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*Original scientific paper*

# MODEL-BASED DESIGN STRATEGY FOR MECHANICALLY INTELLIGENT BUILDING BLOCKS

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A b s t r a c t: Soft robots developed by smart materials and structures present advantages in adaptability and flexibility for tailored functions in complex environment. However, conventional design methodologies, which heavily depend on experimental procedures, present obstacles to rapid and efficient design iterations. Thus, employing model-based design emerges as an effective approach to support the designs of soft actuators. In this study, the building blocks was proposed employed by model-based design strategy to investigate the novel actuation approach in mechanically intelligent morphing structures. The simulation results demonstrate, utilizing model-based strategy is the efficient way to develop building blocks of different morphing structures. Furthermore, the combined effort of various smart materials enables varied adapabilities and flexibilities. In summary, by integrating different modeling approaches, material models, and contact models, it is feasible to efficiently design the inteligient structures based on the tailored building blocks to specific requirements, thereby providing guidance and support for engineering design.

**Key words:** soft actuator; smart material; model-based design; mechanically intelligent; building block

## СТРАТЕГИЈА ЗА ДИЗАЈН ЗАСНОВАН НА МОДЕЛИ НА МЕХАНИЧКИ ИНТЕЛИГЕНТНИ ГРАДБЕНИ БЛОКОВИ

А п с т р а к т: Меките роботи направени од структури со паметни материјали имаат предност во приспособливоста и флексибилноста за извршување функции во сложено опкружување. Сепак, конвенционалните методологии за дизајн, кои во голема мера се темелат на експериментални пробувања, претставуваат пречка за брзи и ефикасни итерации на дизајнот. Дизајн базиран на модели се разви како ефективен пристап за поддршка на иновативен дизајн на меки актуатори. Во ова истражување се предложени градбени блокови со промени на кои нова методологија за дизајн базиран на модели може да придонесе за нова генерација механички интелигентни структури кои ја менуваат формата самостојно. Резултатите од симулацијата покажуваат дека користењето на стратегија заснована на модели е ефикасен начин за развој на градбени блокови со посебни променливи структури. Понатаму, комбинирањето на различни паметни материјали овозможува различни приспособувања и флексибилност. Накратко, со интегрирање на различни пристапи за моделирање, модели на материјали и модели за контакт, се овозможува ефикасно дизајнирање на интелигентни структури врз основа на градбени блокови приспособени на специфични барања.

**Клучни зборови:** мек актуатор; паметен материјал; дизајн базиран на модел; механички интелигентни структури; градбен блок

## 1. INTRODUCTION

Soft robotics exhibit a notable advantage in enhancing flexibility and adaptability, finding extensive utilization in diverse industrial applications [1, 2], from medical to agriculture and offshore. Soft actuators are essential components enabling soft robots to achieve various deformation behaviors, with morphing structures playing a central role in the design and functionality of these actuators. Soft actuators can be categorized into various traditional types, encompassing electrical, pneumatic, particle jamming, and chemical reaction-based actuators. Dielectric elastomers (DE) represent a prominent class of materials primarily employed in electrical actuation, utilizing electrical systems as power sources to induce deformation. These materials find significant application in the construction of self-folding structures [3, 4]. Pneumatic actuators, widely favored for actuation in soft actuators, experience consistent deformation and elongation due to the exertion of air pressure through pneumatic systems [5]. Utilizing pneumatic principles, a technique known as particle jamming actuation has been devised to augment the rigidity of soft robots [6]. Through the removal of air within the enclosed space, a phenomenon of particle interlocking emerges, enabling grippers based on particle jamming to securely grasp a diverse range of objects, spanning from delicate to substantial ones [7]. The chemical reaction actuator, fueled by combustion, finds application primarily in jumping robots and bioinspired designs [8]. However, traditional actuation methods often require additional power systems, which limits their applicability. Smart materials, possessing distinct capabilities, offer novel avenues for advancing the design of adaptable and dynamic soft actuators. These materials can undergo structural or compositional changes in response to various external stimuli such as electricity, magnetic fields, light, heat, or chemical reactions [9, 10].

The evolution of soft actuators frequently necessitates cumbersome and ineffectual experimental investigations. Alternatively, computational simulations offer a more streamlined and potentially superior adjunct to this procedure. Modeling soft actuators poses significant challenges due to their pronounced nonlinear behavior and complex geometries. The finite element method (FEM), a widely utilized technique in nonlinear mechanics modeling, provides an efficient means to address these challenges without relying on explicit analytical frameworks [11]. FEM excels in accommodating substantial deformations and material nonlinearities during deformation processes. Consequently, FEM-based models offer a viable means to predict the performance of soft actuators and evaluate the viability of different designs under varying input conditions, thereby streamlining both cost and development timelines [12]. Besides, as for the actuator actuated by particle jamming, coupling method of finite element method and discrete element method (FEM-DEM) is also an effective method to investigate the interaction behaviors between the granular materials and flexible boundary [13]. In the coupling method, FEM serves as a precise tool for characterizing the deformations occurring within the chamber under external loads. Furthermore, the discrete element method (DEM) proves invaluable in modeling particle interactions within granular materials, particularly when dealing with a limited quantity of particles. Notably, DEM offers a computationally efficient alternative to traditional FEM approaches, making it particularly advantageous in scenarios where computational resources are constrained [14]. However, the prevailing focus of contemporary soft robot designs predominantly serves industries such as agriculture, logistics, and food processing. However, there exists a noticeable scarcity of designs tailored specifically for deployment in marine, offshore, and port engineering.

In this study, we developed a model-based design strategy using smart material structures to create mechanically intelligent building blocks for soft robotics. The key contributions are as follows: First, we demonstrated the effectiveness of the model-based approach for designing smart actuators. Second, we introduced the concept of building blocks to establish mechanically intelligent morphing structures for soft robotics. Third, we constructed numerical models, including FEM and coupled FEM-DEM models, to capture the nonlinear behavior of smart materials and the interactions between particles and soft bodies, verifying the feasibility of the proposed design strategy. Finally, this approach was successfully applied in various scenarios, such as underwater pipe manipulation, windmill blade installation, and seabed pipe maintenance.

