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4D-PRINTED SOFT PNEUMATIC ACTUATORS GUIDED BY MACHINE LEARNING AND FINITE ELEMENT MODELS

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Abstract

This paper explores the field of four-dimensional 4D-printed soft pneumatic actuators (SPAs) made completely by additive manufacturing. After manufacturing, these actuators can produce bending motions when exposed to vacuum or pressurized air stimuli. Their functionality is determined by a combination of material qualities and geometric details, which gives the pressures and motion trajectories required for fine activities like non-invasive surgery and food handling. This introduces an innovative approach to achieve four-dimensional (4D) printing of soft pneumatic actuator robots (SPAs). This method leverages nonlinear machine learning (ML) techniques combined with finite element modelling (FEM). The core of this methodology involves the development of a precise FEM that emulates experimental actuation. The primary purpose of this FEM is to generate essential training data for the subsequent ML modelling phase. The wide range of 3D printers and materials used to create pressurized air-bending-style SPAs is thoroughly examined in this paper. It also examines different approaches to modelling and regulating these actuators and provides a comparative study. This paper concludes with a summary of general considerations regarding future directions and the inherent difficulties in developing these state-of-the-art actuators

Keywords: *Soft pneumatic actuators, 3D printing, Machine Learning, Finite element models, 4D Printing, Soft robots.*

1. Introduction

Robotics has been linked to rigidity and precision. Nevertheless, a new level of flexibility and adaptability has been made possible by recent technical advancements in soft robotics, which was previously impossible with rigid robot designs. The development of three-dimensional (3D) printing technology and its subsequent advancement into four-dimensional (4D) printing within the field of soft robotics have made this paradigm shift conceivable. Regarding 4D printing, the fourth dimension is the printed mechanisms' response to different stimuli like heat, electricity, magnetism, and pneumatic pressure over time.

This work focuses on 4D-printed soft pneumatic actuators (SPAs), including bellows attached to finger-like structures. These actuators expand under pressure, which results in bending and extension. They have some advantages over their rigid equivalents, including being more affordable, lightweight, easily manufactured, flexible, adaptive, and malleable. Furthermore, their softness and flexibility minimize the possible effects on human skin or sensitive objects and surfaces. These qualities make them appropriate for creating wrist and finger exoskeletons for joint movement aids and soft surgical manipulators in closed-loop systems. It is possible to create soft robots and actuators with complex internal structures using 3D/4D printing technology. Ninja Flex is a good option among the materials examined because it can be 3D printed without creating air bubbles, and its hyperelastic qualities give it the required flexibility and sensitivity to applied stress.

Pneumatic actuators, which operate using air instead of hydraulics, are simpler, cleaner, and more compliant because of their reduced density and viscosity. Their use in situations where the working fluid must move quickly via small lumens is made possible by this property. Because these actuators are easily produced by utilizing elastomeric materials, they are especially well suited for 4D printing. When exposed to simple pressurized air input, the 3D/4D-printed SPAs perform complex movements such as bending, rotating, twisting, jumping, rolling, and combinations, all controllable.[1]

Accurately modelling and forecasting the motion of soft robots and actuators using 4D printing presents a significant difficulty because of the nonlinear nature of the materials used. The actuation behaviour of 4D printed actuators is often not well predicted by linear analytical models; hence, nonlinear material principles must be included in numerical simulations to improve accuracy. Using machine learning (ML) algorithms trained on numerical findings presents a promising way

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to expedite the design process and save significant time and effort.

Soft pneumatic actuators (SPAs) were first created for their passive compliance and were considered appropriate for handling delicate objects with different textures and shapes, even without expensive sensors and controllers. Pick-and-place tasks have proven difficult to execute without feedback information, especially on soft objects with different shapes and orientations. Therefore, improving SPAs with sensing capabilities would increase their applicability to a larger range of difficult manipulation tasks and allow for control that is more precise. Flexible electronic connections and integrated sensors are crucial to controlling 3D/4D printed spas. These elements support decision-making by offering crucial feedback data while maintaining compliance and soft manipulator body shape. Including a wide range of chemical and biological sensors improves the precision and subtlety of the operations that may be performed using SPAs even more [2].

