)-based filament (as the flexible non-conductive matrix) and carbon black (CB) (as the conductive filler). In another study, a polylactic acid (PLA)-based filament with a CB filler as a conductive agent is employed to 3D print a strain gauge sensor [49]. An acceptable gauge factor for using the aforementioned sensor as a 3D-printed strain gauge in soft robotic applications is revealed through a tensile test that is performed in combination with four-probe measurements. Carbon fibre-filled silicone rubber is also printed by extrusion 3D printing and tested for resistive sensing to different deformation modes, such as bending, extension, compression, and twisting. The results show that the resistivity hysteresis is reduced by cyclic folding, bending, and twisting loading and unloading [50].

Capacitive-based strain gauge sensors have also been 3D-printed to measure the extensional strain [51,52]. It is shown that the sensitivity of these sensors could be customised by monitoring the 3D printing parameters, such as nozzle size, ink flow rate, layer thickness, and printing speed [52]. Printing inks that contain nanoparticles, graphene, and nanotubes have recently been investigated to enhance the electrical conductivity while maintaining the conformity of 3D-printed sensors in soft robotic applications [53–55]. With the introduction of graphene into the 3D printing of soft sensors, a multi-dimensional flexible sensor with a porous nanostructure is developed. This sensor uses a highly conductive graphene aerogel with gesture manipulation applications [52].

Three-dimensional-printed fibre optic sensors that operate based on changes in the intensity of reflected light caused by the deformation of

Table 1
Overview of 3D-printed sensors in 4D-printed soft robot applications.

3D-printed sensors	Mechanisms	3D printers	Materials	Pros (+) and cons (−)	4D-printed soft robots
Strain	Capacitive [52] Optical waveguide [56] Resistive [48]	Extrusion Extrusion FDM	Silicone OrmoClear TPU	+High elongation +Hysteresis free -Coaxial +Low optical loss -Fugitive ink +Force and contact point -Hysteresis	Grasping Trajectory tracking
Tactile	Capacitive [66] Piezo-resistive [63]	FDM SLA	TPU Cilia	+High sensitivity -Simple geometries +High resolution -Nonlinearity	Gesture differentiations Holding different shapes
Pressure and stress	Capacitive [68] Optical FBG [78] Piezoelectric [67]	Extrusion FDM Inkjet	Ionic gel ABS Tango Black	+High sensitivity -Environmental effects +Linear response -High Deviation +Pressure and shear –High-stress deviation	Safe manipulation
Displacement	Eddy current [84,85,123] Hall effect [82] Optical waveguide [79]	FDM FDM Inkjet	Copper/ABS Magnetite/ABS InkOrmo/InkEpo	+Non-contact +High temperature range -Low sensitivity -Environmental effect +Mass production -Coupling loss	Path planning
Accelerometer	Capacitive [86]	Inkjet	Polyethylene terephthalate (PET)	+Biodegradability -Post-assembly	Maneuvering
Magnetic field	Inductance [93] Ultrasonic [91]	Inkjet Inkjet	VisiJet/silver Plaster (zp150)	+Wireless -Dissolving sacrificial +Large size -Limited range	Direction and orientation Contraction in length and force
Flow	Inductance [98] Vortex [96]	FDM FDM	Magnetite/polycaprolactone Polyurethane/graphene	+Linear response -Delamination +Multi-axis -Post-assembly	 Stiffness adaptation
Temperature and humidity	Capacitive [102] Solvato/Thermochromic [100]	DLW Extrusion	Nanocrystals 1D coordination polymer (CP1)	+High Spatial resolution -Coupling loss +Multi-stimuli -limited cycles	Stiffness adaptation Multi-stability
Chemical	Electrochemical [110] Optical waveguide [113]	FDM SLA	Graphene/PLA Accura®60	+High precision -Post-treatment +Disposable -Low resolution	Detection/classification
Bio	Bioluminescent [115] Electrochemical [122] Vibratory [121]	FDM SLA DLP	Bio agents/PLA/ABS PEGDA Bisphenol A ethoxylate diacrylate	+Smartphone based -low robustness +Bio-functionality -millimetre scale +Self-standing +Single step fabrication	Detection/classification

the soft robotic arm have been reported. In terms of hysteresis, these sensors eliminate many of the deficiencies of conductive materials that are employed in resistive and capacitive 3D-printed sensors. These fibre optic sensors can be directly 3D-printed for soft robotic applications [56]. Moreover, an entirely 3D-printed mechanoluminescent device is developed from polydimethylsiloxane (PDMS) and metal ion-doped ZnS particles, which emit light upon the compression or stretching of the assembly. This 3D-printed soft sensor can be used as a directional strain sensor [57].

2.2. 3D-printed tactile sensors

Tactile sensors could be integrated into 4D-printed soft robots as artificial skin to sense the texture of materials in the surroundings. Most of the recent 3D-printed tactile sensors are developed by embedding conductive meshes in 3D-printed thermoplastic polymer substrates (Fig. 2(h)) [58]. The 3D printing of capacitive-based tactile sensors is reported to be more problematic mainly because of the constraints in depositing conducting materials in the form of thin layers. There have been some successful studies, however, on the fabrication of capacitive touch sensors by embedding conductive wires in FDM-printed layers [59,60]. A fully encapsulated capacitive sensor is designed and fabricated by using polyphenyl sulphone as substrate and FDM-printed polycarbonate [61]. Carbon nanotube (CNT)-Ecoflex is also 3D-printed as highly stretchable capacitive sensors with sensing applications, such as tactile recognition [62]. The printed CNT-Ecoflex exhibits promising results that are not possible with traditional counterparts. This is attributed to the enhanced controllability and tenability of stretchable structures by 3D printing. A piezo-resistive tactile sensor is 3D-printed using a composite filament of TPU and polylactic acid–graphene (PLA–G). The repeatability of a sensing function within a broad range of bending-induced strains is promising [63]. A graphite/PDMS sensor for small soft structures to measure small forces in the range 3.5–7.5 mN is also developed by 3D printing [64]. Stretchable tactile sensors are 3D-printed on a free-form surface using multi-materials [65]. These soft sensors that are capable of measuring various types of tactile forces are printed in series. In another study, hair-like structures with a strand size of 100 μm are 3D-printed on complex geometries for a tactile sensor in soft robotic applications, such as touch location and intensity sensing, to identify different gestures (Fig. 2(j)) [66].

