Towards 6G and Beyond: Smarten Everything with Metamorphic Surfaces

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ABSTRACT

6G is on the horizon. A key paradigm being proposed for 6G involves a shift from device-centric to user-centric services, i.e., multiple devices collaborate to serve user demands. This paradigm shift and the potential applications require handling wireless signals from multiple sources collectively in a 3D space and potentially at close proximity to the end user. Conventional approaches of optimizing individual communication endpoints are ill-suited to collaborative 3D signal shaping. Recent *smart surface* proposals to program the radio environments appear a better fit, but existing designs implicitly require planar, rigid substrates. Optimizing 3D coverage would require very large surface implementations and incur many scalability and deployment challenges. In this paper, therefore, we propose a notion of *metamorphic smart surfaces*, i.e., shape-changing smart surfaces to cater to complex 3D propagation environments. Based on early explorations with HFSS simulations and two simple prototypes, we discuss the pros and cons of metamorphic surfaces and potential future directions.

CCS CONCEPTS

• **Hardware** → **Wireless devices**; **Analysis and design of emerging devices and systems**;

KEYWORDS

Metamorphic Surfaces, Programmable Radio Spaces, 6G

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1 INTRODUCTION

Wireless connectivity forms the backbone of diverse Internet of Things (IoT) services. With 5G in early deployment, 6G is starting to take the center stage of the research world. It is expected that future wireless networks will interconnect the physical and digital worlds via distributed, intelligent communications, sensing, and computing. In particular, 6G technologies and beyond are expected to tap into pervasive, human-centric, data-rate-intensive applications such as holographic, tactile and human-bond communications [5, 14, 25, 34] to enable sensory interconnection remotely. Besides supporting information transfer, it is anticipated that emerging wireless infrastructures will support low-power operations via techniques like ambient backscatter and wireless power transfer [14, 25, 36]. Whether to transfer information or power, optimal beamforming to direct RF energy propagation will be essential to realize the 6G vision. As IoT devices continue to diversify, we are increasingly contending with managing wireless propagation in complex 3D geometries [43].

Until recently, typical IoT designs tend to be endpoint-centric, reflected in radio or protocol designs at the sender and the receiver (including decode-and-forward relays used in mesh networking) of a wireless link [39]. They are ill-suited to shaping the signal propagation behavior over the medium, and hence are far from the most effective "signal shapers". While various analog relay systems [4, 9] can route signals, they still provide limited capability in shaping the signals while incurring significant design complexity.

An emerging concept is to instrument the environment with reconfigurable devices to alter the signal propagation behavior directly. Variously referred to as *reconfigurable intelligent surfaces*, *smart surfaces*, or simply a new form of massive MIMO [8, 10–12, 15, 17, 19–23, 26–31, 34, 38–40, 42–44], these proposals aim to customize passing signals in real time and improve the perceived channel conditions at the endpoints. The early end-to-end prototypes to date use commodity antenna arrays or specially constructed metasurfaces [6, 12, 13, 16, 27, 43]. The former adopt discrete array element layouts, whereas the latter embrace roughly continuous unit interactions. These prototypes have all focused on instrumenting a planar, rigid substrate in an indoor environment. To achieve pervasive 3D beamforming and coverage, these surfaces will need to be sufficiently large. This then incurs scalability issues in terms of hardware complexity and deployment constraints.

In this paper, we propose the notion of smart *metamorphic surfaces*, i.e., "soft" reconfigurable surfaces that can change the surrounding RF propagation behavior via shape change. The addition of a "soft" touch to existing work is motivated by two observations. First, metamorphic surfaces can be non-planar, which can potentially achieve high 3D beamforming quality with less hardware. Second, metamorphic substrates can be non-rigid, lending to easy placement overlaid on diverse objects and shape change to adapt signal coverage, thus expanding previous application scenarios. Large soft substrates like curtains or tents are suitable as indoor-outdoor interfaces for long-range operations. At another end of the spectrum, garments are closer to the wireless user than furniture or walls and are uniquely suited to human-centric body area or medical implant applications, potentially becoming part of a tactile Internet [18], i.e., extending real-time haptic interactions over the Internet through ultra-low latency communication. This aligns with the projected shift from device-centric to human-centric operations for 6G [25].