4D printing – It is the process, when taken out of a 3D printer, changes shape. These items are self-assembled because of the material's chemical reaction when subjected to heat, air, water, etc. A well-programmed design, smart material, and a 3D printer work together to create 4D printing. Variations in the environment are used in 4D printing to build different metamaterial structures. In contrast to 3D printing, 4D printing has several advantages, including the ability to produce smart and multi-materials quickly, create more flexible and deformable structures, and expand on the possible uses for both 3D and 4D printing.

Machine Learning - Using data and algorithms to simulate human learning processes and improve their accuracy over time is the core of machine learning, a subdomain of computer science and artificial intelligence (AI). This field is essential for Statistical techniques used to train machine-learning algorithms so they can produce predictions, classifications, and important insights during data mining processes. These insights perfectly guide Critical growth indicators, significantly influencing decision-making processes across various applications and businesses. Here are a few instances of machine learning that you might encounter daily: Speech recognition, computer vision, automated stock trading, Fraud detection, etc.[3].

Machine learning using ANN - A machine learning technique called neural networks is organized as directed graphs. Like biological neurons, these networks comprise interconnected nodes connected by arcs that symbolize dendrites and synapses. Every arc has a distinct weight, and each node modifies the incoming arc values by applying an activation function based on the matching arc weights.[4]

Neural networks are a potent machine learning technique inspired by the complex network of neurons that make up the human brain. Like the brain's millions of neurons, which process and send chemical and electrical signals, artificial neural networks use various synthetic neurons to do intricate tasks. These artificial neurons imitate the communication channels of their biological counterparts by connecting via synapses.

Finite element models - By breaking the issue area up into smaller, more manageable components, the Finite Element Method (FEM) simplifies and approaches complicated problems. These elements are usually triangles in two-dimensional applications and tetrahedral in three-dimensional geometries. Using linear or quadratic equations, the FEM reduces the complex field solution inside each element. These equations are then simultaneously solved for the entire system. To successfully capture the field distribution in Magnetic Induction Tomography (MIT), precise modelling of the sensor geometry, the material properties of the item under examination, and the surrounding environment are essential, especially if the sensor array is not isolated.

FEM has many benefits, such as being widely accessible through academic and commercial software packages and having the capacity to represent different problem geometries with a physically accurate representation. The computational needs of FEM, however, can be high and frequently result in a trade-off between computational speed and accuracy. Mesh convergence studies can be used to estimate how many elements the finite element mesh needs to achieve an acceptable level of accuracy; these investigations evaluate meshes with different sizes and distributions. It can be difficult to balance accuracy and computational efficiency when mesh size increases because it directly affects computation time.

Soft robots - Soft robotics is a cutting-edge field in creating robots with flexible bodies instead of conventional rigid-bodied robots. Unlike their stiff counterparts constructed of metals, ceramics, or hard plastics, this method allows soft robots to adapt and interact safely near humans. By building robots with flexible bodies and circuitry, soft robotics developers hope to emulate the adaptability of biological things. For delicate manipulation tasks, this flexibility can be localized to specific sections of the robot, such as end effectors, or applied throughout the entire robot. Because of their intrinsic stiffness, rigid-bodied robotic arms are dangerous in human-robot interactions even though they are accurate and dependable. This problem is tackled by soft robotics, which uses flexible materials that can absorb shocks and flex without breaking. [5]

Soft robotics brings a paradigm shift in robotic design, prioritizing compliance and adaptability above rigid structures. Soft robots may now accomplish tasks that would be difficult or impossible for regular robots because of this technique. For example, soft-end effectors may precisely manage delicate or oddly shaped objects without inflicting harm. Soft parts, such as shock-absorbing footpads or springy joints, are frequently incorporated into rigid-body robots to improve their durability and performance. Robots that are primarily or exclusively made of. These robots have a lot of potential because of their natural adaptability and versatility. They are crucial for disaster relief efforts because they can manoeuvre through tight areas that rigid robots cannot. Imagine a soft robot squeezing through small openings or crawling over debris to get to stranded survivors. These robots might help with rescue operations, deliver essential supplies, and serve as communication links. Additionally, soft robots have potential for use in medicine. Their delicate touch and capacity to fit into intricate geometries could transform focused medication delivery, minimally invasive surgery, and even artificial organs. The possibilities are virtually limitless as soft robotics advances and blur the lines between machines and living things. [6]

Soft pneumatic actuators are systems that enable flexibility and adaptation. Soft pneumatic actuators (SPAs) are known for their benefits, but there have not been many thorough approaches to modelling and building them. It is challenging to characterize and anticipate the behavior of soft actuators due to the intricate interplay between the nonlinear properties of the materials they are comprised of and the broad range of motions they can produce to overcome this difficulty, this research uses new design ideas and mathematical techniques to improve soft actuator performance over earlier models.