## 2. DESIGN PROCESS

Model-based design offers a highly efficient and optimized approach in engineering, emphasizing the creation of an optimal design plan based on specific requirements. Unlike traditional methods that rely on physical prototypes, model-based design utilizes numerical models and simulation techniques for iterative improvements, resulting in resource savings and optimized structural designs. The basic design process is shown in Figure 1. In the initial phase, selecting the appropriate smart materials is critical, as they form the foundation for actuation. Once this is determined, the "building blocks" are created. These building blocks are fundamental units of mechanical intelligence, designed by integrating the chosen smart materials, geometric configurations, and external stimuli.

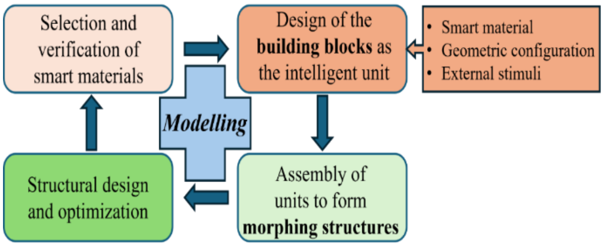


**Fig. 1.** The design process of the model-based design strategy

Using the modular concept of these building blocks, various configurations can then be assembled to achieve specific deformation behaviors, which are referred to as morphing structures. Furthermore, structural designs for specific applications are created by combining different building blocks. After optimization, different smart materials can be integrated to enhance the actuator's performance. Throughout all stages of this process, numerical modeling is the main approach in guiding the design.

## 3. METHODOLOGY

The model-based design approach is fundamental for developing the building blocks. The modelling flowchart, illustrated in Figure 2, begins with defining design requirements based on application scenarios, such as scale, environmental conditions, and boundary constraints. From these requirements, spatial and temporal domains are established.

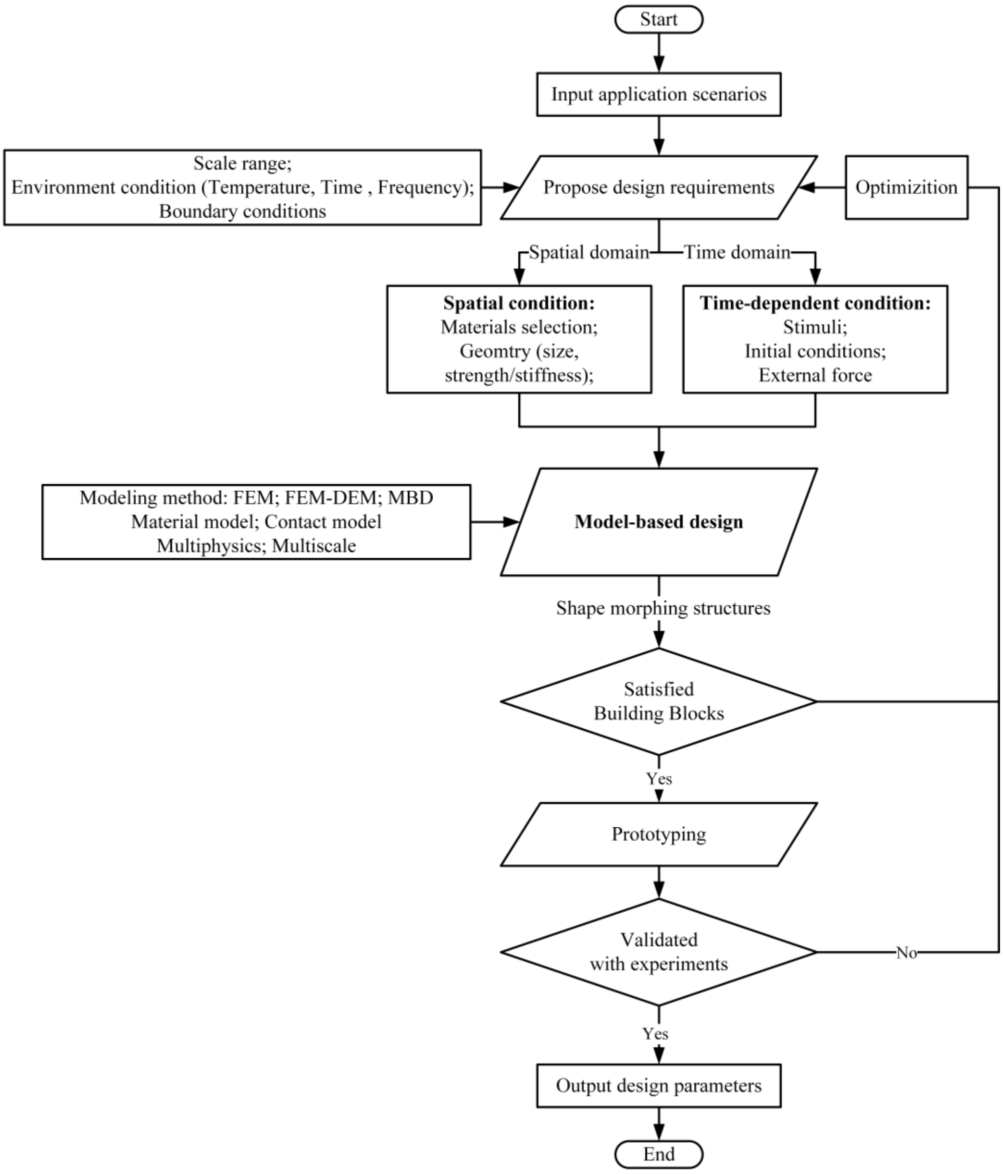


**Fig. 2.** The design process of the model based design

Spatial conditions include smart materials and structural geometries, while time-dependent factors involve environmental stimuli, initial conditions, and external loads. These inputs are incorporated into the model-based design framework. In the model-based design step, various numerical methods, such as FEM, DEM, multibody dynamics (MBD), and coupling techniques, are then employed for simulations across multiple scales. The simulation results inform the analysis of different design configurations, which are further refined through optimization. The final design is realized through fabrication and experimental validation. In general, numerical modeling, particularly for capturing the nonlinear properties of materials, is a critical aspect of this process, with commonly used methods also discussed in this section.