2.3. 3D-printed pressure and stress sensors

Closed-loop 4D-printed soft robots require feedback information, including pressure and deformation, because of their interactions with the environment. To achieve this goal, several different sensor principles have been developed. In one approach, a gel piezoelectric sensor is 3D-printed and embedded into a jellyfish-like soft robot that utilises certain composite gel materials, including ion gel, ionic liquid, and shape-memory gel. The study demonstrates that ion gel could be used as a suitable material for pressure sensing because of its variable impedance properties at different payloads (Fig. 2(c)) [67]. A capacitive sensor that can measure the shear and normal stresses in an amputee's leg is also 3D-printed [68]. The test results demonstrate that this sensor has a highly linear performance, thus making it suitable for soft robotic applications. A capacitive force sensor is made of a combination of fibre encapsulation and 3D printing of thermoplastic elastomer as a dielectric spacer [69]. The sensor, however, exhibits a certain deficiency in terms of signal delay upon unloading. A similar methodology is utilised for developing a shear capacitive force sensor that provides sensing capabilities for autonomous space mission soft robotic applications [70]. Furthermore, an array of capacitive pressure sensors is fabricated using a CB-doped TPU that is designed in the shape of a foot. This 3D-printed sensor is tested to measure pressure in the absence and presence of loads on the foot. A plantar sensor array that could be integrated into 3D-printed soft wearable robots is also developed (Fig. 2(e)) [71].

Three-dimensional printing can be employed in the fabrication of piezoelectric sensors, but with certain problems. When crystal deformation is introduced during bonding, temperature-induced charges may cause pre-strain to a preceding layer made of a material with a different thermal expansion coefficient, thus leading to inaccurate electrical outputs [72].

Polyvinylidene fluoride (PVDF), which is both processible and piezoresistive, is investigated as a 3D-printed sensor [73–75]. A simple method for the fabrication of a 3D-printed pressure sensor is demonstrated by utilising commercial PVDF powder and multi-walled carbon nanotubes (MWCNT) [76]. Furthermore, another study on 3D-printed capacitive sensors with a pressure sensing function in soft organs using the PVDF is conducted. The 3D-printed PVDF sensor is successfully used in a prosthetic ear to measure both pressure and temperature [77]. Fibre Bragg grating (FBG) is also used as a pressure sensor by embedding it in a 3D-printed acrylonitrile butadiene styrene substrate [78]. The mechanism is based on the wavelength variations of FBG in response to pressure changes.

2.4. 3D-printed displacement sensors

Three-dimensional-printed displacement sensors are either fibre optic or magnetic field-based. The 3D-printed fibre optic sensor measures the displacement of a moving object based on changes in the intensity of reflected light beams. In these sensors, an inert fibre is usually inserted into the 3D-printed structure [79]. As one of the choices for displacement and vibration measurements in 3D-printed soft robots, fibre optic displacement sensors are lightweight, transparent, and inexpensive [80]. The other applications for these types of sensors include tactile sensors and accelerometers [81]. Three-dimensional-printed magnetic displacement sensors have also been developed to detect the motion of a magnet upon flexure as inspired by the Hall effect principle [82,83]. The 3D-printed displacement sensor based on the Eddy-current principle has recently attracted interest mainly because of being a non-contact method and having the potential of measuring a wide range of temperatures in harsh uncertain environments [84,85].

2.5. 3D-printed accelerometers

The 3D printing of accelerometers with high conformity and sensitivity is crucial in the implementation of 4D-printed soft robots. Knowing the acceleration of different segments of soft robots will contribute to the predictability of their dynamics and control when interacting in uncertain environments. In one of the earliest studies on the development of 3D-printed accelerometers, a capacitive accelerometer is fabricated and tested in a suspended structure using a sacrificial printing material and silver paste [86]. An accelerometer is subsequently fabricated by 3D printing and wet metallisation based on the capacitive differential of perpendicular axis accelerations [87]. The high-performance output of this 3D-printed accelerometer makes it an excellent choice for application in 4D-printed soft robots.

2.6. 3D-printed magnetic field sensors

Embedded miniature magnets can be used for the contact-free detection of soft body deformation in 4D-printed soft robots. The hysteresis observed in the stress–strain curves of 3D-printed conductive composite strain sensors is avoided. Custom shape and size magnetic curvature sensors could provide soft robots with proprioceptive feedback for sensing motion and external forces [88,89]. Ferromagnetic photopolymers have been used as appropriate materials for the 3D printing of magnetic field sensors by stereolithography (SLA) [90]. Moreover, the aerosol jet technique is used for the 3D printing of coil winding by nanosilver and copper inks [38]. Frequency-selective electromagnetic soft structures have also been 3D-printed for the electromagnetic control of ultrasonic wave propagation [91].

The use of inductive sensors has attracted interest because of their high reliability function under extreme environmental conditions, such as high temperature and pressure, and underwater operations. These sensors also have other technological features (e.g., higher switching rate) and they offer more flexibility in design with access to a wider range of materials compared with resistive and capacitive 3D-printed sensors [92]. The detection performance of 3D-printed inductance sensors can be characterised based on the geometric parameters and number of turns of a spiral pipe regardless of conductivity changes in the liquid metal [93]. The 3D-printed inductance sensor could incorporate magnetic and ferrofluidic materials into 3D soft robots at room temperature to measure axial, lateral, bending, and dilatational strains [94,95].

2.7. 3D-printed flow sensors

Three-dimensional-printed flow sensors contribute to the development of 4D-printed soft robots, especially pneumatic soft actuators and robots that work in aqueous environments. An entirely 3D-printed whisker sensor is fabricated using TPU and graphene for underwater soft robotic applications to measure vortices [96]. A 3D-printed micro-hair structure is developed for flow sensing [97] and exhibits a reasonable performance in low-velocity air sensing. A flow sensor is also fabricated by a magnetite nanoparticle-loaded thermoplastic composite for measuring water flow rates (Fig. 2(f)) [98]. A 3D-printed microdroplet liquid detector that could be used in self-driven microfluidic applications is developed by employing polyethylene diacrylate and multi-walled carbon nanotube (MWCNT) [99].

