A Practice-Based Study on Deformable Matter Design Based on Four-Dimensional Composition: A Spatio-Temporal Coupling Perspective on Intelligent Interactive System Development

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***Abstract*—With the rapid development of smart materials and digital fabrication technologies, morphing matter — materials capable of changing their shape and function in response to external stimuli — has shown great potential in areas such as intelligent interaction, soft robotics, and kinetic architecture. Despite this promise, most current design approaches for deformable matter remain heavily engineering-oriented, relying on optimization techniques or trial-and-error experimentation. As a result, they lack a systematic, design-driven theoretical framework that supports creative innovation. In particular, there is a notable research gap in methods that can effectively integrate spatial form with temporal behavior.To address this challenge, this study introduces the concept of "Four-Dimensional (4D) Composition" (three-dimensional space plus one-dimensional time), derived from fundamental design theory, as a new framework for developing spatio-temporal coupling strategies in deformable matter design. Using thermo-responsive Shape Memory Polymers (SMPs) as the primary material and 4D printing as the fabrication method, the research systematically investigates the relationship between spatial structural parameters and time-dependent deformation behaviors through parametric modeling.Based on this approach, an intelligent interactive lighting prototype called Dynamic Rhythm was designed and fabricated. Experimental evaluations demonstrate that the prototype can achieve pre-programmed dynamic deformation with an accuracy exceeding 95%, a response time of less than 30 seconds, and stable performance across more than 100 actuation cycles. These results confirm the reliability and repeatability of the proposed design method.Overall, this study concludes that 4D Composition provides a clear logical structure and an effective design pathway for deformable matter. By employing parametric, spatio-temporal coupling strategies, it enables precise control over complex dynamic behaviors. Beyond offering a new theoretical perspective and systematic methodology, this research also expands the possibilities for morphological innovation and experiential design in future intelligent interactive systems.**

Keywords—Four-Dimensional Composition,Morphing Matter,Spatio-Temporal Coupling Design,4D Printing,Intelligent Interactive Systems

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I. Introduction

In recent years, morphing matter based on smart materials has emerged as a cutting-edge interdisciplinary research focus at the intersection of materials science, engineering, and design [1]. These materials are capable of sensing and responding to a wide range of environmental stimuli — including temperature, humidity, light, and electromagnetic fields — thereby enabling autonomous, pre-programmed changes in shape, structure, and even function [2]. The advent of 4D printing has further incorporated time as an intrinsic design dimension, allowing static three-dimensional objects to evolve into dynamic four-dimensional structures. This development has significantly expanded both the expressive and functional potential of material form-making [3][4].

The application landscape of morphing matter is extensive, spanning self-deploying aerospace structures [5], biomedical devices for precise drug delivery [6], and kinetic architectural envelopes that actively respond to environmental conditions [7]. In the domain of human–computer interaction, morphing matter represents a paradigm shift beyond traditional rigid and screen-based interfaces. Shape-changing interfaces utilize physical transformations to convey information, provide haptic feedback, and create immersive user experiences, and are widely recognized as a promising direction for next-generation interaction design [8][9].

Despite this considerable potential, translating morphing matter into reliable, expressive, and usable interactive products remains a substantial challenge. Existing design approaches typically fall into two categories. The first is a technology-driven model that prioritizes engineering optimization and material performance, often at the expense of user experience and aesthetic expression [10]. The second is an artistic exploration model rooted in designer intuition and iterative experimentation. While this approach can produce novel and expressive outcomes, it is difficult to replicate and lacks systematic methodological support [11].

These limitations lead to a central research question: How can a systematic design theory and methodology be established to enable designers to effectively harness the complex spatio-temporal dynamics of morphing matter in the creation of intelligent interactive systems that are functional, reliable, and highly expressive? To date, much of the existing research has concentrated on material development, engineering implementation, or speculative future scenarios. A design-centered investigation that explicitly addresses how to compose with morphing matter remains notably underexplored — particularly with respect to its defining characteristic: the intrinsic coupling between three-dimensional spatial form and one-dimensional temporal behavior.

To address this gap, the present study explores an extension of classical composition theory from three-dimensional space into four-dimensional spacetime, proposing a design methodology for deformable matter based on Four-Dimensional (4D) Composition. Just as two-dimensional composition examines the organization of points, lines, and planes, and three-dimensional composition focuses on volumetric form and spatial structure, 4D composition systematically investigates how material form in 3D space dynamically evolves over time. The objectives of this research are threefold: (1) to construct a 4D composition design framework centered on spatio-temporal coupling; (2) to develop a parametric design workflow and toolset grounded in this framework; and (3) to validate the effectiveness and practical value of the methodology through a concrete design case involving an intelligent interactive system.

The remainder of this paper is organized as follows. Section 2 reviews related work on 4D composition, morphing matter, and temporal design. Section 3 introduces the proposed spatio-temporal coupling design methodology based on 4D composition. Section 4 details the design, fabrication, and experimental implementation of the intelligent interactive system prototype developed using this approach. Section 5 presents and analyzes the experimental results. Section 6 discusses the findings in depth and compares them with existing research. Finally, Section 7 concludes the paper and outlines directions for future research.

II. Literature Review

To establish the theoretical foundation of this study, an interdisciplinary literature review was conducted across three core domains: composition theory within design research, morphing matter and 4D printing in materials science, and emerging studies on temporal design and dynamic interaction. By systematically examining and synthesizing key contributions from these fields, this review clarifies the current state of research, identifies existing limitations, and situates the present study within the broader academic landscape. In doing so, it articulates the specific research gap addressed by this work and highlights its distinctive theoretical and methodological contributions.

A. The Dimensional Evolution of Design Composition Theory

Composition theory has long been a foundational pillar of modern design education, with its origins tracing back to the Bauhaus school in Germany [12]. Traditionally, design composition has been structured around the so-called "three major compositions": two-dimensional (planar) composition, color composition, and three-dimensional (spatial) composition. Two-dimensional composition focuses on the organization of visual elements on a plane, such as the repetition of points, the rhythm of lines, and the division of surfaces [13]. Three-dimensional composition extends this inquiry into volumetric space, examining the construction and organization of form, mass, space, and structural relationships [14].

Across the transition from 2D to 3D, the core concern of composition theory has remained consistent: how principles of formal aesthetics can be applied to generate ordered, harmonious, and expressive forms within a given dimensional framework. However, as technological and social conditions have evolved, design objects have increasingly shifted from static artifacts toward dynamic systems that unfold over time. Contemporary design practice now places greater emphasis on processes, behaviors, and temporally evolving user experiences, revealing the limitations of composition theories confined solely to three-dimensional space. This transformation calls for an expansion of design theory to incorporate a fourth dimension—time.