*FEM model*

FEM is commonly used in the structure and non-linear mechanics behavior analysis. In our study, we used FEM as the basis for smart materials, including temperature-sensitive hydrogel and shape memory polymers. Also, the hyperelastic properties of nonlinear materials are analyzed by FEM in the membrane configuration.

First, in our study, the thermos-responsive hydrogel is modeled by FEM. The temperature-sensitive hydrogel, polyhydrogel has garnered significant academic interest owing to its distinctive characteristics, including facile synthesis and robust stability. Considering hydrogel as a hyperelastic substance and applying the nonlinear field theory that integrates diffusion and deformation [15], the hydrogel can be expressed by free energy function,

$$W(I_1, I_3, \mu, T) = \frac{1}{2}\, N k_B T (I_1 - 3 - 2\log I_3) - \\ - \frac{k_B T}{\nu}\left[(I_3 - 1)\log\frac{I_3}{I_3 - 1} + \frac{\chi(T, I_3)}{I_3}\right] - \frac{\mu}{\nu}(I_3 - 1), \quad (1)$$

where $I_1 = F_{iK}F_{iK}$ and $I_3 = \det \mathbf{F}$ are the first and the third invariants of the deformation gradient tensor. Furthermore, μ is represents the chemical potential, $T$ denotes the temperature, $N$ signifies the number of chains per polymer volume, $\nu$ is the volume of a solvent molecule, and $k_B$ stands for the Boltzmann constant. Then, it is conventional to establish a reference state wherein the polymer network achieves equilibrium with a solvent possessing a specific chemical potential denoted as $\mu_0$. This reference state involves free swelling, where the swelling coefficient ($\lambda$) remains uniform in all spatial directions, denoted as $\lambda_x = \lambda_y = \lambda_z = \lambda_0$. Given the free swelling nature of the reference state, the swelling ratio ($J$) is determined as the cube of the swelling coefficient $J = {\lambda_0}^3$. Adhering to these stipulations, the equilibrium state can be delineated as follows,

$$\frac{\mu_0}{kT} = \frac{N\nu}{\lambda_0^3}(\lambda_0^2 - 1) + \log\left(1 - \frac{1}{\lambda_0^3}\right) + \frac{1}{\lambda_0^3} + \frac{\chi}{\lambda_0^6} \quad (2)$$

Moreover, the Flory-Huggins interaction parameter, χ, quantifies the enthalpy associated with the blending mechanism and is articulated with respect to $T$ and $I_3$ for a temperature-sensitive hydrogel,

$$\chi(T, I_3) = A_0 + B_0 T + \frac{A_1 + B_1 T}{I_3} \quad (3)$$

The experiments can take the coefficients $A_i$ and $B_i$ as $A_0 = -12.947$, $B_0 = 0.0449\ \mathrm{K}^{-1}$, $A_1 = 7.92$, $B_1 = -0.0569\ \mathrm{K}^{-1}$ [16]. In addition, the expression of stresses immediately follows, and the first Piola-Kirchhoff stress is computed as,

$$\mathbf{P} = \frac{\partial W_0(I_1, I_3)}{\partial \mathbf{F}} = \frac{\partial W_0(I_1, I_3)}{\partial I_1}\frac{\partial I_1}{\partial \mathbf{F}} + \frac{\partial W_0(I_1, I_3)}{\partial I_3}\frac{\partial I_3}{\partial \mathbf{F}} \quad (4)$$

In the simulations, we standardize material stresses and Young's modulus by $k_B T/\nu$, where the estimated value is $4 \times 10^7$ Pa. Different synthesis conditions yield various initial swelling ratios, and without loss of generality, $\lambda_0$ is fixed to 1.5 is uniformly set to 1.5 for all three directions, representing an equilibrium chemical potential of $\mu_0 = -0.01$ for the hydrogel material [17].

In addition, hyperelastic model is also adopted for shape memory polymer (SMP). SMP demonstrates significant visco-elasticity throughout its shape memory, spanning temperatures both above and below the glass transition temperature. This viscos-elastic response exhibits a pronounced time–temperature dependency [18, 19]. In our study, we employed the superimposed generalized Maxwell model and Williams-Landel-Ferry (WLF) equation within FE solver to elucidate the mechanical behavior of SMP. The utilized constitutive equations for the multi-branch viscos-elasticity are as follows [20],

$$\sigma(t) = \varepsilon_0 E_n + \varepsilon_0 \sum_{i=1}^{n-1} E_i e^{\frac{-t}{\tau_i}}, \quad (5)$$

where $\sigma(t)$ represents stress at time $t$, $\varepsilon_0$ is the strain at the initial time, $E_n$ denotes the instantaneous modulus, $E_t$ and $\tau_i$ represent the elastic modulus and relaxation time of the Maxwell element $i$, respectively. The relation of relaxation modulus $E$ in the generalized Maxwell equation with time $t$ is expressed as follows,

$$E(t) = E_n + \sum_{i=1}^{n-1} E_i e^{\frac{-t}{\tau_i}} \quad (6)$$

and satisfies the limit condition, $\lim_{t\to\infty} E(t) = E_n$.

Conducting relaxation experiments at various temperatures and applying the time–temperature equivalence principle is essential. This allows the conversion of the relaxation response curve of SMP across different temperatures into a comprehensive relaxation response curve at a specific temperature. According to the WLF equation [20], the connection between the relaxation time at the present temperature $T$ and the relaxation time at the reference temperature of $T_r$ can be written as,

$$\lg\alpha_T = \lg\frac{\tau}{\tau_r} = \frac{-C_1^s(T-T_r)}{C_2^s+(T-T_r)}, \quad (7)$$

where $\alpha_T$ represents shift factor, $C_1^s$ and $C_2^s$ are material constant.

