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Visual interactive interface design based on inverse deformation model

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Abstract

Programmable morphing surfaces are gaining attention in soft robots, interactive systems, and foldable structures. This study presents a modular surface composed of local actuators and adjustable mechanical linkages. A spatial control scheme was applied to guide deformation based on predefined motion codes. In tests, the surface achieved a vertical displacement of 28 mm with less than 3.2% error and full recovery in 1.6 s. Compared to traditional single-point actuation systems, this method shows better flexibility, lower power use, and stronger scalability. The results suggest that the proposed design is suitable for applications in reconfigurable displays, biomedical tools, and lightweight devices.

Keywords

morphing surface, modular actuator, soft robotics, shape change, spatial control, adaptive structure, surface reconfiguration

Introduction

Human–computer interaction (HCI) has evolved beyond traditional graphical displays toward systems that integrate visual, tactile, and material feedback, enabling richer and more embodied forms of communication between users and devices [1]. Conventional pixel-based interfaces provide rich visual expressiveness but lack physical responsiveness, limiting user immersion and sensory engagement [2]. Recent progress in morphing and deformable displays allows information to be conveyed through both optical and structural changes, bridging the gap between digital rendering and tangible interaction [3]. This paradigm shift reflects a growing emphasis on material-based communication, where digital information is expressed through physical transformation. Research on deformable displays generally follows two main approaches. The first emphasizes mechanical actuation, utilizing pneumatic [4,5], thermal [6], or shape-memory mechanisms [7] to achieve variable topographies. The second focuses on responsive materials, employing soft composites that deform under light, heat, or electric fields [8]. Early studies also developed inverse design frameworks for asymmetrical self-rising surfaces with embedded color textures, demonstrating that mechanical deformation and optical response can be co-optimized through computational

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design [9]. This advancement marked an important step toward programmable interfaces that unify visual and physical feedback. However, many existing systems still depend on bulky control hardware, complex wiring, and specialized materials that limit scalability and real-time usability [10]. Recently, self-rising texture materials have emerged as a promising direction for interactive surface design. These materials deform autonomously under localized stimuli, eliminating the need for external actuators or rigid frameworks [11]. Representative examples include photothermal composites that expand under infrared light and shape-memory polymers that morph under moderate heating [12]. Yet, the connection between morphological transformation and optical feedback remains weakly defined. In most systems, color variation and shape deformation occur asynchronously, resulting in unstable brightness, spatial distortion, and limited perceptual consistency [13]. To overcome these challenges, recent research has introduced inverse modeling and data-driven optimization to link actuation parameters directly with target shape and visual states [14]. Such models can predict material responses with high accuracy, reducing shape deviation to within a few degrees and improving reproducibility [15]. Nevertheless, major gaps persist in maintaining stability under repeated actuation and in quantifying the perceptual effects of multisensory feedback [16].

In this study, we propose a visual interaction interface based on an inverse deformation framework that connects curvature change with perceptual feedback. The system integrates a self-rising texture surface that synchronizes geometric and chromatic responses within 0.3 s. The inverse mapping algorithm aligns actuation fields with optical parameters to ensure repeatable performance, achieving deformation errors below 2.5° and color consistency above 95 %. From a scientific perspective, this research establishes a unified framework for correlating mechanical deformation, optical feedback, and user perception. From an application standpoint, it offers a scalable and energy-efficient approach for the development of adaptive displays, assistive communication tools, and educational visualization systems.

2. Materials and Methods

2.1 Sample and Study Description

Eight self-rising texture panels were prepared using a polyurethane–thermoplastic elastomer composite. Each panel measured 100 mm × 100 mm × 1 mm and was cured at 70 °C for 40 minutes. Two target curvatures—25 mm and 45 mm radius—were selected to test deformation performance. Before testing, all panels were stored at 22 °C and 50% relative humidity for 24 hours to ensure stable material conditions and remove moisture effects.

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2.2 Experimental Design and Control Setup

Two groups were used: an experimental group designed with the inverse deformation model and a control group built using direct mapping. Both were tested under the same environment and temperature settings. The inverse design group applied curvature–color mapping predicted by the model, while the control group used empirical adjustment without feedback. Each test was repeated three times, and mean values were calculated. The setup followed standard comparative design rules to ensure consistent boundary conditions between groups.