Although the concept of "temporal composition" or "four-dimensional (4D) composition" has not been formally codified as a unified theoretical system within classical design theory, it has long been implicitly embedded in fields such as motion graphics, film and television arts, and interaction design [15]. In these domains, time functions as a fundamental element shaping narrative structure, rhythm, and interaction. For example, in motion graphics, the trajectories, velocity curves, and temporal sequencing of visual elements collectively form a time-based mode of visual communication [16]. Nevertheless, such practices are largely media-specific and empirically driven, lacking a generalized composition framework grounded in the physical properties of material form.

This study argues that with the emergence of programmable, deformable matter, time must be elevated from an external parameter applied to static forms to a foundational dimension of material composition itself. When matter is capable of sensing, responding, and transforming autonomously, temporal behavior becomes inseparable from spatial form. Under these conditions, it becomes both necessary and meaningful to establish a genuine theoretical framework of Four-Dimensional Composition, in which material form is conceived as an integrated spatio-temporal construct rather than a static three-dimensional entity.

B. Morphing Matter: From Material to Composable Medium

Morphing matter constitutes the physical foundation for realizing four-dimensional (4D) composition. Among such materials, Shape Memory Polymers (SMPs) are particularly representative, as they can recover from a temporary configuration to a predefined permanent shape in response to external stimuli. This behavior endows them with a form of temporal "memory," in which material transformation unfolds as a time-dependent process rather than an instantaneous event [17]. The emergence of 4D printing, which integrates SMPs with additive manufacturing technologies, enables designers to precisely control material distribution and structural parameters within three-dimensional space. As a result, deformation trajectories, sequences, and behavioral logic can be pre-programmed and embedded into the material itself, effectively encoding temporal behavior into spatial form [18][19]. This development marks a fundamental shift: materials are no longer passive carriers of form, but active and composable design media.

Despite these advances, research on morphing matter and 4D printing remains largely dominated by materials science and engineering perspectives. Materials science research focuses primarily on developing smart materials with faster response speeds, greater recovery forces, reversible deformation capabilities, and multi-stimuli responsiveness [20][21]. Engineering research, by contrast, concentrates on applying these materials to specific functional scenarios—such as self-folding robotic systems [22] and deployable biomedical stents [23]—with an emphasis on performance optimization and reliability.

From a design-oriented perspective, this predominantly goal-driven research trajectory tends to overlook the expressive dimensions of morphing matter, including aesthetic qualities, emotional resonance, and interactive potential. In particular, the deformation process itself—its rhythm, sequencing, and morphological evolution over time—has rarely been treated as a primary design subject. Consequently, existing research largely addresses what morphing matter can achieve, while offering limited insight into how these transformations can be composed in expressive and meaningful ways. Addressing this gap is essential for repositioning morphing matter as a truly composable medium within the framework of 4D design.

C. Explorations in Temporal Design and Dynamic Interaction

Within the fields of human–computer interaction and design theory, an increasing number of scholars have foregrounded time as a central design concern. The Slow Technology movement, for example, advocates extending temporal scales in interactive systems to encourage reflection, mindfulness, and long-term engagement [24]. Similarly, the theory of Temporal Design proposed by Pschetz and Bastian conceptualizes time not as a singular, linear, objective quantity, but as a pluralistic design material shaped by social, cultural, and technological forces [25]. In parallel, research on shape-changing interfaces has explored how dynamic transformations of physical form can enhance information legibility, support intuitive interaction, and enrich user experience [8][26].

While these studies have significantly advanced design discourse by recognizing time as an expressive dimension, they also exhibit notable limitations. Temporal design theory often remains at a philosophical or macro socio-cultural level, offering limited guidance on how temporal concepts can be operationalized through concrete material and formal strategies. Research on shape-changing interfaces, on the other hand, tends to focus on specific interaction scenarios and technical implementations, with design processes still heavily reliant on individual intuition and iterative prototyping.

These gaps indicate the need for a design framework capable of bridging abstract temporal concepts with the material realities of dynamic form, providing both theoretical clarity and practical tools for composing time-based transformations in physical artifacts.

D. Research Gap and Positioning of This Study

Synthesizing the literature across these three domains reveals a clear research gap: there is currently no effective bridge connecting design composition theory, morphing matter technologies, and temporal design thinking. While materials capable of programmable deformation already exist, and the importance of time as a design dimension has been widely acknowledged, a systematic design methodology that enables designers to intentionally compose and control material behavior in spacetime remains absent.

This study positions itself to address this gap by proposing Four-Dimensional (4D) Composition as a design-theoretical framework. Supported by parametric design strategies and enabled through 4D printing technologies, the proposed approach shifts morphing matter design from a predominantly technology-driven paradigm toward one guided by design intent, experiential quality, and expressive control.

III. Methodology and System Design

This study adopts a comprehensive research strategy that integrates theory construction, computational design, and experimental validation. Central to this approach is the proposal and application of a novel Four-Dimensional Composition Design Framework (4D-CDF), which provides systematic guidance for the design of intelligent interactive systems based on deformable matter. This section details the theoretical foundations of the framework, outlines the corresponding design workflow, and describes the experimental methodology employed to evaluate and validate its effectiveness.

A. Four-Dimensional Composition Design Framework

To systematically address the complex spatio-temporal characteristics of deformable matter, this study constructs a Four-Dimensional Composition Design Framework (4D-CDF). The framework decomposes the design process into three interrelated core modules: Spatial Dimension Design, Temporal Dimension Design, and the Spatio-Temporal Coupling Mechanism, as illustrated in Figure 1. Together, these modules provide designers with a structured analytical and operational tool that translates abstract design intentions into concrete, controllable physical parameters.

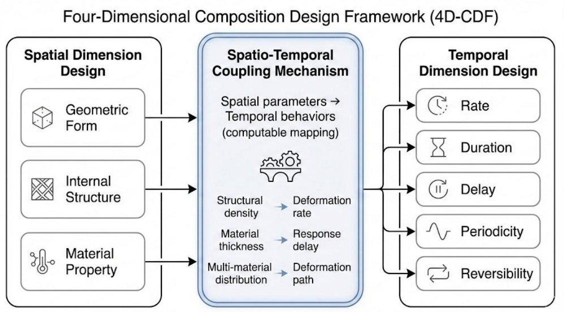

Fig. 1. A diagram of the 4D Composition Design Framework, including the modules of Spatial Dimension, Temporal Dimension, and Spatio-Temporal Coupling, along with their sub-elements, should be inserted here.