Besides, silicone is frequently employed as the standard material in soft actuators to facilitate substantial deformations. The Neo-Hookean constitutive model is utilized in the finite element solver to articulate the stress-strain correlation and manifest hyperelasticity traits,

$$W_{\mathrm{NH}} = \mu_{\mathrm{NH}}(\overline{I_1} - 3), \quad (8)$$

where $\mu_{\mathrm{NH}}$ represents a material constant, $\overline{I_1}$ denotes the first invariants of the deformation gradient tensor.

### FEM-DEM model

The FEM typically analyzes deformations of components under external loads, while the DEM focuses on particle-level materials. To model a soft actuator driven by granular materials, it is essential to couple FEM and DEM for a comprehensive analysis.

The movements of both discrete element and finite element nodes adhere to Newton's Second Law. Consequently, the external force $F_i$ acting on both discrete element and finite element node $i$ is expressed as follows,

$$F_i = m_i\left(\frac{d^2\boldsymbol{u}_i}{dt^2}\right), \quad (9)$$

where $m_i$ denotes the mass of element $i$, and $\boldsymbol{u}_i$ represents the displacement of element $i$. Furthermore, the centroidal moment of the discrete element $i$ is expressed as follows [21],

$$M_i = I_i\left(\frac{d^2\boldsymbol{\theta}_i}{dt^2}\right). \quad (10)$$

where $I_i$ is the inertia moment of element $i$ and $\boldsymbol{\theta}_i$ is the rotation angle of element $i$. Both of the equation (8) and equation (9) are solved using explicit finite difference method.

Furthermore, the interaction force can be divided into normal force and the tangential force, the normal force $F_n$, and the tangential force $F_s$ can be expressed as,

$$F_n = F_{n,e} + F_{n,v} \quad (11)$$

$$F_s = \begin{cases} F_{s,e} + F_{s,v} & |F_s| < \mu|F_n| \\ \mu F_n & |F_s| \geq \mu|F_n| \end{cases}, \quad (12)$$

where $F_{n,e}$ and $F_{n,v}$ are the normal spring force and the normal damping force. Moreover, $F_{s,e}$ and $F_{s,v}$ denote the tangential spring force and tangential damping force. Additionally, the $\mu$ is friction coefficient.

During the coupling process, FE elements, along with their grid information, are mirrored into the DEM solver as a wall condition [22]. This involves calculating interaction forces and loads between particles and the wall within each DEM time step. Subsequently, node forces are computed based on particle loads and interpolated onto each FEM element. These node forces are then transformed into distributed loads to facilitate interpolation onto each FE element, enabling the calculation of mesh element deformations and node displacements.

### FEM-MBD model

The MBD approach is employed to comprehensively capture the motion information, enabling the simulation of scenarios involving significant deformations and the loading process. A coupling between the MBD and FEM models is established to facilitate the transfer of information between rigid and deformable components. This coupling strategy leverages the intrinsic properties of the MBD module to effectively constrain the actuator's motion. Additionally, the embedded characteristics of the MBD module allow for the formation of a rigid linkage between components, irrespective of the motion framework. In the coupling strategy, during each time step of the FEA-MBD algorithm, stress and strain are computed using the FE solver, while displacements are determined by the MBD model. Importantly, throughout this process, nodes involved in rigid connections receive stress information from the FE solver to aid in displacement calculations.

Additionally, the presence of various rigid connections restricts structural motion to a certain degree, allowing the MBD model to accurately represent the motion characteristics of the multibody system.

## 4. CASE STUDY

In this section, various building blocks have been proposed to demonstrate the feasibility of the model-based design strategy. The building block is the modular concept consists of structure geometry, smart materials and environmental stimuli. Shown in Figure 2, the structure geometries include the meta-structure or particles as the selection in our design, then the smart materials include smart hydrogels, shape memory polymers (SMPs), and shape memory alloys (SMAs). In addition, the envioremental stimuli include temperature and chemical relating stimuli. To fit specific scearios, different structure geometris, smart materials, and stimuli will be combined into any new building blocks to achieve tailored functions, then based on the building blocks, the mechanically intelligent morphing structures can be developed.

### *Smart materials and smart mechanism building blocks*

The first is the proposition of a particle-based actuator, formulated through model-based design, aims to fulfill the demands for significant deformation and substantial bending stiffness. The analysis of this proposed actuator is conducted utilizing the FEM-DEM approach. The design concept is shown in Figure 3, different sized particles are filled into different chambers, separated by a middle layer. The chambers are enveloped by an elastic membrane. During the actuation phase, the membrane undergoes contraction, facilitated by a specified shrinking coefficient, resulting in the deformation of the whole element. This deformation causes the actuator to exhibit a bending motion towards the left, propelled by the discrepancy in volume between the two chambers. Furthermore, subsequent to the contraction process, the actuator's stiffness experiences augmentation due to the phenomenon known as particle jamming. The phenomenon of particle jamming denotes a transition in the packing state of particles. Initially, particles are loosely encapsulated, representing a state of natural packing that permits particle mobility within the membrane. However, as the packing state transitions to a tighter configuration, the spatial arrangement of particles undergoes alteration. Consequently, the inter-particle contact forces and interactions between particles and the membrane intensify, impeding particle mobility. This transition results in the aggregation of particles into a solid-like state, leading to the formation of a jammed configuration.