The FEM tool offers a strong foundation for comprehending and forecasting soft actuator behaviour in a range of scenarios. The tool creates intricate actuator deformation and motion models by combining material properties, actuator geometry, and external forces. This makes it possible for researchers to optimize actuator design purposes, such as minimizing energy usage, maximizing force production, or obtaining specified bending angles. The creation of this FEM tool offers a much-needed framework for the design and analysis of soft actuators, which represents a substantial advancement in the field of soft robotics. By using this technology, researchers can fully realize the potential of soft actuators, which will enable the development of more advanced and adaptable soft robots for a variety of use [7].

2. Literature work

Modelling Soft Pneumatic Actuators (SPAs) of the Bending Type for 3D/4D Printing. The corrugated design of a multi-chambered soft pneumatic actuator (SPA) is analyzed experimentally to observe the radial, longitudinal, and lateral expansions of different chambers, i.e., ballooning of the chambers under air pressure. An analytical model is developed to determine the bending of the SPA at different pneumatic pressures. Bending-type SPAs are primarily designed in two ways: Tubular Fiber-Reinforced Actuators: These actuators use pressure differentials within one or more fiber-reinforced chambers to achieve bending. The pressure differential between the chambers determines the direction of bending.[7]

Bellow-type SPAs: These actuators use asymmetrically shaped air chambers. Whereas the upper layer can be extended, the lower layer cannot. According to [7], this design translates pressure changes into bending towards the side with higher bending stiffness. Compared to tubular designs, the enclosed chambers improve dependability at high pressure by shielding the walls from excessive deformation. Bellow-type SPAs have benefits that make them especially suitable for 4D printing

i. Quick Motions: The bellows can be actuated more quickly by unfolding quickly.
ii. Decreased Radial Expansion: Decreased radial expansion improves durability and reduces the chance of failure.
iii. Lower Pressure for Bending: Compared to tubular designs, full bending can be accomplished at a lower pressure.
iv. Greater Speeds: Bellows may reach greater actuation speeds.

3. Modelling

3.1 Geometrical parameters effects on the bending angle of soft pneumatic actuators

The bellows design of a soft pneumatic actuator is a critical factor in determining its bending ability, independent of material qualities. This is especially useful for 3D/4D printing since it allows the creation of complex bellow shapes that may perform better than conventional designs. The 3D model ofthe pneumatic finger is shown in Figure 1.

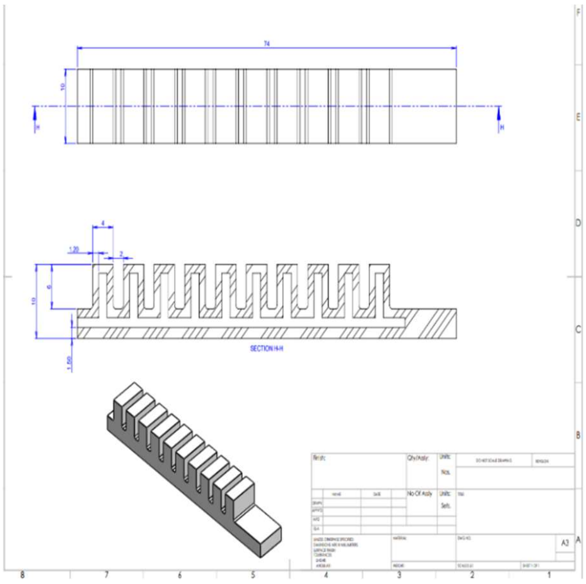

Figure 1 3D model of pneumatic finger

Studies have looked into how different bellow geometries affect deflection [9]. According to studies, U-shaped bellows, as opposed to elliptical, rectangular, crimped-plate, S-shaped, and triangular designs, obtain the largest bending angles under pressure. Corresponding to this, studies on 3D-printed chambers have shown that R-shaped designs flex better than B and D-shaped designs. Pressure levels and the direction of airflow are thought to have an impact on how effective these shapes are. Rectangular shaped design shows the maximum bending angle than the other shapes.[8]