1) . Spatial Dimension Design

This module focuses on the static physical properties of an object prior to deformation — namely, its composition within three-dimensional space. Beyond serving as the carrier of functional performance, spatial design forms the foundational basis that determines subsequent dynamic behavior. In the proposed framework, the spatial dimension is decomposed into three fundamental elements:

- Geometric form refers to the macroscopic shape, contour, and overall dimensions of the object. It defines the object's visual appearance as well as its interface with users and the surrounding environment. Within parametric design environments, geometric form is typically described using basic primitives such as points, lines, and surfaces, along with their topological relationships.
- Internal structure denotes the object's micro-scale construction, including lattice configurations, infill patterns, and local density variations. In 4D printing, internal structure plays a critical role in enabling differential deformation. By modulating parameters such as structural density, orientation, or localized material distribution, designers can precisely program stress distribution and deformation pathways when the object is subjected to external stimuli.
- Material properties encompass the intrinsic physical and chemical characteristics of the material, including thermal, mechanical, electrical, and optical behavior. This study focuses on thermo-responsive Shape Memory Polymers (SMPs), whose key parameters include glass transition temperature (Tg), shape fixity ratio (Rf), shape recovery ratio (Rr), and modulus variation. Material selection directly determines the actuation mechanism, response range, and performance limits of the deformable system.

2) Temporal Dimension Design

As the core of four-dimensional composition, this module addresses the dynamic evolution of an object as it transitions from an initial state to a target state. To operationalize temporal behavior, the deformation process is decomposed into a set of designable temporal parameters, allowing abstract concepts such as "dynamic aesthetics" or "interactive rhythm" to be translated into measurable variables:

- The speed of shape transformation, which may be constant, accelerating, or decelerating. Deformation rate defines the perceived rhythm of interaction, ranging from slow and gentle to rapid and energetic.
- The total time required to complete a deformation cycle or maintain a specific state. Duration influences user perception and determines the temporal window available for interaction.
- The time interval between stimulus input and the onset of deformation. By designing varied delays across different regions or components, designers can achieve sequential transformations and complex temporal choreography.
- The presence and frequency of repetitive deformation behavior. Periodic motion enables the creation of life-like dynamic effects such as breathing, pulsing, or oscillation.
- The ability of the system to transition repeatedly between multiple states. Reversibility is essential for sustained interaction and adaptive functionality.

3) Spatio-Temporal Coupling Mechanism

The spatio-temporal coupling mechanism serves as the critical bridge between spatial and temporal dimensions and represents the core logic of the 4D-CDF. It defines how temporal behavior can be precisely controlled through spatial parameter design. These relationships are governed by fundamental principles of material physics and structural mechanics, and a key objective of this methodology is to establish computable models that formalize such couplings.

Representative coupling relationships include:

- Structural Density – Deformation Rate Coupling: In SMP-based systems, regions with lower structural density (e.g., porous or lattice structures) generally exhibit faster heating and cooling, resulting in more rapid deformation.
- Material Thickness – Response Delay Coupling: Thicker cross-sections require longer times to reach the glass transition temperature, leading to increased response delays.
- Multi-Material Distribution – Deformation Path Coupling: By combining SMPs with different glass transition temperatures, or integrating SMPs with passive materials, designers can generate multi-stage and multi-path deformation behaviors within a single structure.

By establishing these "spatial parameter → temporal behavior" mapping relationships, designers gain the ability to consciously and predictably choreograph dynamic behavior. Adjustments made within the 3D parametric model (spatial dimension) directly shape the object's deformation rhythm, sequence, and expressive qualities over time (temporal dimension), enabling systematic control over complex spatio-temporal interactions.

B. Design and Fabrication Workflow

Based on the framework described above, we have developed a systematic workflow from design intent to physical prototype, as shown in Figure 2. This workflow is designed to ensure the innovativeness of the design and the feasibility of its implementation, and it emphasizes the central role of parametric tools.

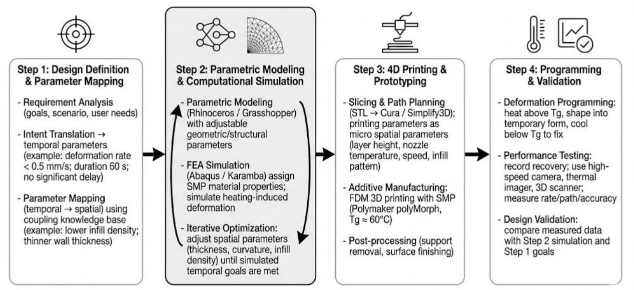

Fig. 2. A diagram of the design and fabrication workflow based on 4D composition, drawn in the style of a Nature journal, should be inserted here.

1) *Step 1: Design Definition & Parameter Mapping*

a) Requirement Analysis: The process begins with clarifying the design objectives, application context, and user needs. For example, a design brief may specify the creation of a smart lamp capable of "slow and gentle" atmospheric transformation.

b) Intent Translation: Qualitative design intentions—such as "slow" and "gentle"—are translated into explicit temporal parameters. For instance, these descriptors may correspond to a deformation rate of less than 0.5 mm/s, a total deformation duration of approximately 60 seconds, and minimal or no response delay.

c) Parameter Mapping: Drawing on the spatio-temporal coupling knowledge base, the defined temporal parameters are preliminarily mapped to controllable spatial parameters. For example, slower deformation behavior may be achieved by selecting lower infill densities and thinner structural wall thicknesses.

2) *Step 2: Parametric Modeling and Computational Simulation*

a) Geometric Modeling: Parametric modeling software (e.g., Rhinoceros/Grasshopper) is used to construct the three-dimensional geometry. Key dimensions, structural features, and material distributions are controlled through adjustable parameters, enabling rapid iteration.

b) Physics-Based Simulation: The parametric model is imported into a finite element analysis (FEA) environment—such as Abaqus, Karamba, or an equivalent open-source or commercial solver—and assigned the material properties of the selected SMP. Thermally induced deformation behavior is predicted by simulating the heating process. In cases where a fully coupled thermo-mechanical solver is unavailable, a simplified calibration-based model, derived from controlled-variable experiments (see Section 4.3), can be employed to guide design iteration.

c) Iterative Optimization: Simulation outcomes are evaluated against the target temporal parameters defined in Step 1. Spatial parameters — such as wall thickness, curvature, or infill density—are iteratively adjusted until the simulated dynamic behavior aligns with design expectations. This step replaces costly physical trial-and-error with efficient, low-cost digital iteration.