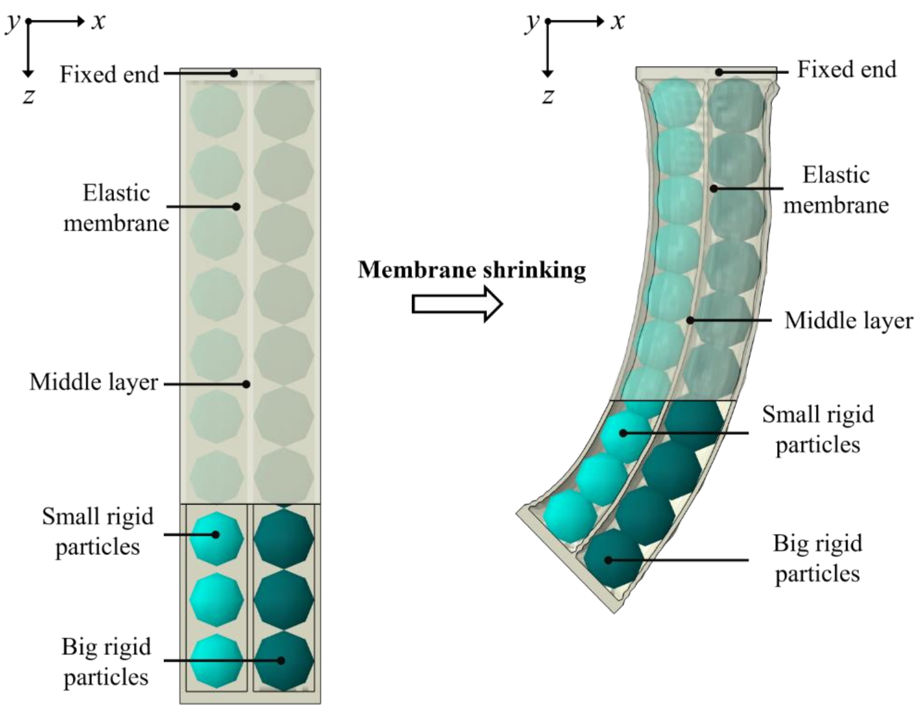


**Fig. 3.** The actuation process of the particle-based actuator

Secondly, to meet the demands of active actuation, the adoption of responsive materials capable of autonomous response to external stimuli holds promise for integration into soft grippers. Operating as an active smart material, hydrogels demonstrate changes in shape in response to particular external stimuli. Among these, thermally responsive hydrogels offer enhanced adaptability and compatibility [23]. Actuators employing thermally responsive hydrogels undergo alterations in hydrogel volume in response to fluctuations in ambient temperature, consequently demonstrating notable directed deformations within defined temperature ranges. Thus, this section elucidates the characterization of hydrogels and other nonlinear materials through the hyperelastic model by employing FEM. The smart structure depicted in Figure 4 employs a thermally responsive hydrogel as its foundation. This hydrogel particle is connected to a conventional soft particle, typically composed of silicone or rubber, known for its stable chemical characteristics. Initially, both the hydrogel particle and the normal soft particle exhibit identical dimensions. Subsequently, the hydrogel particle undergoes swelling upon exposure to a water environment with temperature change. As the results, this smart element will exhibit a configuration featuring particles of two distinct sizes, which can be used as the basis for different configurations.

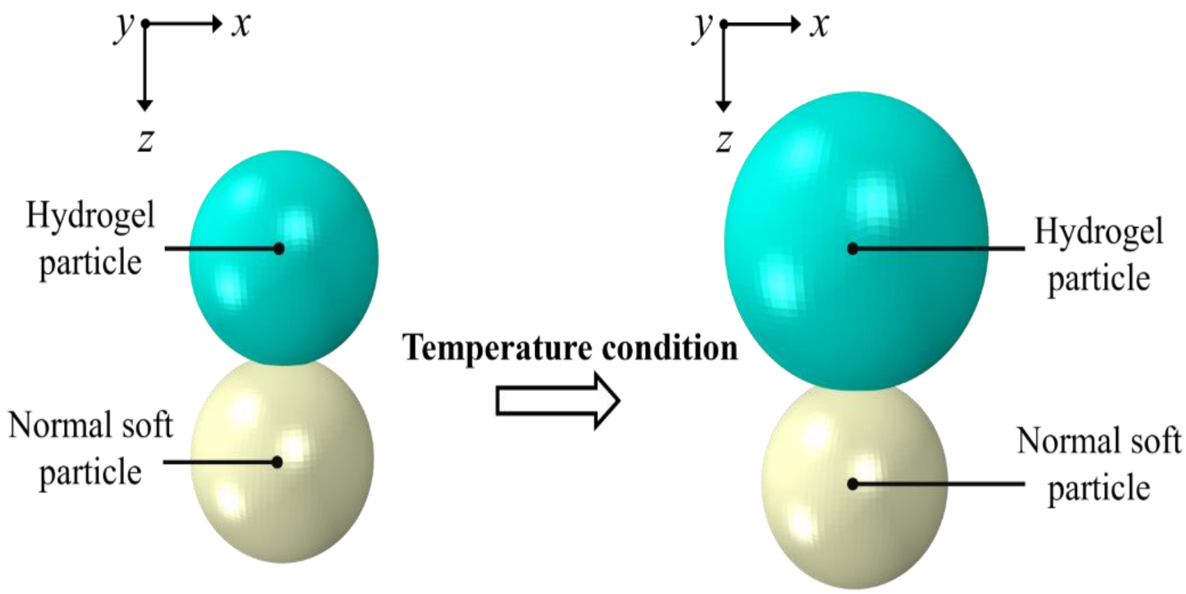


**Fig. 4.** Smart structure element based on hydrogel particle

The smart structures based on the smart element are developed by the modeling and the configurations are shown in Figure 5. Figure 5a illustrates a smart structure capable of both expansion and contraction. This smart structure comprises elementary smart elements arranged in an alternating fashion. In the initial state, all the particles are in the same size. Subsequently, the hydrogel particles undergo swelling induced by changes in temperature, leading to elongation of the structure. Hydrogel particles assume a primary role in actuation, with normal soft particles serving a supplementary function in maintaining structural stability. Temperature manipulation is employed to achieve the expansion and contraction of the hydrogel particles, thus governing the elongation and contraction of the structure. Figure 5b shows a smart structure that can achieve grasping behaviours. This smart structure consists of modular smart elements organized to construct a dual-layered framework with 4 branches. In the initial phase, all branches exhibit a straight configuration characterized by uniform-sized hydrogel and normal elastic particles. Subsequently, the hydrogel particles undergo a swelling phenomenon. Due to constraints imposed by the normal elastic particles, each branch gradually undergoes bending towards the central axis during the swelling of the hydrogel particles, thereby manifesting a grasping behavior.