The researcher looked at various 3D-printed chamber forms by expanding upon earlier research on U-shaped bellows. Their testing showed that the R-shaped design produced the best bending performance compared to the B and D-shaped designs. It's interesting to note that at low pressures (0–3 bar), the bending angles of the R and S-type chambers were equal, but at higher pressures (>4 bar), the D-type design performed better than the B-type. These differences in bending angles were explained by the researchers as a result of the chamber walls' alignment with the direction of the airflow. Additionally, the bellow chamber's cross-sectional geometry has an impact on deflection. According to their research, there appears to be a hierarchy of effectiveness: circular shapes were the least effective, whereas honeycomb, rectangular, and semi-circular patterns demonstrated comparable deflection.

Dilibal, Sahin, and Celik (2018) investigated the effect of asymmetry on the bending behaviour of 3D/4D-printed Soft Pneumatic Actuators (SPAs) in a study. According to their research, a tapered design, akin to an elephant trunk that progressively tapers towards the tip, produced a larger bending angle than non-tapered versions. Additionally, Auysakul et al. (2020) looked into bellow-type 3D/4D-printed SPAs and the optimisation of chamber height. They found that the appropriate degree of deflection and tip force could be maintained by varying the chamber's height while also optimising material consumption.

Finite Element (FE) non-linear simulations were used to investigate the bending effects of SPAs at different cross-section ratios. It was found that a drop in the cross-section ratio resulted in a considerable reduction in the bending angle, but an increase in the ratio led to a larger bending angle. This realisation implies that the best curvature for gripping various items can be obtained by optimising the cross-section ratio throughout the same length. Furthermore, Sun et al. (2019) employed a genetic algorithm (GA) optimisation technique to determine the best actuator design for the gripping task. They suggested adjusting the SPA's design parameters to follow the intended trajectory by combining FE and analytical modelling.

3.2 3D Printing Technology and Its Materials

Soft pneumatic robots and actuators, primarily made of silicone elastomers through moulding and casting techniques, have been the subject of extensive research and development. However, these techniques have several drawbacks, such as labour-intensive post-processing, low design flexibility, and inconsistent bespoke manufacturing, especially when it comes to intricately carved elements. Soft actuators' intricate structural makeup adds complexity and lengthens fabrication times.[9]

However, the development of additive manufacturing has shown promise in overcoming these obstacles, providing a workable method for producing sophisticated soft pneumatic actuators and robots with improved repeatability and resolution. More specifically, under some circumstances, 3D printing technologies have made it possible to produce thermoplastic and elastomeric materials. Diverse 3D printing methodologies have been utilised to produce bending-type soft pneumatic actuators, hence promoting progress in the domain.

Table 1 3D printing different technologies with their materials [10]

3D Printing Technology	Pros	Cons	Material
Fused Deposition Modelling (FDM)	* Inexpensive materials and printers * Commercially available filaments	* Limited compatible filament options * Rough surface finish	* Thermoplastic Polyurethane (TPU) - NinjaFlex (NinjaTek, PA) * Silicone
Direct Ink Writing (DIW)	* Flexibility for incorporating fillers and novel materials	* Requires printer modification for two-stage curing materials * Lower resolution	* Silicone (Ecoflex 00-30 A, Dragonskin 30A, Sylgard 184)
Filament Fused Printing (FPP)	* Ability to modify characteristics	* Requires printer modifications	* Styrene-Ethylene-Butylene-Styrene (SEBS) - Kraton G1657
Digital Light Processing (DLP)	* Fast prototyping	* Risk of void formation * Limited print volume	* Tangoplus FLX 930, Rhodamine B EAA, AUD TangoPlus
Stereo lithography (SLA)	* Potential for incorporating fillers * High resolution	* Limited print volume	* Elastomeric precursor (Spot-E resin)
Selective Laser Sintering (SLS)	* High strength	* Difficult purging process * Shape limitations	* Polyurethane-TPU92A-1
Multi Jet Fusion (MJF)	* Fast and high resolution	* Limited material options	* Polyamide 12 (PA12)
PolyJet	* Fast and high resolution	* Poor mechanical properties	* Tango Black, TangoBlack+, VeroWhite, VeroWhite+, Agilus30, AR-G1L, VeroClear