In the rest of the paper, we present an exploratory study along with thoughts for future work. Considering the 3D beamforming capability, we discuss the potential and design considerations of metamorphic surfaces (§2). Using simple reflective antenna array-based surface designs, we then explore two surface shape-change modalities with HFSS (High-Frequency Structure Simulator) [1] simulations and two early prototypes (§3). Compared to a planar surface, a spherical surface can achieve the same 3D beamforming quality using 23% to 68% *less* hardware. Experimental results with the prototypes show that, even without precise control over their shapes, the metamorphic surfaces can increase the received signal strength at endpoints by up to 15 dB. These results highlight both opportunities and challenges from shape changes (§4).

2 TOWARDS METAMORPHIC SURFACES

We first examine the key limitations of previous surface designs to argue for metamorphic surfaces instead, and then discuss design challenges.

2.1 Why Shape Change

The applications that will drive the 6G revolution will require unparalleled environmental control over signal propagation. However, existing surface designs are susceptible to significant deployment complexity, regardless of whether they are built into or retrofitted to the underlying built structure.

Limitations of existing surfaces. In terms of *scalable* deployment, previous designs suffer from two main drawbacks.

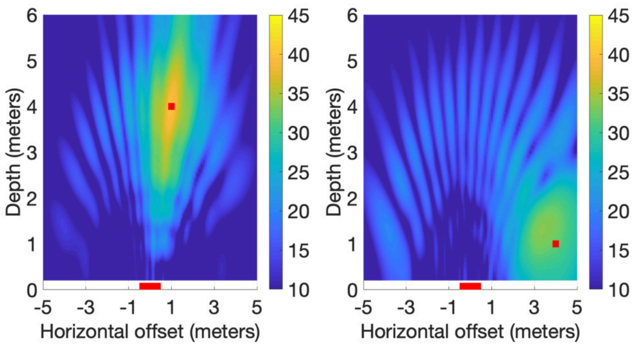
First, they are implicitly flat, i.e., with a planar element layout. This constrains the 3D beamforming efficiency of a surface, since a target point can never receive the optimal contribution from all individual elements simultaneously. This is the case regardless of the per-antenna beam pattern. This means planar surfaces might need to be prohibitively large, requiring significant amounts of hardware, to cover a reasonably-sized area. These designs are also implicitly optimized for 2D signal coverage, except [43].

To illustrate this, we simulate a planar surface with a 16×16 patch antenna array in HFSS. To focus our attention on the power delivery from the surface to the receiver, we set each antenna as an active signal source. The surface beamforms towards two different target locations by setting appropriate phase shifts on the signals from the antennas: first a target in front of the surface, at (2,1,4) meters (Figure 1(a)); then a target with a large horizontal offset, at (2,4,1) meters (Figure 1(b)). We use the coordinate system labeled in Figure 3(b) throughout the paper. We measure the signal power on a horizontal plane 2 meters above the surface. Although the antennas are linearly polarized, we measure the sum power across both orthogonal polarization orientations. While both targets are equidistant from the center of the surface, beamforming suffers over 5 dB loss at the second target point compared to the first one due to a large horizontal offset. This suggests that the surfaces would have to be prohibitively large to avoid any such offsets, i.e., by ensuring optimal phase alignment between the surface elements closest to the beamforming target, and optimize for the entire 3D space.

Second, existing surface designs are rigid and often implicitly assume deployments across walls. Surfaces have better performance near the origin or destination of wireless signals, which may not be near walls. The rigidity, combined with the potential size for a large coverage area, constrains the locations of feasible deployments.

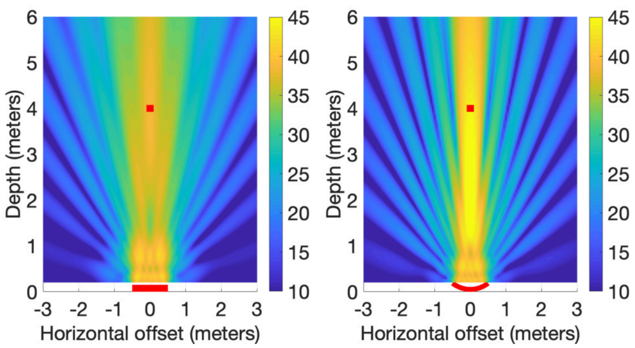
Breaking away from planar, rigid surfaces. The proceeding discussion hints at instead deploying non-planar, non-rigid smart surfaces, i.e., *shape-changing surfaces*, to improve 3D beamforming efficiency. We hypothesize that a non-planar element layout is more efficient at beamforming energy, as seen in previous circular arrays or spherical "surface" designs ranging from satellite dishes to radio telescopes. On the other hand, a non-rigid design is amenable to flexible deployment settings beyond walls and can provision large surface coverage areas via shape change instead of pervasive surface hardware deployment.