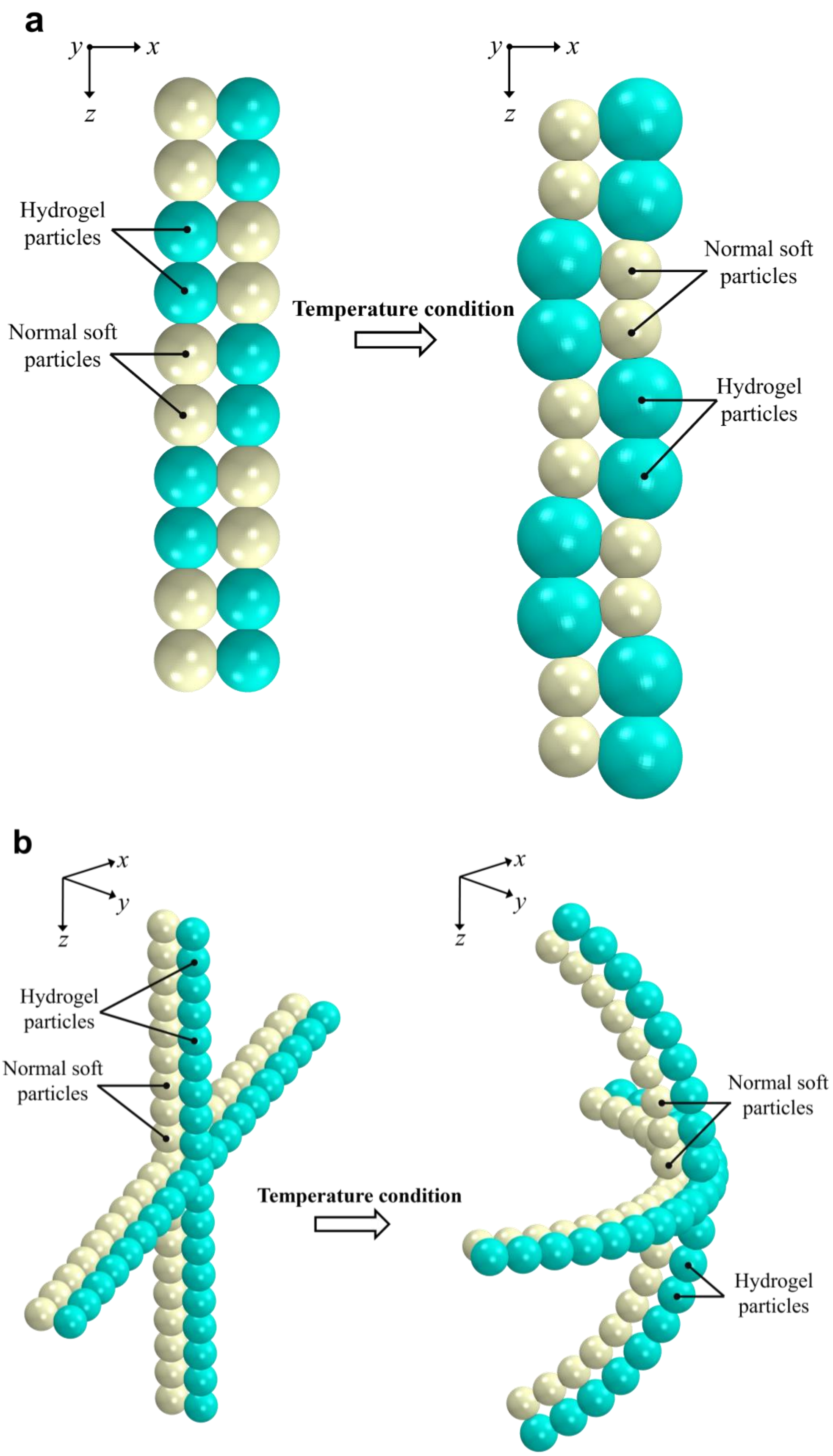


**Fig. 5.** Different smart structures based on the smart elements:
(a) Configuration of elongation structure.
(b) Configuration of grasping structure

*Multiple smart materials based building blocks*

In the situation of underwater pipe manipulation and seabed pipe maintenance installation, attaining active deformation along with high stiffness and adaptability is imperative. Consequently, the integration of various smart materials becomes essential for effective implementation. SMPs are materials distinguished by their ability to retain a predetermined, permanent shape, undergo manipulation to adopt a temporary configuration under specific conditions of temperature and stress, and subsequently revert to their original, stress-free state upon exposure to thermal, electrical, or environmental stimuli. Given their unique capacity to maintain two distinct shapes under varying conditions, SMPs hold significant promise for utilization in smart actuator systems. The illustration presented in Figure 6 depicts the integration of a building block incorporating SMP as its base along with hydrogel protrusions. The SMP base primarily functions as the actuation mechanism facilitating substantial deformation. Conversely, the hydrogel protrusions serve as the supportive framework aimed at enhancing the adaptability of the smart actuator. In the initial state, the SMP base exhibits a curved form, while the hydrogel protrusions maintain a state of minimal swelling. Upon the application of an external force or stimuli, the SMP base undergoes a temporary morphological change. Subsequently, when the temperature surpasses the critical threshold of the SMP, the material reverts to its original shape. Following the shape recovery process, lowering the temperature again serves to both fix the SMP shape and induce further swelling of the hydrogel protrusions. Through this cycle process, the SMP base achieves bending behavior, facilitated by the swelling and contraction of the hydrogel protrusions to modulate the structure's thickness and enhance its adaptability.