3) *Step 3: 4D Printing and Prototyping*

a) Slicing and Toolpath Planning: The optimized model is exported as an STL file and processed using commonly available slicing software (e.g., Cura or PrusaSlicer). Printing parameters—including layer height, nozzle temperature, printing speed, and infill pattern—function as micro-scale spatial parameters that directly influence deformation behavior. For reproducibility, all such parameters are fully documented.

b) Additive Manufacturing: Prototypes are fabricated using an FDM 3D printer compatible with thermo-responsive SMP filaments. In this study, a commercially available SMP filament with a glass transition temperature of approximately 60 °C (e.g., Polymaker polyMorph) is employed, though equivalent materials with similar Tg values may be substituted.

c) Post-Processing: Printed parts undergo necessary post-processing procedures, including support removal and surface finishing.

4) *Step 4: Programming and Validation*

a) Deformation Programming: The printed prototype is placed in a controlled thermal environment and heated above its glass transition temperature to soften the material. An external force is then applied to impose a temporary shape, followed by cooling below Tg to fix this configuration. This procedure constitutes the deformation programming stage.

b) Performance Testing: The shape recovery process is recorded under controlled thermal conditions. For reproducible measurement, deformation rate and response delay are extracted using consumer-grade video capture (e.g., smartphone recording) combined with marker-based tracking and open-source video analysis tools. Temperature is monitored using low-cost thermocouples or thermistors. When available, thermal imaging and 3D scanning may be employed to obtain higher-resolution spatial and temporal data.

c) Design Validation: Experimental measurements are compared with simulation results from Step 2 and the design targets established in Step 1. This comparison enables quantitative evaluation of the accuracy, reliability, and effectiveness of the proposed 4D composition design methodology.

C. Experimental Design

To validate the proposed Four-Dimensional Composition Design Framework and to generate quantitative evidence for the spatio-temporal coupling mechanism, a series of controlled-variable experiments was conducted. These experiments were designed to systematically investigate how key spatial parameters influence core temporal behaviors in deformable matter.

1) *Data Collection Method*

a) Independent Variables (Spatial Parameters)

Three spatial parameters that are both influential and readily controllable in 4D printing were selected as independent variables:

- structural thickness,
- infill density, and
- curvature.

b) Dependent Variables (Temporal Parameters)

Two primary indicators of dynamic behavior were defined as dependent variables:

- Deformation rate, measured as the average displacement speed of a designated marker point during the recovery process; and
- Response delay, defined as the time difference between the ambient temperature reaching the target value and the onset of observable displacement at the marker point.

c) Control Variables: To isolate the effects of the independent variables, all other experimental conditions were strictly controlled. The ambient temperature was maintained at a constant 75 ° C, and the same material batch, printer model, and printing parameters — including layer height, nozzle diameter, extrusion temperature, printing speed, cooling settings, and infill pattern — were used throughout all trials. A complete specification of these parameters is provided in Appendix/Table S1 to ensure reproducibility.

d) Sample Design: Each independent variable was examined at five discrete levels (e.g., thickness = 1, 2, 3, 4, and 5 mm). To balance statistical robustness with practical feasibility, an orthogonal experimental design was adopted (e.g., a Taguchi L25 array for three factors at five levels). Each experimental condition was repeated five times (n = 5), enabling reliable estimation of main effects while minimizing the total number of specimens required.

2) Data Analysis Method

a) Descriptive Statistics: Mean values and standard deviations (SD) were calculated for all measured variables to characterize central tendencies and data dispersion.

b) Analysis of Variance (ANOVA): One-way ANOVA was performed to determine whether variations in each spatial parameter produced statistically significant effects on the temporal parameters. The significance threshold was set at $\alpha = 0.05$.

c) Regression Analysis: For spatial parameters demonstrating statistically significant effects, linear or non-linear regression analyses were conducted to establish quantitative relationships between spatial and temporal variables. These relationships take the form:Temporal Parameter = f(Spatial Parameter).The resulting regression models serve as the algorithmic foundation for parametric design control and iterative optimization in the computational workflow described in Step 2.

d) Model Validation: The predictive accuracy and generalizability of the regression models were evaluated by comparing model predictions with data from additional experimental test groups not included in the initial fitting process.

Through this rigorously structured experimental methodology, the study seeks to transition from intuitive, experience-based design judgments toward quantitatively grounded and reproducible scientific relationships. By providing robust empirical support for the spatio-temporal coupling mechanism, these experiments close the theoretical - practical loop of the 4D composition design method and reinforce its reliability, predictability, and applicability in real-world design scenarios.

IV. Experiments and Results

This section presents the core findings of the study in two parts. The first part reports the results of a series of quantitative experiments conducted to establish the spatio-temporal coupling mechanism, revealing how key spatial parameters influence deformation behavior. The second part presents a comprehensive design case — an intelligent interactive lighting system titled Dynamic Rhythm — which demonstrates the application and validation of the proposed Four-Dimensional Composition Design Framework (4D-CDF) within a complete design process.

A. Quantitative Analysis of the Spatio-Temporal Coupling Mechanism

To bridge the gap between designers' qualitative intentions (e.g., "fast" or "slow") and engineers' quantitative parameters, we implemented and analyzed the controlled-variable experiments described in Section 4.3. These experiments systematically examined the effects of three spatial parameters — structural thickness, infill density, and geometric curvature — on two core temporal parameters: deformation rate and response delay.

1) Effect of Structural Thickness on Deformation Behavior

A series of flat rectangular specimens (curvature = 0) with thicknesses ranging from 1.0 mm to 5.0 mm were fabricated and tested at 100% infill density. As shown in Figure 3, structural thickness exhibited a significant non-linear influence on both deformation rate and response delay. With increasing thickness, the time required for heat to penetrate the interior of the structure increased substantially, resulting in a marked rise in response delay (Figure 3a). At the same time, thicker specimens possessed greater thermal capacity and internal stress, leading to a deformation rate that was initially slower and then gradually stabilized (Figure 3b).

One-way analysis of variance (ANOVA) confirmed that thickness had a highly significant effect on both response delay ($F(4,20) = 45.8$, $p < 0.001$) and deformation rate ($F(4,20) = 28.3$, $p < 0.001$). Regression analysis revealed a strong quadratic relationship between response delay (D_t) and thickness (T):

$$D_t \approx 1.8T^2 + 2.5T + 8.1 \quad (R^2 = 0.98) \tag{1}$$

These results demonstrate that thickness is a primary determinant of temporal responsiveness in SMP-based structures.