2.8. 3D-printed temperature and humidity sensors

Three-dimensional-printed temperature and humidity sensors are essential components for enhancing the environmental awareness of soft robots under various conditions. Functional polymers are the most widely used materials in the 3D printing of soft robots. The physical behaviours of these polymers are highly dependent on the temperature and humidity of the surrounding environment. Using 3D printing, the temperature and humidity data can be acquired in spatial layers of the soft structure using embedded and integrated sensors. A 3D-printed composite copper–thymine sensor with a high level of sensitivity is developed for measuring environmental temperature and humidity in organic solvents. The sensor mechanism is based on changes in the structure and colour with water loss and temperature variations (Fig. 2(i)) [100]. Conductive inks, including nanosilver particles [101], have been broadly used via direct laser writing (DLW) for implementing 3D-printed capacitive-based temperature and humidity sensors [102]. A 3D-printed wireless humidity sensor is also developed to detect moisture levels in soil. The mechanism of this sensor is based on resonant frequency shifts in response to the soil moisture level [103]. A PLA resistive-based temperature sensor that could be used in soft robots in food industries is also 3D-printed [104].

2.9. 3D-printed chemical sensors

Three-dimensional-printed chemical sensors can be used in diverse 4D-printed soft robot applications, such as microfluidics and chemical leak detection [105,106]. In soft robots associated with microfluidics working in electrolyte and polyelectrolyte mediums, 3D-printed electrochemical sensors performs a significant function [107]. These sensors are developed based on the double-layer formations on electrodes and subsequent disturbance of space charges with fluid movement. Another advantage of 3D printing in the fabrication of these sensors is its specific calibration customisation based on electrolyte ions and concentrations. There have been some promising reports on 3D-printed graphene-based PLA electrodes using an FDM printer for electrochemical sensing purposes [108]. A 3D-printed artificial dog nose, which could be embedded in an autonomous surveillance soft robot, is developed for gas detection purposes (Fig. 2(g)) [109]. An e-tongue is developed using an FDM 3D printer and transparent graphene-based PLA filaments to detect different materials, such as N, P, K, S, Mg, and Ca (Fig. 2(d)) [110]. A biological tissue-compatible pH sensor made of hydrogel has also been 3D-printed. A 3D-printed soft sensor made from pH-sensitive poly(3,4-ethylene dioxythiophene) and hydrophilic polyurethane provides soft robotic applications in wet environments with extreme cyclic deformations, including twisting and bending [111]. A wireless sensor made of a mixture of silver nanowires and cellulose nanofibres is 3D-printed for selectively detecting quantitative ion concentrations [112]. Furthermore, optical fibres are integrated into a microfluidic particle counter by 3D printing. The size of particles is identified based on the light intensity variations through the fibre [113].

2.10. 3D-printed biosensors

Three-dimensional-printed biosensors can perform a significant function in the realisation of miniaturised 4D-printed soft robots to detect and measure biological changes in bio-related applications [1,114]. There have been several successful studies of 3D-printed hydrogel sensors with proven biocompatibility to measure enzymes, toxicity, and drug release as well as to detect cancer [115–118]. Non-invasive 3D-printed electroencephalography (EEG) sensors have been developed to record brain activity and could soon be used in 4D-printed surgical

Table 2
Overview of materials used in 3D-printed actuators with applications in 4D-printed soft robots.

Materials	Stimuli	Pros (+) and cons (−)	References
PDMS/silicones	Pneumatic Fluidic	+Light weight and Inflatable +Biocompatible +High force transmission -Needs external pump/compressor -Difficult controlling of force	[140,154]
TPUs	Pneumatics	+Light weight and Inflatable +Biocompatible -Needs external compressor -Difficult controlling of force	[155,156]
SMPs	Electrical Heat Magnetic Chemical-Reaction Light	+Biodegradable +Low cost -Slow response -Low-medium power density -Too sensitive to thermal noise	[157–164]
Hydrogels	Moisture Heat pH Magnetic Electrical	+Low operating voltage +Biocompatible +Biodegradable -Slow response -Low mechanical strength	[1,107,165,166]
Paper/celluloses	Moisture Electrical	+Biodegradable -Slow response	[167,168]
IPMCs	Electrical	+Fast response +High strain +Low operating voltage +Lightweight -Medium power density -Requires electrolyte layer	[129,169]
Dielectric elastomers	Electrical	+High elastic energy density +High longevity -High operating voltage -Low power density -Requires pre-strain in fabrication	[170] [171]
Piezoelectrics	Electrical	+Fast response +High longevity -High operating voltage -Not biocompatible -Low strain -Low power density -Large hysteresis	[172,173]
Magnetics	Magnetic	+Remotely control +low energy loss/friction -Brittle and hard to print -Locking mechanism required	[174–176]

soft robots [58]. Three-dimensional printing can contribute to the development of easy to fabricate and inexpensive dry and waterproofed electrodes that are suitable for EEG sensors [119]. The use of a 3D-printed glucose sensor that could be attached to miniaturised soft robots for biomedical applications in diabetes has been recently demonstrated [120]. A mass-sensitive biosensor based on the vibratory measurement of a microcantilever is developed in one-step 3D printing. A mixture of a photocurable resin and acrylic acid is prepared to 3D print a functionality tunable sensor in a standard immunoassay protocol [121]. A flexible 3D-printed sensor with a surface electromyography capability for soft robot and medical applications is also developed by the FDM of dielectric and conductive TPU (Fig. 2(b)) [43]. Compared with regular AgCl electrodes, the signals of 3D-printed sensors, especially in the lower frequencies, exhibit a significant sensitivity to muscle activity [122].

3. Integrated 3D-printed soft sensors and actuators

The integration of 3D-printed soft sensors and actuators is a key feature in developing 4D-printed soft robots. Further details regarding different 3D printing methods and materials for developing 3D-printed soft actuators and soft robots can be found in previous articles (Table 2) [44,45]. Three-dimensional-printed soft sensors for measuring strain, stress/pressure, touch, and displacement are embedded into soft robot bodies to send sensory feedbacks without compromising the conformity and flexibility of the system when the robots interact with the surrounding environment. Thus far, in the literature, reports of integrated 3D-printed sensors and actuators that create a significant scope and potential for future development and innovative research are limited. The further contemplation of possibilities invokes concepts of 4D-printed soft structures.