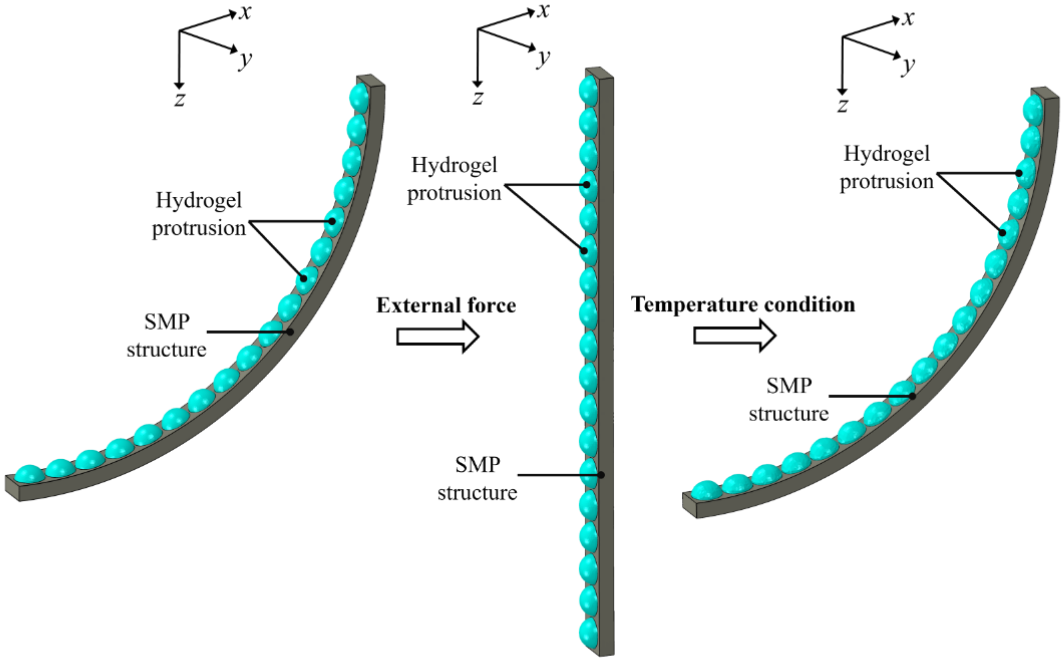


**Fig. 6.** The building block based on SMP and hydrogel

As shown in Figure 7, the proposed building block exhibits potential for development in specific applications. This potential finds utility within underwater environments for tasks of pipeline maintenance. The operational sequence involves initial deformation of the composite structure through external force, maintaining it in a temporary configuration. Following immersion in water, the entire structure gradually approaches the local section of the pipeline. Subsequently, the pressure valve initiates opening to release high-pressure hot gas. As a result of the elevated temperature of the hot air, adjacent water experiences thermal conduction, leading to its heating. With the increased temperature, the SMP base undergoes bending, reverting to its original configuration, thus enveloping the pipeline in need of maintenance to ensure safety. Upon the gradual decrease in nearby water temperature, the hydrogel protrusion undergoes swelling, subsequently making contact with both the pipe valve and its outer wall. The inherent softness of the hydrogel structure serves to shield the pipe from potential damage due to collisions. Furthermore, the hydrogel functions to fill the space between the pipe and actuator, thereby promoting pipe stability.