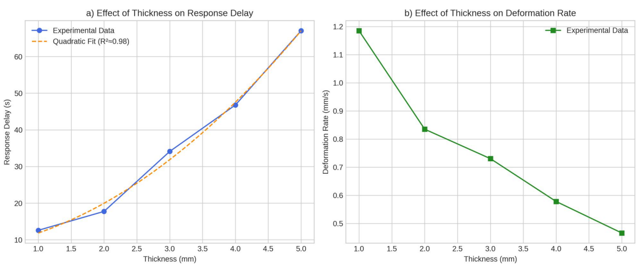

Fig. 3. Effect of structural thickness on deformation behavior. a) Quadratic non-linear effect of structural thickness on response delay; b) Effect of structural thickness on average deformation rate

2) Effect of Infill Density on Deformation Behavior

To isolate the influence of internal structure, specimens with a constant thickness of 2.0 mm and zero curvature were fabricated with infill densities ranging from 20% to 100%. As shown in Figure 4, infill density proved to be another critical parameter for temporal modulation. Lower infill densities created more porous internal structures, facilitating faster heat penetration and convection, and thereby significantly reducing response delay (Figure 4a).

However, excessively low infill densities (e.g., 20%) resulted in insufficient structural stiffness and reduced actuation force, which negatively affected the average deformation rate (Figure 4b). The deformation rate remained relatively stable within the 40% – 80% infill range. ANOVA results indicated that infill density had a highly significant effect on both delay ($F(4,20) = 55.2$, $p < 0.001$) and rate ($F(4,20) = 19.7$, $p < 0.001$).

These findings suggest that local modulation of infill density enables precise control of deformation timing and sequencing without altering external morphology.

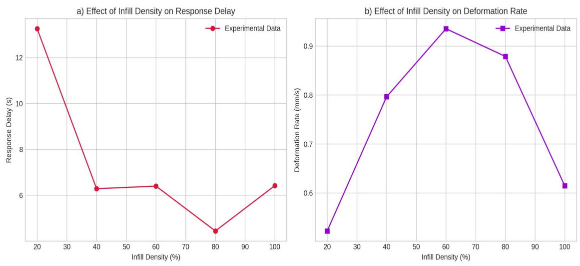

Fig. 4. Effect of infill density on deformation behavior. a) Negative correlation between infill density and response delay; b) Non-monotonic effect of infill density on average deformation rate.

3) Effect of Geometric Curvature on Deformation Behavior

The influence of initial geometry was further examined by fabricating arched specimens with varying curvatures (thickness = 2.0 mm, infill density = 100%). Results indicate that curvature primarily affects the initial deformation stage and final stability. Compared with thickness and infill density, its influence on average deformation rate and response delay was smaller, though still statistically significant ($p < 0.05$).

As summarized in Table I, specimens with larger initial curvature stored greater elastic potential energy, causing deformation to initiate more abruptly. At the same time, the total time required for full recovery to a flat state increased slightly. This observation suggests that geometric form itself functions as a means of energy programming, reinforcing the role of spatial composition in temporal behavior design.

TABLE I. DESCRIPTIVE STATISTICS OF DEFORMATION TEMPORAL PARAMETERS UNDER DIFFERENT INITIAL GEOMETRIC CURVATURES (N=5).

Curvature Radius (mm)	**Response Delay (s, Mean±SD)**	**Deformation Rate (mm/s, Mean±SD)**
0 (Flat)	19.79 ± 1.1	0.84 ± 0.04
100	21.62 ± 1.3	0.82 ± 0.03
80	22.32 ± 1.2	0.79 ± 0.05
60	22.82 ± 1.5	0.80 ± 0.04
40	24.07 ± 1.4	0.75 ± 0.05

Note: Statistical analysis shows that curvature has a significant effect on both delay and rate ($p<0.05$). Larger initial curvature results in slightly longer response delay but maintains relatively stable deformation rate.All measurements were conducted at 75°C using the same printer/material batch and identical printing settings; delay/rate were computed via video-based marker tracking (see Appendix/Table S1 for printing settings).

B. Design Case: "Dynamic Rhythm" Intelligent Interactive Lighting System

To validate the practical applicability of the 4D-CDF, we designed and implemented an intelligent interactive lighting system titled Dynamic Rhythm. The design goal was to create a lamp capable of simulating a life-like "breathing" rhythm to gently modulate ambient lighting.

1) Design Concept and Parameter Translation

The core of Dynamic Rhythm is a lampshade composed of multiple petal-like units that open and close dynamically. Upon receiving a touch input, the lamp is intended to bloom slowly and gracefully, then gently close after a short interval, producing a rhythmic and expressive interaction.

Following the 4D-CDF workflow, this qualitative design intent was translated into explicit temporal parameters:

- Periodicity (Opening/Closing Cycle): ~120 seconds (60 s opening, 60 s closing)
- Deformation Rate: Slow and non-linear, faster at initiation and slower toward completion; average rate ≈ 0.8 mm/s
- Response Delay: ~2 seconds after touch input
- Multi-Part Sequencing: Inner petals activate before outer petals to create spatial depth and temporal layering

2) Parametric Modeling and Simulation

Using the spatio-temporal coupling models established in Section 5.1, the target temporal parameters were reverse-mapped to operable spatial parameters. To generate sequential deformation behavior, inner petals were designed with thinner walls (T = 1.5 mm) and lower infill density (80%), while outer petals employed thicker walls (T = 2.5 mm) and higher infill density (100%).

A fully parametric model of the lampshade was developed in a parametric CAD environment (e.g., Grasshopper) and evaluated using a thermo-mechanical simulation workflow in an FEA solver (e.g., Abaqus). Simulation results predicted that, under a 75 ° C thermal stimulus, the inner petals would initiate deformation at approximately 15 seconds, while the outer petals would activate at approximately 28 seconds—closely matching the intended temporal sequence (Figure 5).

All parametric definitions, STL files, and simulation settings are provided as supplementary materials to support reproducibility.

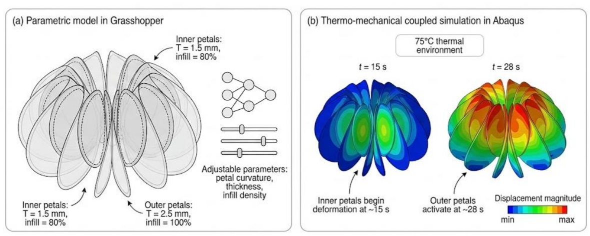

Fig. 5. Parametric modeling and computational simulation.(a) A parametric CAD definition (e.g., Grasshopper) enables flexible adjustment of geometric parameters such as petal curvature, thickness, and infill density. (b) A thermo-mechanical simulation using an FEA solver (e.g., Abaqus or an equivalent tool) predicts that inner petals (T=1.5 mm, 80% infill) begin deformation at ~15 s, while outer petals (T=2.5 mm, 100% infill) activate at ~28 s under a 75°C thermal stimulus.