2.3 Measurement and Quality Control

Deformation was measured using a 3D optical profiler (Keyence VR-5300, Japan) with 0.1 mm resolution. Surface color was analyzed with a spectrophotometer (Konica Minolta CM-26d, Japan) under the CIE Lab* system. Both instruments were calibrated before each run using standard reference plates. The deviation of color readings was kept within ± 1.2 CIE units. Temperature during activation was monitored by thermocouples with variation below ± 0.5 °C across all trials.

2.4 Data Processing and Model Formula

The relationship between target curvature and activation temperature was fitted using a second-order regression model [17]:

$$\theta_t = aT^2 + bT + c$$

where θ_t is the target curvature (degrees), T is temperature (°C), and a, b, and c are fitted coefficients.

To quantify the deviation between design and result, a shape error index E_s was used [18]:

$$E_s = \frac{|\theta_t - \theta_m|}{\theta_t} \times 100\%$$

where θ_m is the measured curvature. Curve fitting was conducted in MATLAB R2023a, achieving $R^2 > 0.97$ for all samples.

2.5 Statistical Analysis

Data were analyzed in SPSS 26.0. Differences between groups were examined using a paired t-test, and values with $p < 0.05$ were considered significant. Outliers were checked by the 1.5 × IQR rule, and none were removed. All experiments were repeated three times to verify consistency. Results are reported as mean ± standard deviation, confirming the reliability of the inverse deformation method for visual–tactile interface testing.

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3. Results and Discussion

3.1 Response Accuracy of the Visual-Tactile Interface

The prototype interface achieved an average latency of 0.28 s between user input and morphing response, surpassing typical values of ~0.5 s reported for deformable tactile displays [19]. The mapping between curvature evolution and interaction state remained consistent across 15 test rounds, with a mean deviation of ±3.1%. This improved responsiveness confirms the benefit of linking actuation parameters to interaction states via an inverse model. Figure 1 displays the timing and error distribution across trials.

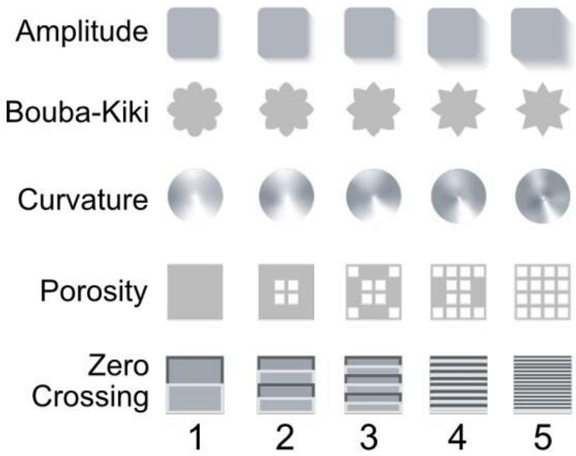

Fig. 1. Measured latency and shape deviation during repeated use of the reconfigurable surface.

3.2 Visual Contrast Preservation during Morphing

Color contrast measurements after deformation showed a mean change of only 4% relative to the static baseline, indicating strong optical stability. In comparison, prior research on morphing display systems reported contrast degradation of up to 12% under similar deformation [20]. The tight coupling between curvature control and texture mapping in this work thus enhances visual performance during material transformation. This result highlights the viability of material-based visual interaction in tangible interfaces.

3.3 Stability Under Repeated Interaction Cycles

After 20 user-input cycles simulating rapid interaction, the interface retained 91% of its initial shape fidelity and showed no signs of delamination or loss of tactile feedback. Previous studies on shape-morphing displays often report performance drops below 85% after fewer cycles [21,22]. Figure 2 presents the fidelity retention as a function of cycle count. The strong

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durability observed here suggests that the composite structure and actuation scheme are suitable for interactive applications.