Table 1 shows the different technologies with their advantages and disadvantages and the materials used for different technologies. Plott and Shih conducted a study investigating the creation of high-performance soft pneumatic actuators (SPAs) through Direct Ink Writing (DIW) 3D/4D printing and silicone elastomer cured with moisture. They aimed to design SPAs with good elongation at break, high strength, and few voids. To reduce void formation during the printing of thin-walled silicone SPAs, the study optimised the DIW process parameters. Actuators with good mechanical qualities, including a noteworthy fatigue life of more than 30,000 cycles before failure, were produced due to this optimisation. Although Fused Deposition Modelling (FDM) is a widely used 3D printing method for producing soft pneumatic actuators (SPAs), its materials are restricted. A broader spectrum of thermosetting elastomers should ideally be supported by FDM, allowing for the concurrent printing of various and multi-material actuators. FDM has several benefits over Stereolithography (SLA), Digital Light Processing (DLP), and Selective Laser Sintering (SLS). This makes it an extremely appealing additive manufacturing approach with lower costs, a more reproducible process, and substantially less post-processing requirements. Eco Flex 00-30 (Smooth-On) was extruded for SPA creation using a customised FDM printer in a study by Morrow to investigate these benefits. The performance of these 3D-printed actuators was contrasted with that of conventionally produced actuators that were formed from moulds. For SPAs, Stereolithography Apparatus (SLA) provides an alternate 3D printing method. Compared to FDM, this resin-based technique produces smoother surfaces and greater resolution using photochemical processes. However, SLA has drawbacks, such as a restricted library of compatible materials and slower printing speeds. A digital mask projection SLA technology was used in one of the first attempts at producing entirely 3D-printed spas. The researchers employed a thin layer of Sylgard 184 (PDMS) as a polymerization inhibitor and an elastomeric precursor called Spot-E resin. This actuator had an impressive fatigue life of 9 ± 3 cycles, but its final strain was only 1.40, which was rather low.

A quick and efficient option for creating SPAs is PolyJet printing. This process allows for the quick deposition of materials using several jetting nozzles, allowing for the fabrication of intricate structures with thin walls and excellent resolution. However, compared to FDM or SLS processes, PolyJet actuators frequently have poorer mechanical qualities, and material prices may be greater. In one work, Zhu used PolyJet printing (with the Stratasys Object350 Connex3) to produce a multi-material, four-dimensional SPA that resembled a finger. The inflation chambers' walls were made of a rubber-like material called TangleBlack, which allowed for a claimed wall thickness of just 0.03 mm.

This experiment demonstrated the possibility of PolyJet printing for glossy coatings, variable stiffness qualities, and metamaterial designs. A study investigated the benefits of using a dual-material PolyJet technique to create 3D/4D printed SPAs. This study demonstrated a notable decrease in the "balling effect" (material clumping) encountered with soft materials in single-material printing when comparing single-material printing to dual-material printing. Furthermore, Drotman reported that PolyJet was used to create a three-chambered SPA design that allowed for planar motion and basic bending. Using a different strategy, Wang produced a pre-stressed bellow-type SPA that performed comparably to a vacuum SPA by using PolyJet printing (Objet260 Connex3). This actuator blended VeroBlue (hard) and TangoPlus (rubber-like). The main innovation of this effort was creating a pre-curled, 3D-printed SPA that provides better dexterity for gripping tasks like fruit picking.

Digital Light Processing (DLP) is another resin-based 3D printing technique that uses light sources to build SPAs, much like Stereolithography Apparatus (SLA). However, DLP sets itself apart by concurrently curing all of the layers, giving it an advantage over SLA regarding speed and post-processing. DLP is particularly good at producing high-resolution features during 3D/4D printing of SPAs, reducing the need for additional post-processing operations. However, DLP has certain drawbacks, such as a smaller total printing volume and a limited range of photo-curable silicone elastomers readily available.

A desktop DLP 3D printer was successfully used to build a study's SPA. They used a combination of Rhodamine B and TangoPlus FLX 930 resins. Interestingly, it took less than 30 minutes to finish the printing procedure. Direct Ink Writing (DIW) has become a particularly promising technique for 3D/4D printing of Soft Pneumatic Actuators (SPAs), as Table 1 illustrates. The approach outperforms existing methods like Digital Light Processing (DLP), Selective Laser Sintering (SLS), Stereolithography (SLA), and PolyJet with low voids, controlled variable stiffness, acceptable fatigue qualities, and high strength and elongation at break.