3) Prototype Fabrication and Performance Evaluation

All lampshade components were fabricated using FDM 3D printing with SMP material and assembled with an LED light source, an Arduino-based microcontroller, and PTC heating elements to form the complete prototype system (Figure 6). All electronic components were off-the-shelf and low-cost, and equivalent hardware may be substituted without altering the workflow.

Performance testing showed strong agreement between simulation and physical behavior. The measured response delay averaged 17.2 s (SD = 1.8 s) for the inner petals and 30.5 s (SD = 2.5 s) for the outer petals, successfully achieving the designed deformation sequence. The average deformation rate was 0.75 mm/s, with an error of less than 7% relative to the target value. Furthermore, after 100 continuous opening - closing cycles, the system exhibited no significant performance degradation, maintaining a shape recovery rate above 98% (Figure 7).

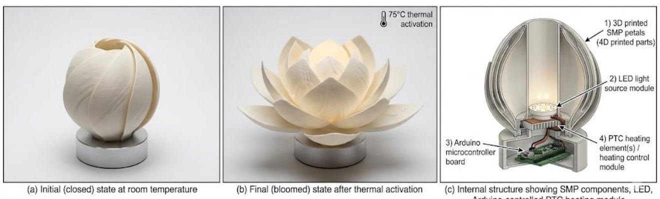

Fig. 6. Physical prototype of the "Dynamic Rhythm" intelligent interactive lighting system. a) Initial (closed) state at room temperature; b) Final (bloomed) state after thermal activation; c) Internal structure showing 3D printed SMP components, LED light source, and heating control module.

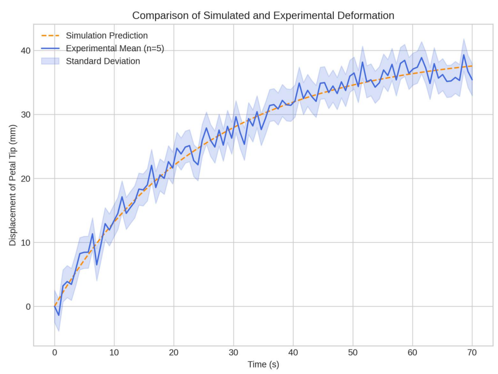

Fig. 7. Comparison of simulated and experimental deformation behavior. The curve chart compares the simulated displacement of the petal tip with the average displacement measured in 5 physical experiments, demonstrating high consistency and validating the predictive accuracy of our proposed spatio-temporal coupling model.

Fig. 8. User experience evaluation results presented in radar chart format. Based on 7-point Likert scale questionnaire responses from 12 users, the results demonstrate exceptionally high ratings in dimensions including "Organic," "Life-like," and "Novelty."

4) User Experience Evaluation

Finally, a preliminary user evaluation was conducted with 12 participants using a 7-point Likert scale questionnaire. As shown in Figure 8, participants rated the lamp highly in terms of being life-like (M = 6.8), organic (M = 6.5), and relaxing (M = 6.2). These results confirm that the 4D composition approach successfully translates controlled spatio-temporal behavior into positive aesthetic and experiential qualities. The moderate score for predictability (M = 5.5) suggests a balance between intuitive interaction and subtle surprise, which is desirable for ambient interactive systems.

V. Analysis and Discussion

The central contribution of this study lies in the proposal and validation of a systematic design methodology for deformable matter grounded in the theory of Four-Dimensional (4D) Composition. Through a combination of quantitative experimentation and a complete design case study, the research not only elucidates the intrinsic coupling between spatial parameters and temporal behavior, but also demonstrates the practical potential of this approach in the creation of expressive intelligent interactive systems. This section interprets the research findings in depth, situates them within existing scholarly work, and discusses their theoretical significance, practical implications, and current limitations.

A. Interpretation and Internal Logic of the Results

The results of this study reveal a coherent and complete logical progression from theoretical construction to empirical validation. The quantitative experiments presented in Section 5.1 constitute the empirical foundation of the proposed methodology. By systematically controlling spatial parameters—such as structural thickness and infill density—and measuring their effects on temporal parameters including deformation rate and response delay, the study successfully quantified these relationships and formalized them into computable mathematical models. These findings directly confirm the study' s central hypothesis: temporal behavior can be precisely programmed through spatial design.

This step is particularly significant because it establishes a reliable bridge between designers' qualitative temporal intentions (e.g., " the motion should be slower ") and engineers' precise, operable spatial parameters (e.g., "increase wall thickness to 3 mm"). In doing so, it transforms temporal design from an intuitive, experience-based practice into a predictable and controllable design variable.

The Dynamic Rhythm lighting system presented in Section 5.2 serves as a comprehensive application and validation of the Four-Dimensional Composition Design Framework (4D-CDF). The case study demonstrates that 4D-CDF is not merely an abstract theoretical construct, but a practical design tool capable of guiding the entire design process — from intent translation and digital simulation to physical fabrication and performance evaluation. By leveraging experimentally derived coupling relationships, the dynamic behavior of the system could be accurately predicted and optimized in a computational environment prior to fabrication. The high degree of agreement between simulation results and physical measurements (Figure 7) provides strong evidence for the scientific validity, predictability, and robustness of the proposed method.

Importantly, this shift represents a transition in deformable matter design from an experience-dependent trial-and-error approach to a data-driven and generative methodology, substantially improving design efficiency, reliability, and success rates.

B. Comparison with Related Work: Differentiation and Advancement

When situated within the broader research landscape, the distinctiveness of this study lies in its integration and advancement of several existing paradigms.

First, in comparison with the dominant engineering-oriented approach in 4D printing research, this study introduces a shift from a function-oriented to a process-oriented design perspective. Traditional 4D printing research primarily aims to achieve precise transformations between predefined states to fulfill specific engineering functions [27][28], often treating the deformation process itself as secondary. In contrast, the 4D composition approach foregrounds the deformation process — its rhythm, cadence, and expressive qualities — as the central object of design. By treating time as a composable design material, the proposed method enriches 4D printing with aesthetic, experiential, and human-centered dimensions.

Second, relative to the mechanical-driven paradigm prevalent in kinetic architecture, this research explores a fundamentally material-driven alternative. Conventional kinetic structures rely on external mechanical components such as motors, linkages, and actuators, which often result in complex, heavy, and maintenance-intensive systems with limited motion typologies [29][30]. By exploiting the intrinsic "intelligence" of morphing materials, this study integrates actuation, structure, and behavior into the material itself, enabling seamless, quiet, and organic transformations. This de-mechanized approach supports the development of lighter, more integrated, and more sustainable dynamic systems [31].