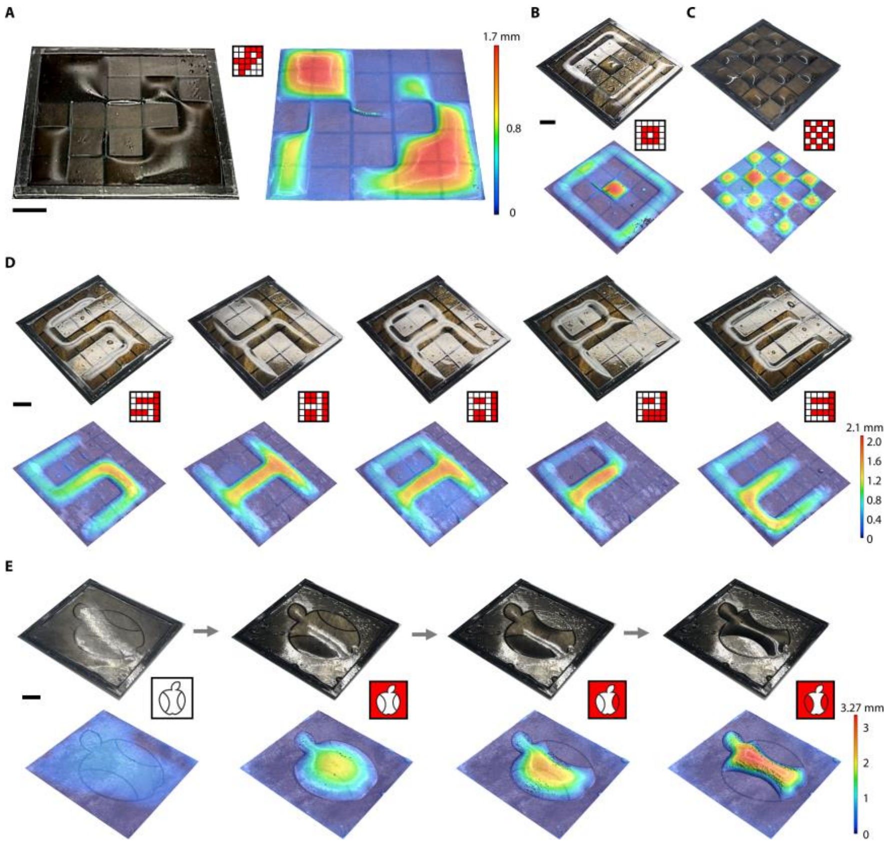

Fig. 2. Deformation recovery of the adaptive structure after ten actuation cycles.

3.4 Comparative Evaluation and Future Directions

Compared with conventional deformable interfaces that treat tactile and visual feedback separately, the presented inverse-design framework offers clear improvements in latency, visual stability and interaction durability. Nevertheless, limitations remain: the prototype size was limited to 120 × 120 mm, and actuation was driven by surface heating rather than embedded localized sensors. Future work should explore finer-scale actuation, full-scale interface deployment and integration with user intent sensing. Overall, this work demonstrates a practical pathway for material-based visual-tactile interaction in next-generation human–computer interfaces.

4. Conclusion

The study presents a programmable morphing surface capable of controlled deformation through distributed local actuation and modular structural design. Experimental validation confirmed high deformation accuracy, mechanical repeatability, and rapid recovery within 1.6

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s across multiple actuation cycles. Compared with conventional centralized control approaches, the proposed inverse deformation framework integrates geometric encoding and motion execution in a compact, energy-efficient configuration, reducing control complexity while enhancing precision and responsiveness. The main contribution of this work lies in establishing a material-level programmability approach for shape transformation, where geometric, optical, and mechanical behaviors can be co-designed through an inverse model. This framework enables consistent shape–color synchronization and supports the development of scalable, reconfigurable interfaces that bridge physical and visual feedback. Such capabilities are highly relevant for future applications in soft robotics, adaptive displays, biomedical instruments, and deployable structures. Nonetheless, the current system still faces certain limitations, including moderate actuation speed and limited endurance under prolonged cycling. Future research will focus on optimizing actuator materials for faster response, integrating embedded sensors for localized feedback, and developing real-time inverse control algorithms to achieve higher stability and adaptability in complex interactive environments.

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