Compared to SPAs made via projection SLA, the Fused Deposition Modelling (FDM) method performs better regarding fatigue durability. Although SLA may not be the best at reaching minimal wall thickness, which limits its potential to achieve higher bending deflection and blocking force, it performs exceptionally well when creating highly accurate 3D/4D-printed SPAs, which makes it ideal for actuators with self-healing characteristics. The Selective Laser Sintering (SLS) SPAs exhibit superior strength; nevertheless, the purging of the chamber at the end of printing is a challenge when creating intricate geometries. Furthermore, the materials employed in SLS may yield and plastically deform under bending because they are thermoplastics rather than elastomers. In comparison to DIW and FDM, PolyJet printing is more expensive but provides glossy surface finishes, functional grading, and multi-material possibilities. Compared to FDM or SLS, it is inferior in terms of mechanical qualities [11]. While digital light processing (DLP) is preferred for highly stretchy, miniaturised 3D/4D-printed micro SPAs, it might not be appropriate for applications with longer life cycles and higher volume requirements.

3.2.1 FBG Sensors Monitor Soft Actuators' Bending Curvature

This paper investigates the measurement of the bending curvature of soft actuators using Fibre Bragg Grating (FBG) sensors. The actuator's curvature is adjusted between 0 and 25 m^{-3}, and the changes in the FBG sensor values that result from these adjustments are examined [1] [3].

Stress-Resistant Wavelength Changes: The polyimide skin of the soft actuator changes curvature as it bends. The FBG sensors' grating properties are changed by this strain variation, which results in a shift in their peak wavelengths. This shift offers a responsive and instantaneous response to form changes in the actuator [8].

Multiple Point Detection Using Various Wavelengths:

The experiment shows that when the curvature grows, so do the peak wavelengths of the two FBG sensors, which are at rest located at 1544.498 nm and 1546.611 nm. For example, the peaks move to 1545.956 nm and 1547.541 nm at the maximum bending state (curvature of 25 m^{-1}). These shifts, which are around 0.93 nm and 1.458 nm for the two sensors, demonstrate how sensitive they are to bending. A sensitive and instantaneous way to track the dynamic shape deformation of soft actuators is via FBG sensors. Multi-point shape sensing can be accomplished using FBG sensors at several wavelengths along a single optical fibre. The connection between the wavelength shift and the soft actuator's curvature changes when the FBGs' curvature goes from 0 m^{-1} to 25 m^{-1}. The corresponding average values for measurements are derived from data collected from six separate studies. Due to varying strain loads caused by bending at different sensing sites, the soft actuator bends at distinct states, which causes variations in the bending curvature recorded from the wavelength shift of the FBG sensors and the interpolation algorithm.

The findings demonstrate that the wavelength shift of the FBG sensors increases nonlinearly with the soft actuator's curvature. This nonlinearity is caused by the extensibility of the smooth silicone material and its variable thickness under different driving loads and contact forces at different bending states [7]. Different strain loads are caused by the deformation of the soft silicone actuator at different sensing locations due to variations in the microstructure's thickness(h). The equation indicates that as the soft actuator's bending curvature grows from 0 m^{-1} to 25 m^{-1}, it shows a nonlinear variation trend. It is possible to compute the wavelength shift of the FBG sensors with accuracy by using polynomial curve fitting. Furthermore, these data can create calibration equations that accurately evaluate the soft actuator's bending curvatures. Figure 2 displays two FBG sensors' wavelength shifts at various bending states.