Finally, in contrast to the prototype-driven exploration common in shape-changing interface research within human–computer interaction, this study provides a theory-driven and systematic design methodology. While prior work has yielded numerous innovative prototypes, it often relies heavily on designer intuition and iterative experimentation, making successful outcomes difficult to generalize or reproduce [26][32]. The proposed 4D-CDF offers a shared analytical language and structured workflow that allows dynamic form design to be decomposed, predicted, and optimized systematically. In doing so, it lays a methodological foundation for the field to evolve from artisanal experimentation toward scalable and industrialized design practices.

C. Value, Implications, and Limitations of the Research

The value of this research manifests at both theoretical and practical levels. Theoretically, it represents a systematic extension of classical design composition theory into four-dimensional spacetime, offering a new conceptual lens for understanding and designing dynamic material systems. Practically, it provides designers with a complete and operable methodology that enables conscious and precise control over complex dynamic behaviors, thereby lowering the barrier to innovation in deformable matter design.

The broader implications of this work suggest that the convergence of smart materials and computational design may give rise to fundamentally new forms of products and interactions. Future domestic artifacts, for example, may evolve from static objects into responsive, life-like entities that engage users emotionally. Similarly, information displays may move beyond flat screens to communicate data through intuitive and expressive physical transformations. Such developments point toward a more organic and humane human–machine relationship, in which systems adapt to users rather than requiring users to adapt to machines.

Nevertheless, several limitations of the present study must be acknowledged. First, material limitations: the research focuses primarily on a single class of thermo-responsive SMPs, which exhibit relatively slow response times and require external heating, restricting applicability in scenarios demanding rapid or self-actuated responses. Second, scale limitations: the demonstrated design case operates at a desktop scale, and extending the methodology to architectural or infrastructural scales will introduce new challenges related to energy delivery, structural stability, and gravitational effects. Third, control simplicity: the current system employs open-loop, on/off thermal control, lacking integrated sensing and feedback. Truly intelligent systems would require closed-loop control capable of real-time adaptation. Finally, model simplification: the spatio-temporal coupling models developed in this study consider only a subset of influencing factors, while real-world deformation behavior is also affected by residual printing stresses and environmental fluctuations.

D. Future Research Directions

Building on these limitations, several promising directions for future research can be identified:

1) Multi-material and multi-stimuli systems: Investigating composite 4D printing with materials of varying properties (e.g., SMPs with different glass transition temperatures, elastomers, conductive materials) and alternative stimuli such as light, electricity, or magnetic fields to enable richer and faster deformation behaviors.

2) Integrated sensing and closed-loop control: Embedding flexible sensors within deformable structures to enable self-perception of shape and user interaction, coupled with machine learning algorithms to transition from pre-programmed behavior to adaptive intelligence.

3) Human factors and experiential metrics: Conducting in-depth studies on user perception and emotional response to temporal parameters such as rate, rhythm, and delay, with the goal of establishing quantitative experience metrics for dynamic form interaction.

4) Cross-scale applications: Applying the 4D composition methodology across a wider range of scales—from micro-scale biomedical devices to macro-scale architectural envelopes—to test and refine the generality and scalability of the approach.

VI. Conclusion

This study began by addressing the long-standing disconnect between theory and practice in the design of deformable matter and has successfully constructed and validated a systematic design methodology grounded in the theory of Four-Dimensional (4D) Composition. By treating time as an intrinsic design dimension and establishing a computable coupling relationship between spatial parameters and temporal behavior, the research demonstrates that designers can choreograph the dynamic form of matter with a level of precision, predictability, and creative freedom that was previously difficult to achieve.

The central conclusion of this work is that the Four-Dimensional Composition Design Framework (4D-CDF) offers a clear, effective, and operable pathway for the design of deformable matter. The framework enables the translation of abstract design intentions—such as "elegant" or "gentle" dynamics—into quantifiable spatio-temporal parameters. Through parametric modeling, computational simulation, and 4D printing, these parameters can then be faithfully transformed from digital concepts into physical prototypes. The successful realization of the Dynamic Rhythm interactive lamp provides direct evidence of the framework's effectiveness and illustrates the broader potential of theory-driven design in producing intelligent interactive systems that are expressive, reliable, and life-like.

At the theoretical level, this research extends classical design composition theory from three-dimensional space into four-dimensional spacetime, introducing a new conceptual language and analytical framework for understanding and designing dynamic material systems. At the practical level, it delivers a complete and reproducible workflow—from design definition to experimental validation—that lowers the technical barrier to controlling complex dynamic behaviors. In doing so, it supports the transition of deformable matter design from the domain of a small group of experts toward a more accessible and scalable design practice. More fundamentally, this work signals a paradigm shift in design thinking—from crafting static "objects" to composing dynamic "processes"—opening new imaginative possibilities for future developments in human–computer interaction, smart domestic environments, kinetic art, and adaptive architecture.

Nevertheless, several limitations remain. The study primarily relies on thermo-responsive shape memory polymers with relatively slow response speeds, focuses on desktop-scale applications, and employs an open-loop control strategy. These constraints point directly to future research opportunities. Subsequent work could explore multi-material composite 4D printing, integrate flexible sensing technologies to enable closed-loop adaptive control, and more deeply investigate users' temporal perception and emotional responses to dynamic form. Such efforts would further expand the applicability, intelligence, and experiential richness of 4D composition, advancing it toward broader and more sophisticated real-world applications.

References

[1] Patel, D. K., Zhong, K., Xu, H., Yao, L., Islam, M. F., & Yao, L. (2023). Sustainable morphing matter: Design and engineering practices. Advanced Materials Technologies, 8(16), 2300678. https://doi.org/10.1002/admt.202300678

[2] Walther, A. (2020). From responsive to adaptive and interactive materials and materials systems. Advanced Materials, 32(20), 1906111. https://doi.org/10.1002/adma.201906111

[3] Tibbits, S. (2014). 4D printing: Multi-material shape change. Architectural Design, 84(1), 116–121. https://doi.org/10.1002/ad.201300175

[4] Momeni, F., Hassani, N. S. M. M., Liu, X., & Ni, J. (2017). A review of 4D printing. Materials & Design, 122, 42–79. https://doi.org/10.1016/j.matdes.2017.02.074

[5] Mitchell, A., Lafont, U., Hołyńska, M., & Semprimoschnig, C. J. A. M. (2018). Additive manufacturing—A review of 4D printing and future applications. Additive Manufacturing, 24, 606–626. https://doi.org/10.1016/j.addma.2018.08.017