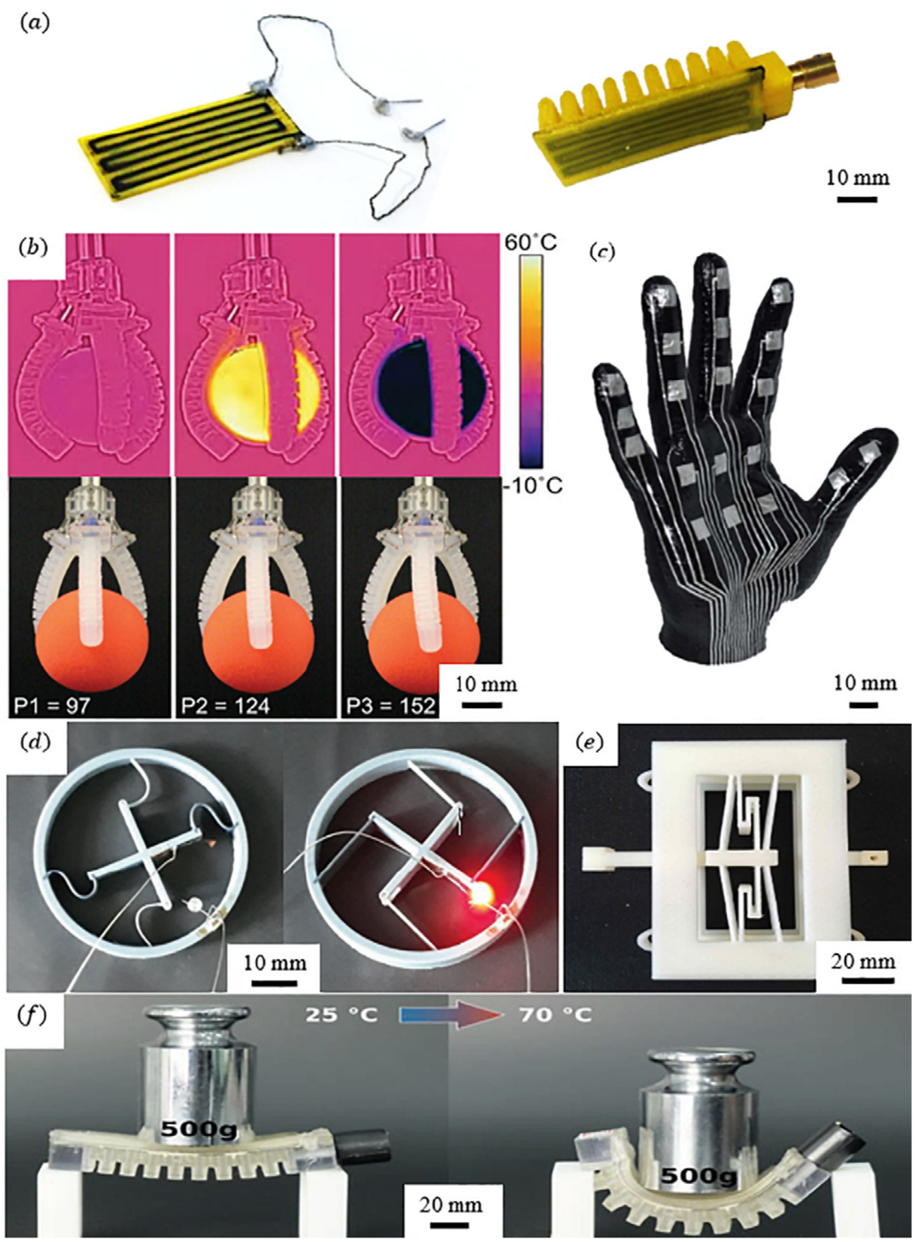

Fig. 3. Integrated 3D-printed soft sensors and actuators: (a) 3D-printed embedded sensor in pneumatic soft actuator (reproduced with permission from SPIE [126]); (b) 3D-printed soft gripper with printed embedded sensors (reproduced with permission from John Wiley and Sons [9]); (c) 3D-printed tactile sensor on 3D-printed prosthetic hand (reproduced with permission from the American Chemical Society [34]); (d) 4D-printed multistable thermal actuator (reproduced with permission from John Wiley and Sons [150]); (e) Bistable 3D-printed soft actuator (reproduced with permission from MDPI [148]); (f) 3D-printed variable stiffness soft actuator with an integrated joule heating circuit (reproduced with permission from John Wiley and Sons [151]).

One of the earliest practices in the integration of 3D-printed sensors and actuators in a soft robot is achieved by the 3D printing of a synthetic sensory-motor onto a soft fluidic elastomeric actuator (Fig. 3(b)) [9]. Pneumatic actuation is the response to tactile sensing and kinaesthetic feedback measured by the 3D-printed sensor made of silicone and conductive hydrogel inks. This mechanism can simultaneously measure the external load on the surface of the soft robot and the internal pressure of the soft actuator in 3D-printed prosthetic soft robots [124]. There have been some previous investigations on embedding 3D-printed soft sensors in separately 3D-printed soft robots and actuators for acquiring feedback information. The bending angle of common 3D-printed pneumatic actuators has been predicted and controlled by using sensory feedback data provided by resistive-based flexible sensors [125]. A data-driven regression-based approach is developed to model and control the soft actuator's complex behaviour. The result of this study demonstrates the application of ML in calculating the bending angle of 3D-printed soft robots under different operating conditions by simply using the embedded soft sensor and without any prior knowledge of the soft robot's material properties or geometric configuration (Fig. 3(a)) [126,127]. An ionic polymer–metal composite (IPMC) sensor, which could be embedded into 3D-printed pneumatic soft actuators, is also a feasible choice [128]. The IPMCs are soft transducers that can be fabricated through 3D printing [129,130] and utilised as either sensors or actuators. A 3D-printed soft robot that has sensing and actuation capabilities is fabricated using a commercial silicone-based elastomer. An IPMC is used as a sensor embedded within the strain-limiting layer, which is a thick layer of material on the pneumatic actuator; the sensor embedded layer resists deformation leading to anisotropic bending. The developed soft robot is suggested for underwater vehicles and requires laminated coating for a long-standing dry application For [131].

More recently, there have been a few reports on the integration of entirely 3D-printed soft sensors and actuators. A sensory paper robot is 3D-printed by a commercial FDM PLA–graphene composite filament as a resistive heating element and actuator. An electric potential is used to locate a finger that moves on the surface of the 3D-printed paper actuator [132]. A double-network thermo-responsive hydrogel is employed to 3D-print a multifunctional artificial skin. The use of 3D printing enables the magnification of the capacitive sensory response via the customisation of the fibre diameter that allows the system to measure body temperature and motion. The strategies employed in the study yield an example of a thermo-responsive, highly sensitive, and mechanically compliant ionic skin that could contribute to the development of closed-loop 4D-printed soft robotic ionic devices based on hydrogels [133].