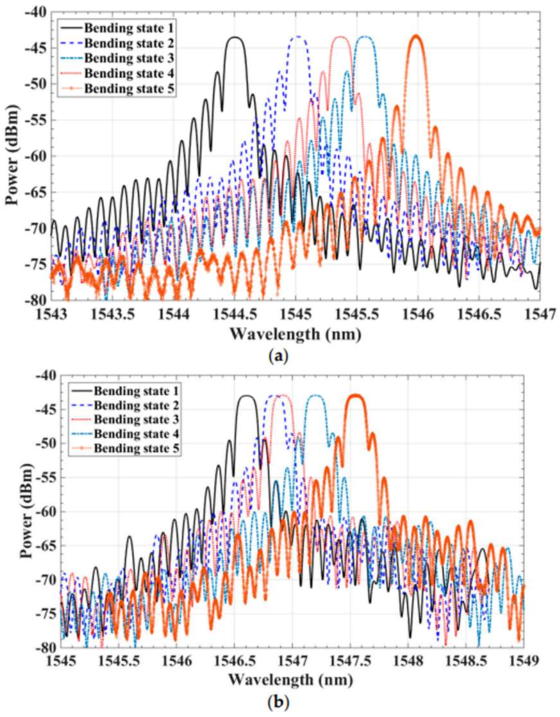

Figure 2 FBG sensors' wavelength shifts at various bending states. (a) FBG 1. (b) FBG 2.[9]

The wavelength shift data was used to calculate the bending curvatures of the two FBG sensors to rebuild the 3D shape of the soft actuator at different bending states. The 3D geometry of the soft actuator was reconstructed using curve fitting methods and interpolation using the data gathered from each sensor site. The picture shows the reconstructed 3D shapes of the soft actuator at various bending states. The figures are numbered 1 to 5. The actuator shapes have been accurately recreated, demonstrating the efficiency of the curve fitting and interpolation approaches.[12] The actuator's shape is reconstructed from the figures, and the spatial resolution is set at about 30 mm based on the density of FBG sensors. This suggests that the technology provides a workable and efficient way to use embedded FBG sensors to reconstruct the soft actuator's 3D shape [13]. Figure 3 illustrates two FBG sensors' wavelength shifts under various curvatures. Figure 4 shows the soft actuator's shape reconstruction at various bending states.

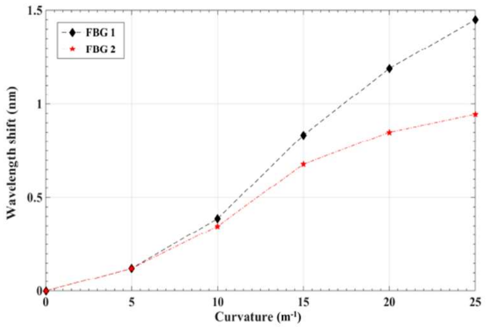

Figure 3 Two FBG sensors' wavelength shifts under various curvature

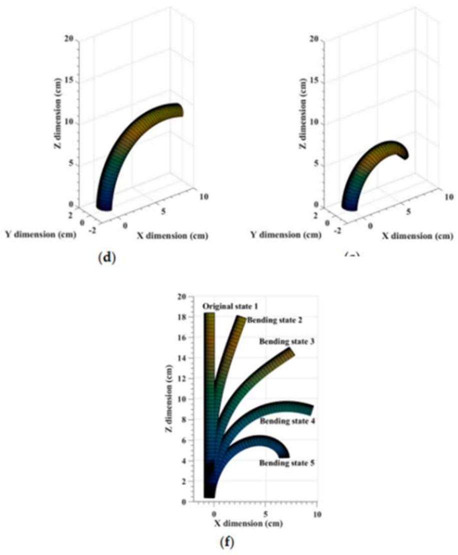

Figure 4 Reconstructing the soft actuator's shape at various bending states. A) Initial condition 1; B) Bending condition 2; C) Bending condition 3; D) Bending condition 4; E) Bending condition 5; F) Bending states 1 through 5.

3.2.2 Soft Robotic Applications of Printable Soft Pneumatic Actuators

Though it is still in its early phases, 4D printing technology has drawn interest from several scientific and industrial fields, including the defence industry. Acknowledging its revolutionary potential, the US Army has partnered with three institutions to investigate the creation of 4D-printed materials for defence and protection purposes. This technique could lead to the development of defence vehicles that are more effective in various climates and terrains by allowing them to change shape in reaction to external changes. Furthermore, the use of 4D-printed materials has the potential to completely transform troop protection by allowing the creation of uniforms that can change form in response to external stimuli, such as sharp objects, to improve protection. 4D-printed materials' capacity to self-assemble offers enormous promise for flexible and quick deployment in conflict areas. Imagine self-assembling buildings or shelters that may establish strategic outposts in difficult areas or offer instant protection.

These developments have the potential to completely transform military infrastructure and logistics by facilitating the quick installation of flexible structures and tools that are suited to the demands of particular missions. Moreover, using 4D printing could create intelligent medical equipment that can react to changes in the body and distribute drugs in a targeted manner or adjust to aid in the healing process. With further research, 4D printing has the potential to revolutionise several industries and usher in a new era of responsive, flexible materials that blend in perfectly with their environment.