To validate our intuition, we compare the aforementioned planar surface (Figure 2(a)) to a *spherical* surface (Figure 2(b)),



(a) (b)

Figure 1: Signal power distribution (dB) when a planar surface (red line) beamforms towards a target (red dot): (a) directly in front; (b) with a large horizontal offset.



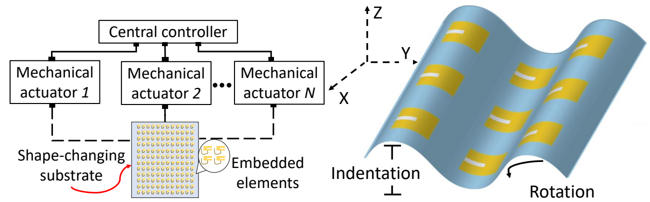
(a) (b)

Figure 2: Signal power distribution (dB) when beamforming towards a point 4 meters in front of the surface using: (a) planar vs. (b) spherical surface.

both embedded with the same 16×16 patch antenna array. Each antenna on the spherical surface *orients* towards the target point, 4 meters in front of the surface center, while the antennas on the planar surface *beamform* towards the same point via phase alignment. We then measure the signal power on the horizontal plane through the center of each surface. The spherical surface shows a narrower beam and a higher power at the target point. This suggests that shape-changing surfaces can potentially perform 3D beamforming in a more scalable way.

2.2 Design Considerations

We expect the general system architecture of a metamorphic surface to resemble that of similar surfaces, as shown in Figure 3(a). The surface consists of a shape-changing substrate, electronic units (or *elements*) embedded in the substrate to interact with incident electromagnetic waves, an actuation mechanism to position the elements in a desirable layout (or surface *shape*), and a central controller to make the actuation decisions. Realizing this vision poses three challenges:



(a) System architecture. **(b) Shape-change modalities.**

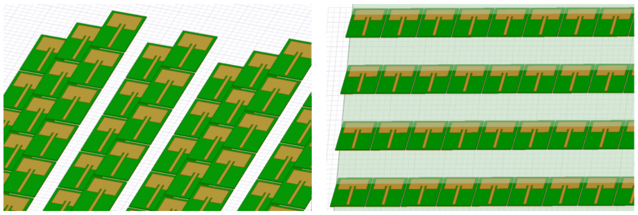
Figure 3: Metamorphic surface design.

Challenge 1: Substrate design and element embedding. The first challenge is to identify the material characteristics of the underlying substrate to allow shape change. The design decision will depend on a balance between the natural intended usage of the substrate and its ability to offer different shape change modalities. At one end of the design spectrum, it can be fabricated with ultra-flexible soft materials, like cloth and plastic film; at another end, it can be manufactured with stiff components but permit a dynamic geometric arrangement.

Furthermore, since metamorphic substrates will not provide new signal manipulation modalities, incorporating electronic elements (e.g., patch antennas) into the substrate and determining an adequate geometric disposition are key. The elements can be woven into the fabric, in a process reminiscent of e-textile manufacturing [33], or they can simply be attached with adhesives. The choice may depend on whether the surface reflects or transmits incoming signals. The latter, for instance, requires through-surface waveguide circuitry that might prohibitively complicate element embedding.

Challenge 2: Channel conditions inference and channel-to-shape mapping. As with any environment-centric approach, knowledge of channel conditions is necessary to derive desirable surface shapes to optimize for RF energy propagation at arbitrary 3D locations. So far only LAVA [43] can operate independently from endpoint-provided channel feedback to provide amplify-and-forward, relying on pervasively deployed power sensors to infer active communication sessions.

Moreover, given an endpoint location, the initial element arrangement, and the current perceived channel conditions, a metamorphic surface must map a target environmental state to a specific surface shape. This *channel-to-shape* mapping necessitates a procedure to ascertain which shape best fulfills a given optimization objective. This procedure might be bootstrapped with offline measurements, and can be refined through iterative online optimization techniques. Machine learning models, for example, have already been used to adjust the shape of soft robots [35] and other everyday objects [37, 41].



(a) Indented **(b) Rotated**

Figure 4: Metamorphic surface designs in HFSS.