A smart stent combined with a wireless pressure sensor by using biocompatible and biodegradable polycaprolactone (PCL) and poly (D-lactide) (PDLA) is 3D-printed. Coating the stent with a drug enables real-time blood pressure measurements in the vessel via resonance frequency changes [134].

A proximity measurement skin is 3D-printed using eutectic gallium—indium (EGaIn) liquid metal alloy on a 3D-printed prosthetic hand surface. The hydro-printed circuit over the hand shell utilises electromyography (EMG) and tactile inputs from reciprocal human—machine interactions to control the hand [34] (Fig. 3(c)). An autonomous soft inflatable robotic module with embedded microfluidic sensor channels is developed using 3D-printing [135]. When filled with a liquid conductor, the channels function as tactile sensors to determine the locations and measure the magnitudes of external forces. The soft robots situated within the elastomeric skin actively inflates and deflates in response to measured forces.

To improve the autonomous task handling of the robot, deep learning is proposed for accurately localising the contacts [136]. More than one sensor could be 3D-printed to provide more sensory feedback information to 3D-printed soft robots. In another study, a piezo-resistive composite of carbon black-filled thermoplastic polyurethane is 3D-printed by FDM as a pressure and position sensor. The integrated sensors exhibit adequate flexibility to provide the inherent compliance of a 3D-printed pneumatic soft actuator. One advantage gained from this work is the co-printing of all soft sensors and actuators in a single process. The 3D printing of all pressure and position sensors and soft robotic closed-loop control enables the grasping of delicate objects [137].

There have been other recent approaches to endow 3D-printed soft actuators and robots with sensing capabilities using 4D printing instead of integrating sensors [6,138–140]. This paradigm has offered an efficient 3D printing of soft robots with stimuli-responsive materials, such as shape memory polymers, liquid crystalline elastomers, ionic polymers, gels, and hydrogels [1,4,107,141,142]. To utilise such 4D-printed soft robots in practical applications, they are designed in bistable and multi-stable mechanisms that are driven based on passive sensing [143–147]. For example, the transition of a gripper from an open to a closed stable state occurs by applying a minimum excitation force to the system in the right direction (Fig. 3(f)) [125,148]. The strain energy in such soft bistable mechanisms is released upon the contact with the excitation force. The total sensing and actuation time of the sensor-less mechanism for grasping an unknown object is reported to be reasonably acceptable compared to sensory feedback. The sensitivity and snap-through energy of the soft gripper could be tuned by controlling the bistable properties for sensor-less dynamic grasping [125]. A shape-reconfigurable structure is also developed by the 3D printing of a bistable mechanism with shape memory strips. This 3D-printed soft mechanism exhibits expansion and contraction in response to surrounding temperature changes. Assembling these mechanisms in series and parallel configurations results in multi-state structures with variable triggers [149]. Rotational multi-stable structures are also 4D-printed by integrating multi-shape memory polymers (SMPs) with a thermal actuation control on the bending angle. By tuning the geometry of SMP beams within the structure, the mechanism could exhibit controlled actuation in response to thermal stimulus without complicated sensor and control systems (Fig. 3(d)) [150].

Another approach that recently attracted attention for sensor-less 4D-printed soft robots is the capacity to be stiffness-tunable, also known as variable stiffness soft actuators via hybrid multi-material 3D printing. Soft robots that are printed by heterogeneous SMPs allow for passive sensing, which adjusts the stiffness of the body in terms of different environmental changes, e.g., temperature. There are several methods that are employed to autonomously adjust material stiffness, including glass transition monitoring, which can be termed as thermal stiffness control, viscosity-based electrical and magnetic field controls, jamming-based pneumatic and fluidic controls, and acoustic-based acoustic field control (Fig. 3(e)) [151–153].

4. Control of 4D-printed soft robots

Closed-loop 4D-printed soft robots can be realised with the integration of 3D-printed sensors and actuators as well as a controller that can be either embedded into the structure or externally employed. The controller incorporates offline learnt control policies based on a data-driven/ML model of a soft robot. It accomplishes the task of the robot through feedback information supplied by 3D-printed soft sensors through interactions with uncertain environments.

Despite substantial progress in the development of 4D-printed soft robots in terms of material aspects, the accurate control of these robots in different scenarios remains a problematic task because conventional static control methods are not viable solutions. Soft robots are typically characterised by non-linear dynamics because of viscoelastic properties, high number of degrees of freedom, and time-varying physical and chemical properties of actuation bodies, and heterogeneous stiffness of materials and their surroundings, thus making their modelling and control difficult [177]. These have motivated researchers to consider data-driven modelling and control, which can be adopted to realise 4D-printed autonomous soft robots [178,179].

The control methods employed for soft robots thus far can be divided into two major categories: static and dynamic controllers [19]. Static controllers are mainly designed based on constant curvature model [180], beam theory [181], and Cosserat rod theory [182] methods. The progress of these controllers in real-world applications of soft robots, however, is limited because of their high computational cost, and steady-state assumptions [183]. Hybrid compliance/force controllers without force sensors are also developed under the static controller category to handle the coupling effects between the kinematic and static force models of soft robots [184,185]. There have been some unresolved inaccuracies and model deviations that originate from friction, hysteresis, and nonlinear material properties of soft robots. The results do not show significant improvement even with the incorporation of model-free intelligent static controllers, such as Elman neural network [186] and fuzzy logic [187], because of the lack of dynamic coupling effects of soft robots in such controllers. Dynamic controllers, on the other hand, are developed to deal with the multi-dimensional and nonlinear dynamics of soft robots in unstructured and uncertain environments [19]. These controllers require an accurate formulation of the dynamics of soft robots as well as proprioceptive feedback information. In early studies on the implementation of dynamic controllers in soft robots, a conventional hybrid proportional derivative (PD)-computed torque controller [188,189] is developed. Its robustness is low because of model uncertainties compared to later developed sliding mode [190] and model predictive controllers (MPCs) [23]. Sliding mode controllers, however, are mainly implemented for the bending control of soft robots based on the Euler–Lagrangian lumped dynamic parameters only on a planar actuation [24,191,192]. The MPCs are also reported to be incapable of running at a high control cycle in complex dynamic models [23,26]. Directly learning the closed-loop control policies from real-world platforms is also suggested to solve model uncertainties; however, the approach is time-intensive and highly probable to be trapped in the local optima [5,27]. Simply put, this method is unable to fully account for fast morphological changes in soft robot dynamics [193].