3.2.3 High-force soft robotic gripper

Soft robotic systems can adapt to and manage a variety of objects in unstructured situations with minimal control inputs because of their inherent compliance. The creation of compliant and under-actuated grippers with soft pneumatic actuators has been the subject of numerous investigations. Ilievski et al., for example, designed a soft robotic gripper with six starfish-inspired pneumatic actuators. These actuators inflated under pressure and could successfully grip items, including an egg. Likewise, Deimel and Brock presented a cooperative, under-actuated robotic hand that could perform strong gripping tasks and deft manipulation. With the aid of soft pneumatic actuators, their robotic hand could perform various grasping activities outlined in the Feix taxonomy with a level of dexterity similar to that of a human hand. Interestingly, their robotic hand's payload-to-weight ratio was over 300% [4].

Even while earlier soft grippers were quite flexible in grabbing things of different shapes and sizes, they have traditionally been unable to lift large objects, usually weighing no more than 1 kg. This work demonstrates a unique soft gripper that can lift and grab heavy objects. It uses four 3D-printed soft actuators. The gripper achieved a maximum payload-to-weight ratio of 1805% by successfully lifting objects weighing between 1.1 and 5 kg, as seen in Figure 15 and illustrated in

Supplementary Video S1. To our knowledge, the soft gripper created in this work achieves a payload-to-weight ratio higher than soft grippers created in the past using soft pneumatic actuators [14].

3.2.4 Soft robotic exoskeleton for hand and wrist rehabilitation

The creation of wearable soft pneumatic actuators for rehabilitation, specifically for hand and wrist rehabilitation, represents a noteworthy use of soft robotics. Soft pneumatic actuators are well suited for assistive and rehabilitative robotics, as demonstrated by earlier research, which helps to improve and restore patient movement for motor recovery. Soft pneumatic actuators have more compliance than rigid actuators because they are made of materials whose elastic moduli are compatible with human tissues. This adherence considerably lowers the wearer's risk of discomfort and harm. Our investigation aimed to show how well our 3D-printed actuators work in this application. We incorporated dual-channel actuators into a customised wrist brace and single-channel actuators into a customised glove. The actuators interfaced with the fingers and wrist using these wearable devices. The single-channel actuators were positioned at the dorsal side of the fingers to aid in finger flexion and bending action. In the meantime, the radial side of the wrist's dual-channel actuators allowed for bidirectional bending motions that aided in wrist flexion and extension.

A pressure of 200 kPa was used to activate both kinds of actuators. The single-channel actuator's effective operation at the index finger showcases its capacity to produce bending movement and aid in finger flexion. Similarly, the two-channel actuator demonstrated its capacity to accomplish bidirectional bending motions, which helped with wrist flexion and extension.

4. Conclusion

The culmination of this research effort is a model driven by machine learning (ML) and finite element (FE) analysis, capable of precisely estimating the requirements for 4D-printed soft pneumatic actuators (SPAs) to achieve specific bending angles. This process began with the creation and simulation of a finite element model (FEM) meticulously designed to faithfully replicate experimental outcomes while incorporating a suitable nonlinear hyperelastic model. This study emphasises how ML methods are better suited than linear analytical or regression approaches for solving nonlinear situations. The study successfully generated models predicting bending angle, pressure, and shape. The different levels of influence each variable has on the bending angle were shown by an analysis of variance (ANOVA). Notably, the height was found to be the most important variable, with the thickness of the bottom wall having no bearing. The rectangular form had the largest bending angles for a particular geometry out of the three actuator shapes tested (rectangular, circular, and triangular). The design of the actuator's bellows and its height, width, bottom layer thickness, and applied air pressure were all factors considered in this experiment.

A machine-learning model was painstakingly created and refined using this dataset to predict the bending angle based on particular input parameters. After adjusting its hyperparameters, the classification model distinguished between the three actuator shapes with a remarkable accuracy of 94.3%. The significance of this work lies in its ability to accurately model the behaviour of nonlinear materials and intricate geometries within the realm of 4D printing. The ML model's capacity to precisely predict FEM data validated through experimentation underscores its viability as a robust solution for modelling 4D-printed structures, provided an accurate FEM foundation.

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