Challenge 3: Practical and systematic surface actuation. Once channel conditions have been mapped to a specific surface shape, the surface needs to be actuated to "implement the shape". This actuation has to be practical, timely and conducive to the natural function of the substrate.

Unlike previous end-to-end surface prototypes, which take for granted predictable control of discrete-state circuit components (e.g., phase-shifting circuits and RF switches), shape-changing surfaces face the unique challenge of ensuring deterministic *shape-to-control* mapping under the influence of unpredictable physical variations in the underlying substrate. That is, we need to guarantee that a surface shape is reliably set by a predictable sequence of surface *control states*. This is particularly challenging for metamorphic surfaces built on ultra-flexible fabrics. It is critical to determine the fundamental dimensions along which the substrate can be actuated at a sufficient granularity. This actuation granularity will in turn prescribe the number of possible shapes and the number of concurrent endpoints that can be supported.

3 AN EXPLORATORY STUDY

In view of the aforementioned challenges, we sample the design space of metamorphic surfaces through both HFSS simulations and prototype-based experiments. In both cases, we consider simple surfaces made of only dense patch antenna arrays that reflect (or backscatter) incoming signals, and any actuation is applied to the entire surface uniformly. The simulations (§3.1) highlight the potential of achieving the same beamforming performance with fewer elements (antennas) through different shape change modalities in idealized settings. The prototypes, a motorized curtain (§3.2) and motorized blinds (§3.3), correspond to natural objects at the indoor-outdoor interface (§1). They represent non-rigid substrates at opposing ends of the design spectrum and shed light on the potential and challenges of electromechanical actuation and deterministic shape control.

3.1 Simulating Shape Change Effects

We assess the effects of shape change through the simulated beam steering performance of the surface. We consider two basic *shape-change modalities* (Figure 3(b), with the surface laid on the X-Y plane): (a) *indentation*, i.e., changing the relative offset between elements along the Z-axis; and (b) *rotation*, i.e., changing the orientation of the elements around the X-axis (Figure 3(b)) or the Y-axis (Figure 4(b)).

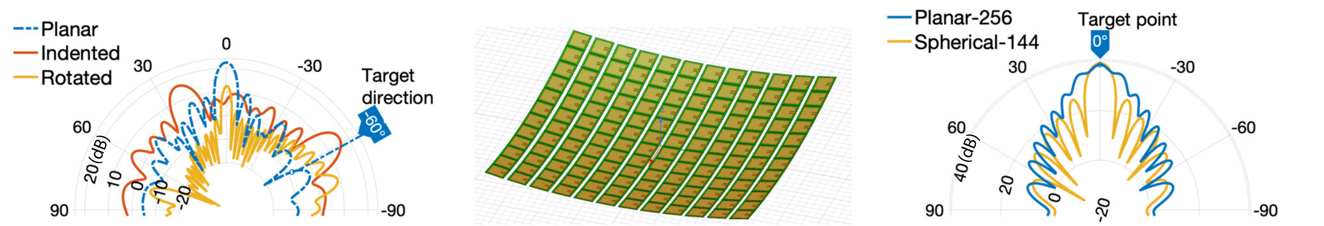
Surface indentation. We begin by simulating a phase-shifter based 256-element reflective planar surface. Each element is a 2.4 GHz patch antenna with open-ended transmission lines, and therefore re-radiates incoming signals due to impedance mismatch. The incoming signals are plane waves with 1 V/m amplitude, propagating downwards from **Z**+. We steer the reflected beam at an angle of -60° by setting the appropriate length for each transmission line. The variable-length transmission lines work as phase shifters for the reflected signals, similar to the designs in [16, 39]. For comparison, we also simulate a 256-element reflective surface with indented columns, a section of which is shown in Figure 4(a). In this design, elements have uniform-length transmission lines, but the surface induces variable phase shifts through indentation. The extent of indentation is set to achieve the same phase shifts as the planar surface.

Figure 5(a) shows the far field radiation pattern of these two surfaces. The beam from the indented surface is around 15 dB stronger. This corresponds to a perceived SNR gain at far-field endpoints placed along this direction. This suggests spatial indentation can achieve phase shifts with much higher efficiency compared to phase shift circuitry.