Data-driven/ML model-based control strategies can be effective in terms of time and energy-efficient trajectory tracking of soft robots. A dynamic closed-loop control strategy, however, is more preferable for enabling the accurate and robust response of 4D-printed soft robots to changing environments or external disturbances. Moreover, the integration of 3D-printed sensors into soft robots requires the implementation of a feedback mechanism. The combination of a data-driven/ML model and a dynamic policy learning controller is therefore necessary to exploit the previous knowledge of the system and track the desired trajectory, respectively (Fig. 4) [19,194].

A typical problem with data-driven/ML algorithms, however, is that they are highly domain-specific, that is, with small changes in the domain, the learnt model could become ineffective [193]. To gain control of such systems, large data are necessary for training the control algorithm. Acquiring training samples from real-world soft robots can be difficult, especially for soft robots with multi-dimensional control states and time-variable properties, and exposed to uncertain environmental disturbances [22,195]. To minimise the repetitious exploratory actions for constructing a data-driven/ML model, the FEM can be used in the offline loop of the control learning algorithms to explore various possible scenarios [196,197], such as variable material properties and environments. It should be noted that the reliability of simulations based on FEM results in the learning control of 4D-printed soft robots could be enhanced by the integration of 3D-printed embedded sensors and proprioceptive feedback information [22,195,198,199]. Additive manufacturing-based topology optimisation (TO) is another tool that is undergoing developments and can be employed to assist in the efficient modelling of 4D-printed soft robots in combination with the FEM [200]. Studies on the multi-material TO of 3D-printed soft grippers

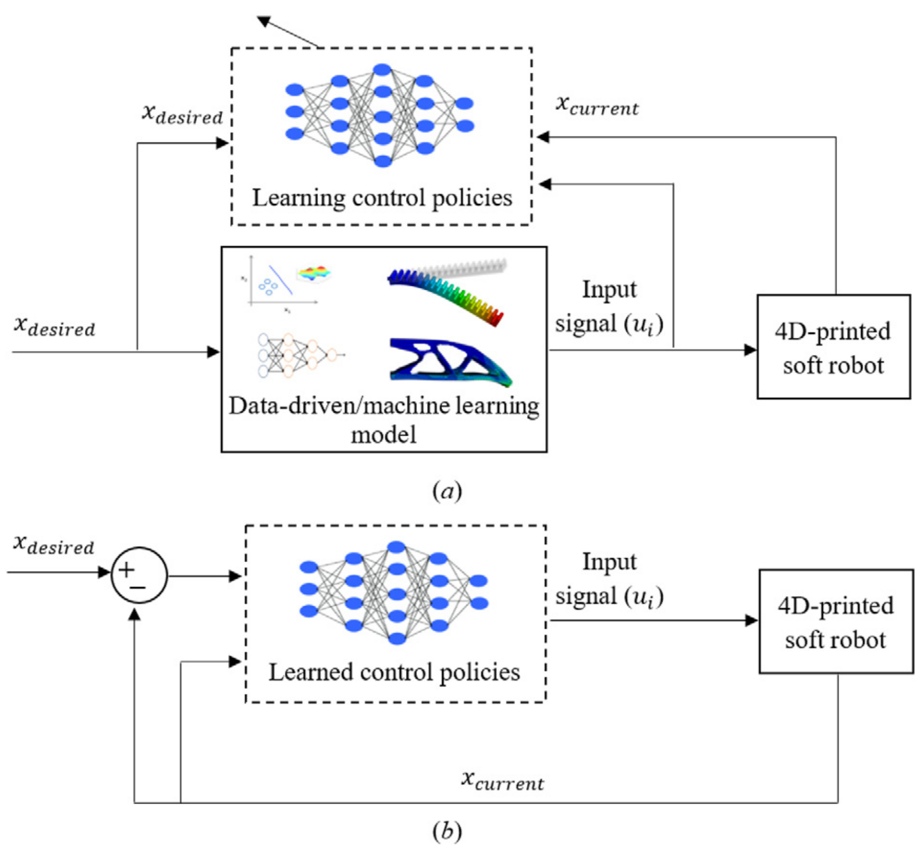

Fig. 4. Closed-loop control diagrams in 4D-printed soft robots: (a) training of closed-loop control policies based on data-driven/ML model; (b) decision-making and calculation of online commands based on learnt control policy.

have demonstrated performance improvements in terms of maximum bending deflection [201–203]. Topology optimisation can be used for modifying the performance of 4D-printed soft robots in two aspects. The TO can be employed to aid in 3D printing aspects, such as material anisotropy [204], self-support design [205,206], and porous infill design [207]. It can also aid in determining the appropriate configuration of sensors and actuators for optimal sensing and control perspectives [208]. The use of TO method in conjunction with the extended FEM that is employed in 4D-printed soft structures to target the preferred displacement upon stimulus change has shown promising results [209,210] [211].

Reinforcement learning is a self-learning control algorithm based on existing data. The algorithm is also capable predicting new possible data by adapting the earlier patterns through various layers of neural network algorithms [213,214]. To achieve closed-loop 4D-printed soft robots, a reinforcement learning control algorithm can be employed to extract the desired information of environment properties from embedded printed sensors and optimise the control algorithm through the interaction with environment [215–219]. Reinforcement learning control in 4D-printed soft robots can be implemented as a model-based learning controller [220,221] in which supervised learning algorithms are used to calculate optimal feedback command based on minimising a cost function [222,223]. On the other hand, there is a model-free approach that does not require learning a model to predict the optimal actions [224]. The control rules of soft robots can also be optimized through model-free approaches, such as Q learning, where a predefined model is not required [5,195,225–227]. Although the latter method has the advantage of predicting the behaviour of soft robots in different environmental scenarios without requiring modelling, the former method can be implemented with the aid of experimental data and FEM. A model-based closed-loop controller for a 4D-printed soft robot can be implemented in three steps:

1- Forward dynamics can be obtained through data-driven/ML methods, recurrent neural network, or convolutional neural network [228].
2- The learnt forward dynamics model is utilised in conjunction with optimisation algorithms to generate the trajectories of soft robots [27,229]. To ensure a satisfactory exploration of the soft robot's end-effector in state space, multiple trajectories can be formulated to achieve the same task. The trajectories provide required samples for attaining optimal control policy and action to drive the soft robot's body to the desired state. The real environment or simulation models aids in the exploration of multiple solutions to the trajectory optimisation problem. This results in the generation of sufficient samples for the unbiased training of the controller.
3- Having obtained all new trajectories, optimal dynamic closed-loop control policies can be directly learnt by the states of the robot through a supervised learning model without an exhaustive search in the state space [27].