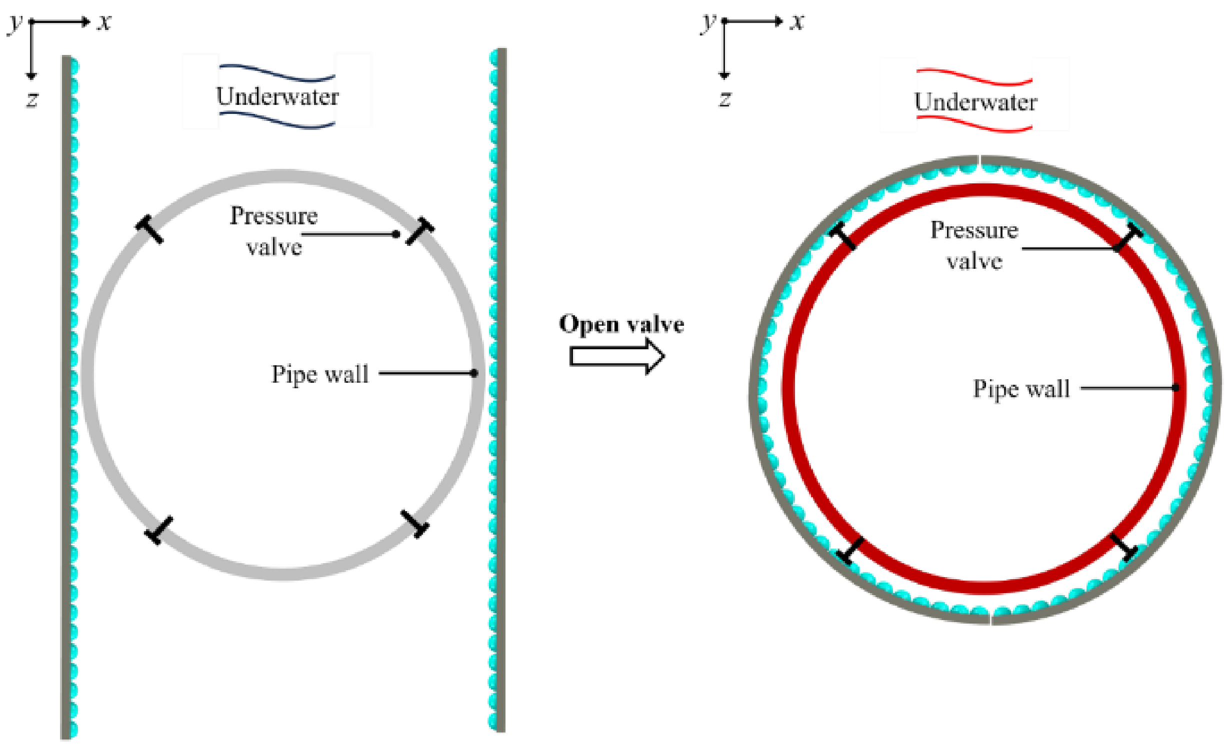


**Fig. 7.** Potential application of the multiple smart materials based building blocks

Based on the cases study, the advantages, application, and stimuli of the smart hydrogels and SMPs can be concluded (Table 1). Hydrogels and SMPs are tailored for distinct applications due to their unique properties. Hydrogels, with their ability to undergo large deformations and respond to stimuli like pH or temperature, are ideal for actuation in soft robotics and artificial muscles. Their flexibility and water absorption make them perfect for dynamic environments. Conversely, SMPs are prized for their stiffness variation and shape recovery, excelling in applications like underwater components in unpredictable environment. Besdeis, the lightweight and programmable properties of SMPs also ensure structural integrity and precision where stability is critical.

Table 1

*Conclusion of hydrogels and SMPs*

| Smart material | Advantages | Stimuli | Applications |
|---|---|---|---|
| Hydrogel | Large deformation capability<br>High water absorption | pH<br>Temperature<br>Light<br>Magnetic field<br>Electric field | Soft actuators<br>Sensors |
| SMP | Tunable stiffness variation<br>High recoverable strain<br>Programmable shapes | Heat<br>Light<br>Magnetic field | Smart textiles<br>Self-healing<br>Underwater component |

In conclusion, the comprehensive design framework is shown in Figure 8. The process begins with the selection of smart materials capable of changing shape, volume, and stiffness in response to environmental stimuli. Replacing conventional soft materials with these smart materials enables energy harvesting from natural sources and reduces dependence on external power, facilitating self-actuation in complex or unpredictable environments. In addition, smart materials like shape memory materials also enable stiffness changes, enhancing adaptability and stability in real-world applications. By combing multiple smart materials, the self-actuation unit, which refers to "building blocks", can be developed to achieve specific deformations, such as surface folding, shell volume changes, or joint bending. Then, the morphing structures are assembled into more complex structures, which can be modularly configured to perform different behav-iours. Finally, the mechanical intelligence relating to the soft robotics can be developed by the structural design based on the morphing structure for various tasks, such as locomotion or manipulation.

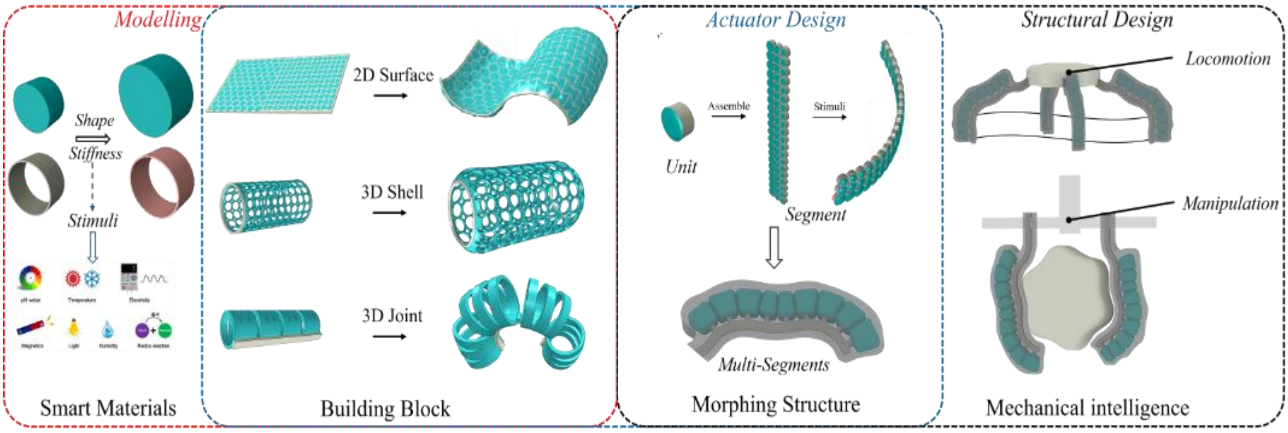


**Fig. 8.** The model-based design process of the smart building blocks

## 5. CONCLUSION

The soft robot in this study demonstrates advanced capabilities with high-level adaptabilities and flexibilities, enabling the creation of complex structures. The soft actuator, a key component of the soft robotic system, is crucial in driving the robot's overall functionality. This research explored the potential of model-based design approaches for developing building blocks of modular components that can be combined to form mechanically intelligent structures with specialized functions.

Numerical methods, such as the finite element method (FEM) and the combined finite element and discrete element method (FEM-DEM), offer significant potential for advancing smart actuator systems. FEM, in particular, is highly effective for characterizing the hyperelastic behavior of shape memory polymers (SMPs) and smart hydrogels. Additionally, the FEM-DEM approach has proven useful in analyzing particle-based mechanisms that undergo large deformations.

By employing variable smart actuation methods, it is possible to tailor the functions of these components to specific applications. Particle-based building blocks, for example, demonstrate substantial deformation capabilities and can increase stiffness. Temperature-sensitive hydrogels exhibit active deformation properties, making the building blocks suitable for applications such as elongation and grasping. A hybrid design combining SMP and smart hydrogel can further enhance these actuators by offering both active deformation and stiffness control, enabling functions such as grasping, installation, and maintenance while improving the adaptability of the modular building blocks.

In the future, an improved methodology grounded in model-based design principles will be developed. This approach will integrate theoretical models with experimental validation, ultimately enabling the systematic design and manufacturing of engineering-ready building blocks for soft robotic systems.

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