Surface rotation. Next, we generate a 256-element reflective surface with rotatable rows (a section shown in Figure 4(b)). We compare the rotated surface to its planar counterpart using an identical setting to the previous simulation. To steer the beam towards -60°, we rotate each row of the surface by 30°. The rotated surface generates a beam at 0° and multiple side lobes pointing towards -60° (Figure 5(a)). It shows around 5 dB gain relative to the planar surface, thanks to the side lobes induced by the rotation. More notably, we can achieve accurate rotation easily in practice (§3.3).

Combining shape-changing modalities. Finally, we derive a spherical shape by combining rotation and indentation. Figure 5(b) shows a 144-element spherical surface. For this simulation, we use active antenna elements, i.e., each antenna has an active signal source. We set the power of each antenna to 0.1 W and control the input signal phase to achieve beamforming. By using the active element design, we keep the beamforming gain comparison comparable, while avoiding confounding factors such as how phase shifts are induced.

Figure 5(c) shows the near field radiation pattern of a 256-element planar surface and a 144-element spherical surface. Both surfaces beamform towards a point at 4 m in front of either surface. We take measurements along a circle with a radius of 4 meters, on which 0° is the target point. Both surfaces show equal peak power at 0°. This implies the spherical



(a) (b) (c)

Figure 5: HFSS Simulations. (a) Radiation patterns of planar, indented, and rotated surfaces; (b) Spherical surface design with 144 antennas; (c) Radiation patterns: Planar vs. spherical surfaces. The 144-antenna spherical surface can achieve the same signal power at the target point as the 256-antenna planar surface.

(a) (b)

Figure 6: Metamorphic surface prototypes: Motorized (a) curtains and (b) blinds with adhesive antennas.

sphere achieves the same beamforming performance with 44% less hardware, due to a more focused beam. Further simulations show that, at 2 meters from the surface center, an 81-element spherical surface (68% less hardware) is equivalent to a 256-element planar surface; at a 6-meter distance, a 196-element spherical surface (23% less hardware) is comparable to the same planar surface.

3.2 Prototype 1: Motorized Curtain

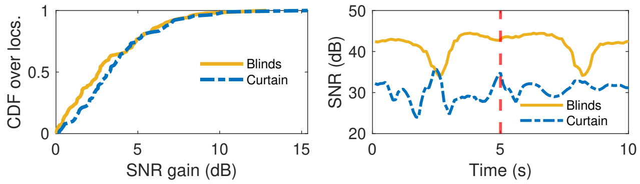
Design. Our first metamorphic surface prototype, shown in Figure 6(a), is a piece of off-the-shelf cloth curtain with adhesive FlexNotch flexible antennas [3] attached. The antennas are organized in a 15×12 grid and their transmission lines are left open. The distance between elements is such that, theoretically, mutual coupling and grating lobes are minimized [7]. This surface roughly corresponds to the indented surface studied in §3.1 and can be considered a soft version of the simplest planar surface to date, RFocus[6]. Since the elements are not individually configurable and the surface can only reflect/backscatter incident signals, it highlights the potential and limitations of free-form shape changes.

Control and actuation. The curtain is suspended on a remotely controlled motorized rail, with a mobile glider attached to the curtain. We use an Arduino and an infrared LED to replicate the track's messages to open and close the curtain. The location of the glider defines a control state leading to wide-ranging curtain shape changes. Curtain actuation is then achieved by selecting one of 20 distinct states.

Experiments. We run experiments in a 10 m by 7 m area, comprising an office and the adjacent hallway. We use WARPv3 nodes with Vert2450 antennas [2] to set up single-antenna OFDM links centered at 2.462 GHz. The transmitter and the curtain prototype are placed at fixed locations inside the office. The transmitter is aligned 50 cm away from the middle section of the surface. To capture the behavior in a 3D space, we move the receiver around the hallway to 90 different locations with varying horizontal and vertical offsets between the endpoints.

For each link, after collecting the baseline SNR measurements without the curtain, we iterate over all curtain control states, measure the SNR gains, and record the maximum SNR gain. Figure 7(a) shows the CDF of the maximum per-link SNR gain over all locations. By simply gliding the curtain along the track, we can derive up to 15 dB of SNR gain across different horizontal and vertical offsets in the 3D space. This is most likely due to the indentations that occur across different columns of the antenna array, matching the simulation results in §3.1.