The suggested approach for closed-loop 4D-printed soft robots has been found to require approximately 2 h of real-world data to develop a data-driven model-based closed-loop controller [27]. Recently, there have been relatively few studies that utilise variously supervised and unsupervised ML methods to improve the learning procedure of reinforcement learning algorithms and optimally control soft robots to adapt to uncertain environments [230–238]. Further exploration, however, is necessary to implement both methods in diverse environments and determine the most appropriate approach with the least computational burden for closed-loop 4D-printed soft robots.

5. Discussions and future perspectives

The rapid advancements in control learning algorithms and the accessibility of 3D-printed sensors and actuators have provided a platform to develop customised soft structures with high self-driven capabilities in terms of managing delicate tasks in fragile environments. The possibilities and processes to realise closed-loop 4D-printed soft robots, including integrated 3D-printed soft sensors and actuators controlled by feedback control algorithms, are discussed in this paper. It is observed that 3D-printed sensors have evolved to an extent that they could be printed in spatial layers of soft robots for measuring a variety of physical and chemical proprioceptive feedback information. Different types of 3D-printed sensors and their specific applications to closed-loop 4D-printed soft robots are categorised and introduced.

The integration of 3D-printed sensors and actuators reveal that unlike their metallic counterparts, most of the current 3D-printed soft materials that utilise embedded sensors are susceptible to viscoelasticity as well as hysteresis and consequently exhibit nonlinear characteristics. Through the incorporation of ML techniques in the control loop, however, the foregoing deficiencies can be compensated.

To evaluate the novelty and possibility of developing closed-loop 4D-printed soft robots, some recent studies on soft robots that include at least two of the four mainly required components are presented herein, as listed in Table 3. Interestingly, there has not been a closed-loop 4D-printed soft robot that contains all of the four components thus far. There have been some initial studies, however, that incorporate the ML into the closed-loop control strategy of these soft robots without considering the FEM and TO in the design stage [126,127]. There are also certain works related to the application of data-driven/ML closed-loop control of 3D-printed soft actuators that do not consider 3D-printed sensor and FEM analysis [125]. Furthermore, a considerable cohort of sensorless 4D-printed soft robots designed and developed as bistable or multi-stable mechanisms that could benefit from closed-loop controller algorithms for autonomous tasks are identified. Although the FEM and TO have been reported in a few cases [125,148,151–153], these have not been applied to closed-loop 4D-printed soft robots for autonomous operation in a broader dynamic environment. Some investigations related to the integration of 3D-printed sensors and actuators to achieve the closed-loop control of 3D-printed soft robots have been performed [9,34,67,128,132–134]. The use of FEM and closed-loop control, however, has not been considered in any of these studies. A large group of current 3D-printed fluidic and pneumatic soft robots is

Table 3
4D-printed soft robots and compositions.

Type	3D-printed sensor	3D-printed actuator	Closed-loop control	FEM & TO	Refs.
Closed-loop 4D-printed soft robots	✓	✓	✓		[126]
	✓	✓	✓		[127]
4D-printed soft robots	✓	✓		✓	[148]
	✓	✓		✓	[125]
	✓	✓		✓	[151]
	✓	✓		✓	[152]
	✓	✓		✓	[153]
	✓	✓		✓	[150]
Data-driven/machine learning control of 3D-printed soft actuators		✓	✓		[125]
Integrated 3D-printed soft sensors and actuators	✓	✓			[34]
	✓	✓			[128]
	✓	✓			[9]
	✓	✓			[133]
	✓	✓			[134]
	✓	✓			[67]
	✓	✓			[132]
FEM and topology optimized 3D-printed soft actuators		✓		✓	[239]
		✓		✓	[155]
		✓		✓	[240]
		✓		✓	[241]
		✓		✓	[156]
		✓		✓	[212]
		✓		✓	[208]

analysed and developed using FEM and TO tools (Fig. 5) [155,156,212,239–241]. These robots, however, still lack 3D-printed sensors for developing accurate and closed-loop control to deal with a variety of tasks in unstructured environments.

Generative design capabilities, including the most advanced simulation options, such as stress, heat, vibrations, and computational fluid dynamics which have recently been included in FEM platforms, have made the collection process of training data based on diverse environmental interactions in simulation more prevalent [242]. Several advanced methods have been reported to create a virtual environment in simulations to reflect variable environmental factors [243,244]. More software contributions to the simulation and control of soft robots with various sizes, shapes, and materials should be made to accelerate the real-world application of 4D-printed soft robots [245–247].

Imitating the biomimetic motions of bio-inspired soft actuators can be further investigated, and the incorporation of ML and imitation learning [248] techniques to develop the autonomous control policies of 4D-printed soft robots with less computational and experimental expense can be explored. The development of 4D-printed amphibian soft robots that can work autonomously in different mediums is an interesting future area of research. Such mechanisms require specific materials for the 3D printing of sensors and actuators that can function in diverse mediums, such as liquid and air. Moreover, such 4D-printed amphibian soft robots could be modelled with multiple operating conditions and data-driven/ML models with optimal controllers that can be switched based on different operating scenarios, including temperature or stiffness in different mediums [193]. The 4D-printed paper-based soft robots that include sensing and actuation components [132] is another area that can employ closed-loop control and FEM for more autonomous behaviour.

The incorporation of 3D-printed variable stiffness and multi-stable mechanisms to constrain the soft robot's motion can be further investigated to develop sensorless closed-loop 4D-printed soft robots [249].

Although the use of the reinforcement learning algorithm can overcome difficulties in the closed-loop control of 4D-printed robots in uncertain environments, problems related to practical applications in the high-frequency control bandwidth remain. The incorporation of the intrinsic controller of 4D-printed soft robots using the morphological properties of voxels acting as zero-lag feedback controller during printing can broaden the control bandwidth for faster and more robust manipulations. The integration of 3D-printed sensors and actuators can add further flexibility to the application of sparse sensing and uncertainty quantification by optimising the locations of sensors and actuators that significantly impact controller performance. The incorporation of the morphological computation of materials into the controller account with the optimal placement of sensors and actuators is crucial to closed-loop 4D printing.