[6] Zarek, M., Layani, M., Cooperstein, I., Sachyani, E., Cohn, D., & Magdassi, S. (2016). 3D printing of shape memory polymers for flexible electronic devices. Advanced Materials, 28(22), 4449–4454. https://doi.org/10.1002/adma.201600806

[7] Forgacs, T., & Lung, T. (2017). Kinetic architecture: Designs for active envelopes. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100596-5.00005-4

[8] Rasmussen, M. K., Pedersen, E. W., Petersen, M. G., & Hornbæk, K. (2012). Shape-changing interfaces: A review of the design space and open research questions. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 735–744). https://doi.org/10.1145/2207676.2208541

[9] Coelho, M., & Zigelbaum, J. (2011). Shape-changing interfaces. Personal and Ubiquitous Computing, 15(2), 161–173. https://doi.org/10.1007/s00779-010-0364-7

[10] Kuang, X., Roach, D. J., & Qi, H. J. (2019). Advances in 4D printing: Materials and applications. Advanced Functional Materials, 29(2), 1805290. https://doi.org/10.1002/adfm.201805290

[11] Oxman, N., & Rosenberg, J. L. (2007). Material-based design computation: An inquiry into digital simulation of physical material properties as design generators. International Journal of Architectural Computing, 5(1), 25–44. https://doi.org/10.1260/147807707779784030

[12] Lupton, E., & Miller, J. A. (1991). The ABCs of the Bauhaus: The Bauhaus and design theory. Princeton Architectural Press. https://doi.org/10.2307/1251447

[13] Karim, M., & Chen, X. (2017). Digital design: Basic concepts and principles. CRC Press. https://doi.org/10.1201/9781315219066

[14] Smulders, M. M., Riddell, I. A., Browne, C., & Nitschke, J. R. (2013). Building on architectural principles for three-dimensional metallosupramolecular construction. Chemical Society Reviews, 42(4), 1728–1754. https://doi.org/10.1039/c2cs35408e

[15] Phillips, N. A. (1963). Geostrophic motion. Reviews of Geophysics, 1(2), 123–176. https://doi.org/10.1029/RG001i002p00123

[16] Krasner, J. (2013). Motion graphic design: Applied history and aesthetics. Routledge. https://doi.org/10.4324/9780203806040

[17] Lendlein, A., & Kelch, S. (2002). Shape-memory polymers. Angewandte Chemie International Edition, 41(12), 2034–2057.

https://doi.org/10.1002/1521-3773(20020617)41:12<2034::AID-ANIE2034>3.0.CO;2-8

[18] Ge, Q., Qi, H. J., & Dunn, M. L. (2013). Active materials by four-dimension printing. Applied Physics Letters, 103(13), 131901. https://doi.org/10.1063/1.4822678

[19] Gladman, A. S., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., & Lewis, J. A. (2016). Biomimetic 4D printing. Nature Materials, 15(4), 413–418. https://doi.org/10.1038/nmat4505

[20] Zhang, Q., Zhang, K., & Hu, G. (2016). Smart three-dimensional lightweight structure triggered from a thin composite sheet via 3D printing technique. Scientific Reports, 6, 19470. https://doi.org/10.1038/srep19470

[21] Barnes, M., Sajadi, S. M., Parekh, S., Rahman, M. M., Ajayan, P. M., & Verduzco, R. (2020). Reactive 3D printing of shape-programmable liquid crystal elastomer actuators. ACS Applied Materials & Interfaces, 12(25), 28692 – 28699. https://doi.org/10.1021/acsami.0c05821

[22] Felton, S., Tolley, M., Demaine, E., Rus, D., & Wood, R. (2014). A method for building self-folding machines. Science, 345(6197), 644–646. https://doi.org/10.1126/science.1252638

[23] Bodaghi, M., Damanpack, A. R., & Liao, W. H. (2017). Adaptive metamaterials by functionally graded 4D printing. Materials & Design, 135, 26–36. https://doi.org/10.1016/j.matdes.2017.06.029

[24] Hallnäs, L., & Redström, J. (2001). Slow technology–Designing for reflection. Personal and Ubiquitous Computing, 5(3), 201 – 212. https://doi.org/10.1007/s007790170016

[25] Pschetz, L., & Bastian, M. (2018). Temporal design: Rethinking time in design. Design Studies, 56, 169 – 184. https://doi.org/10.1016/j.destud.2018.01.004

[26] Qamar, I. P., Groh, R., Holman, D., & Roudaut, A. (2018). HCI meets material science: A literature review of morphing materials for the design of shape-changing interfaces. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (pp. 1 – 23). https://doi.org/10.1145/3173574.3173709

[27] Raviv, D., Zhao, W., McKnelly, C., Papadopoulou, A., Kadambi, A., Shi, B., & Tibbits, S. (2014). Active printed materials for complex self-evolving deformations. Scientific Reports, 4(1), 7422. https://doi.org/10.1038/srep07422

[28] Wu, L., Xia, X., Yin, W., Tang, X., Ju, J., Du, Y., & Yan, A. (2023). Enhancement mechanism of maximum energy product in hot-deformed Nd-Fe-B magnets by addition of ferromagnetic substances. Journal of Rare Earths, 41(12), 1984 – 1989. https://doi.org/10.1016/j.jre.2023.05.012

[29] Fox, M. (Ed.). (2016). Interactive architecture: Adaptive world. Chronicle Books. https://doi.org/10.14236/ewords/9781452145726

[30] Oborn, P. (2014). Al Bahr Towers: The Abu Dhabi Investment Council Headquarters. John Wiley & Sons. https://doi.org/10.1002/9781118732732

[31] Follmer, S., Leithinger, D., Olwal, A., Hogge, A., & Ishii, H. (2013). InFORM: Dynamic physical affordances and constraints through shape and object actuation. In Proceedings of the ACM Symposium on User Interface Software and Technology (Vol. 13, No. 10, pp. 250–259). https://doi.org/10.1145/2501988.2502032

[32] Choi, M., Park, J., & Jeong, Y. S. (2013). Mobile cloud computing framework for a pervasive and ubiquitous environment. The Journal of Supercomputing, 64(2), 331–356. https://doi.org/10.1007/s11227-012-0831-9

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Chufen Shao: Conceptualization, Methodology, Framework development (Four-Dimensional Composition), Parametric modeling, Investigation, Prototype design and fabrication, Data curation, Formal analysis, Writing — original draft. Huisheng Cheng: Supervision, Resources, Validation, Writing — review & editing.

COMPETING INTERESTS

The authors declare no competing interests.

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