Next, we evaluate the fidelity of the surface channel-to-control mapping. Figure 7(b) shows the SNR on a link measured over 10 s. The curtain is in front of one endpoint and moves along the track from left to right during the first 5 s at intervals corresponding to the curtain states, then from right to left for the remaining 5 s. If each control state yielded the same surface shape, and therefore exerted deterministic effects on the channel conditions, we would expect to see a symmetric plot about the 5 s time point. Unfortunately, that is not the case, which indicates that this actuation mechanism does not produce reliable mappings between curtain control states and channel conditions.



(a) SNR gain in 3D space **(b) Channel mapping**

Figure 7: Metamorphic surface performance.

3.3 Prototype 2: Motorized Blinds

Design. Our second prototype (Figure 6(b)) uses common household window blinds made of stiff horizontal plastic slats. We attach the same open-ended adhesive flexible antennas, arranged in a 30×11 grid. This surface represents a rigid substrate allowing limited but precise and repeatable geometry changes, and roughly corresponds to the rotated surface simulated earlier (§3.1).

Control and actuation. We use an Arduino-controlled motor to rotate all the horizontal slats of the blinds. This prototype has 50 states, and the slats can be rotated by discrete angles that are multiples of 3.6°.

Experiments. We use the same experimental setup as before. Figure 7(a) shows that, by simply changing the orientation of the horizontal slats in the blinds, this prototype can provide up to 13 dB of SNR gain across multiple horizontal and vertical offsets between the communication endpoints. We then perform a similar "predictable control" study. Figure 7(b) shows the SNR on a link measured at discrete time intervals over 10 s while the blinds are rotated, upwards in the first 5 s and downwards otherwise. This curve shows symmetry around the 5 s mark, suggesting a deterministic and repeatable mapping between the surface control state and its effects on the surroundings.

4 DISCUSSION

Lessons learned. Our prototypes end up providing similar gains in the 3D space but highlight trade-offs between surface flexibility and fidelity. The cloth substrate for the curtain permits any desirable shape changes. This is amenable to more diverse deployment settings, such as garments and upholstery furniture, but is susceptible to fickle physical deformations that inhibit deterministic shape control. The blinds behave predictably, but in more limited ways. A practical substrate should strike a balance between the two extremes.

Moreover, our prototypes leverage two simple electromechanical actuators operating over the entire surface. Finer-grained actuation can generate more diverse surface geometry and improve the repeatability of the shape change. It can also enlarge the surface state space to better support concurrent links.

Separately, the reaction speed of the actuator will dictate the nature of supported applications. In our experiments, it takes about 10 seconds to explore all the states of either prototype. This is certainly too slow for per-frame channel adaptation, but may be sufficient for slow-time-scale adaptions, e.g., pointing the same surface to a desk in the morning but a couch in the evening.

Finally, our simulations and experiments suggest that simple surface layout designs combined with shape change can already generate favorable channel conditions. This lends to a small search space to optimize for the surface effect, compared to existing rigid, planar surface designs. However, more systematic mapping procedures are needed, and we still face the usual challenges of identifying the endpoint conditions and optimization goals.

Interplay with user experience. As we might anticipate overlaying diverse objects with metamorphic surfaces, it is crucial to ensure that the surface control does not conflict with the natural intended usage of the objects. For example, the curtains may need to be open during the day and closed at night, limiting the shape change possibilities. Optimizing for human comfort for 6G services will necessitate joint consideration of different surface functionalities.

Other shape-changing applications. Beyond leveraging shape change to scale surface deployments, we believe metamorphic surfaces offer synergy with other application domains. For example, a recent work [32] employs mechanically reconfigurable surface layouts to convey real-time traffic information and smarten transportation infrastructure. Shape-shifting soft robotic fabrics [35] can naturally serve as substrates for metamorphic surfaces. Taking a leaf from previous research on textiles [33] and physiological sensing [24], we believe research on metamorphic surfaces is inherently interdisciplinary, weaving together mechanical control, sensing, ergonomics, and wireless system design.

5 CONCLUSION

We propose the notion of *metamorphic surfaces* as a new direction for shaping wireless signal propagation. Using simple reflective antenna array-based surface designs, we explore two shape-changing modalities for surface actuation. Simulations show that, compared to a planar surface, a spherical surface can achieve the same 3D beamforming quality using 23% to 68% *less* hardware. Experimental results with two early prototypes show that, even without precise control over the proposed shape-change modalities, the received signal strength can be increased by up to 15 dB. We believe metamorphic surfaces offer new degrees of freedom for 6G wireless system design, contributing to both the vision of pervasive human-centric services and *smart surfaces.*

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