The miniaturisation of closed-loop 4D-printed soft robots is highly preferred. Scaling down soft robots from centimetre to millimetre with micrometre-sized features and functionalities for practical applications in the manipulation of microscale delicate objects (e.g., cells) in confined and sensitive areas is in high demand. The fabrication process of closed-loop 4D-printed soft robots is scalable in all the key components of soft robots, such as sensors, actuators, flexible electronics, and controllers. In scaling down these soft robots, however, the strategy relies more on the morphological aspects of stimuli-responsive soft materials to incorporate sensing and actuation in material units rather than conventional components [123,166,250]. In this sense, the miniaturisation of printed sensors and actuators is merely constrained by the resolution of 3D printers and 3D printing techniques (including inkjet, extrusion, or digital light processing (DLP) printers) and solidification ((through melt-processing, solvent-processing, or photopolymerisation). It remains problematic, however, to fabricate soft robots at a millimetre-scale because of the difficulty in making microscale voids and channels [251].

6. Conclusion

In recent years, soft sensors and actuators have increasingly impacted soft robotics and human–machine interfaces. Equipped with the incorporation of machine learning, now is indeed the appropriate time for planning the strategic integration of the foregoing technologies through 3D printing to realise closed-loop 4D-printed soft robots. This review article explores the development of closed-loop 4D-printed soft robots considering the advancements in the 3D printing of soft sensors and actuators and the incorporation of a data-driven/machine learning model and closed-loop controller. Four key components are accordingly selected to define closed-loop 4D-printed soft robots: 3D-

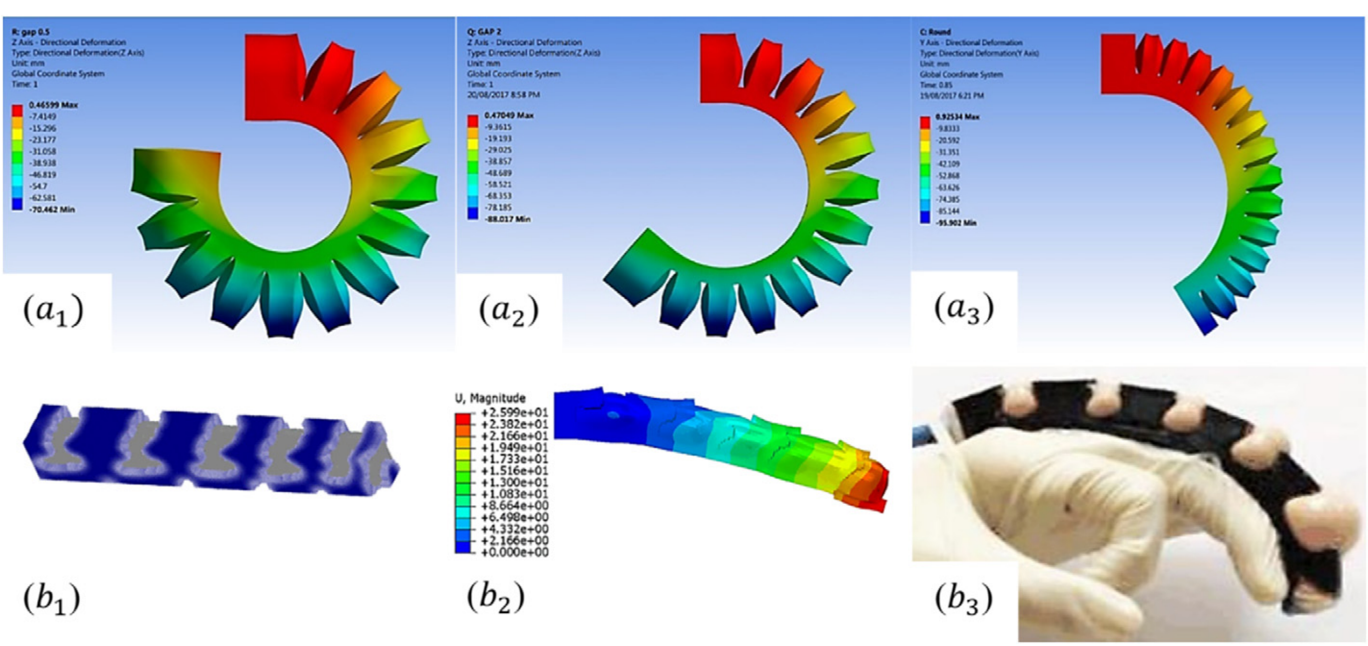

Fig. 5. FEM and TO applications in data-driven modelling of 4D-printed soft robots. $(a_1)-(a_3)$ Different modelling results of soft robotic arm with different geometrical parameter changes (reproduced from [156] with permission from MDPI); $(b_1)-(b_3)$ Topology optimisation of multi-material 3D-printed soft robot (reproduced from [212] National University of Singapore Libraries).

printed sensors, 3D-printed actuators, data-driven models, and dynamic feedback controllers. Different types of 3D-printed sensors and their integration with 3D-printed soft actuators are presented. Various techniques for the modelling and control of 4D-printed soft robots are also reviewed. Moreover, simulation and FEM are suggested to aid in training models. Despite existing problems, 4D-printed soft robots are achievable through the integration of 3D-printed soft sensors and actuators with machine learning algorithms and FEM. Integrated 3D-printed actuators and sensors are feasible but limited by the nature of materials utilised. The future of enhancing closed-loop 4D-printed soft robots accordingly relies on integration of suitable materials, machine learning approaches and control algorithms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary

Soft actuator is a device that can safely manipulate fragile substances by producing flexible motion through the integration of microscopic changes at the molecular level into a macroscopic deformation of actuator materials.:

Soft electronics are flexible and stretchable electronic components produced through the inclusion of soft materials.:

Soft robot is a specific type of robot constructed from highly compliant materials with high adaptivity to its surroundings and less control complexity.:

Soft sensor is a device that transforms physical changes imposed on the robot or its environments, such as stresses and strains, to quantifiable signals.:

4D printing is the action or process of using 3D printing techniques to create an object that can predictably change its shape or properties over time as a reaction to conditions, such as exposure to water, air, heat, or electric current.:

Closed-loop 4D printing pertains to the integration of 3D-printed sensors, 3D-printed actuators, and control policies not only to optimise the configuration of responsive materials but also to equip them with feedback information in order to accomplish the functional target over time while interacting with uncertain environments in real-time.: