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Bioinspired and Biobased Material Programming

Self-Shaping and Responsive Systems for a Sustainable Future

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Introduction

This article proposes a bioinspired approach to design and fabrication as an alternative to conventional methods of making. Through an integration of material, structure, and function, plants change shape over a range of spatial- temporal scales in response to environmental stimuli. The bioinspired interplay of cellulosic materials, mesostructures, and adaptive motions is enabled through material programming and 4D-printing, resulting in self- shaping and biobased hygromorphic systems powered by the free-flowing moisture inputs of the environment. This approach is transferable to diverse materials and processes, as showcased through the upscaling of the developed methods to industrial robot platforms and hybrid materials systems for constructing responsive furniture-scale objects. From self-adjusting orthotic devices to weather-responsive building facades, this work demonstrates the wide-ranging potential of bioinspired and biobased transformation across scales and disciplines by applying design principles from biology to body and building.

Anthropogenic Systems

Although humans account for only about 0.01% of all biomass (Bar-On, 2018), their impact on the Earth outweighs any other species. Human activities are responsible for the changing climate, disrupting the usual balance of nature through the emission of greenhouse gases. Since 1900, anthropogenic mass has grown rapidly from roughly 3% of the world's biomass to surpassing it today (Elhacham, 2020). This estimate considers only human-made artifacts that are in use, from bridges and skyscrapers to clothing and smartphones, which will eventually become waste to be dealt with.

As the second most used substance in the world, after water, concrete is found all over the built environment (Gagg, 2014). Indeed, the embodied carbon of high impact building and infrastructure materials are responsible for 9% of annual global CO2 emissions, while building operations generate 27% (UNEP, 2022). Combined, the buildings and construction sector account for 40% of total emissions. Moreover, the growing population will necessitate the provision of increased urban development, housing, and goods for daily life (UN, 2019). Continuing our current practices will exacerbate the health of the planet and the supply material resources that we rely on (IPCC, 2021).

Natural & Bioinspired Systems

Nature, however, demonstrates another approach. In fact, natural ecosystems are productive, managing interactions between producers, consumers, decomposers, and the environment in a balanced cycle. Moreover, the ability of plants to move without active metabolism has long intrigued scientists, from the self-burial of the Erodium seed awn (Jung, 2014) to the self-opening of conifer cone scales (Eger, 2022). As such, their functional morphologies have served as a rich source of inspiration for humidity-actuated material systems, such as self-drilling seed carriers for aerial seeding (Luo, 2023) or self-shaping flaps (Reyssat & Mahadevan, 2009) for architectural applications (Reichert, 2015).

The fundamental working principle of this actuation is based on the differentiated orientation of cellulose microfibrils in two tissue layers, leading to bending (Speck, et al., 2023). Advances in digital fabrication technologies have made it possible to emulate biological structures in higher spatial-temporal resolutions. In particular, additive manufacturing has been proven to be well suited for 4D-printing (Correa, 2015) and was used for reproducing the multi-phase movement of the Bhutan pine cone scale (Correa D. P., 2020).

Still, examples of 4D-printing have remained as laboratory prototypes, yet to be deployed in real- world applications. Although the use of fused filament fabrication (FFF) machines and off-the- shelf wood filaments has made the technique more accessible, there is no established method for the design of self-shaping structures. Furthermore, the approach should be transferable across different materials, platforms, and scales to meet the diversity of real-world needs.

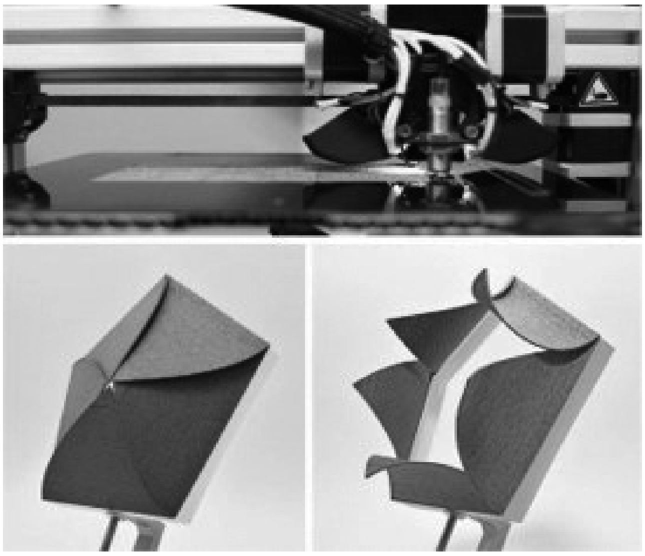

Figure 1. The material programming of self- shaping and responsive material systems is based on the fabrication parameters of extrusion-based additive manufacturing (top). Through the mesostructure design, this 4D-printed aperture closes when wet and opens when dry (bottom). (Image © Tiffany Cheng, ICD University of Stuttgart)

Material Programming

This body of work aims to bridge biological and anthropogenic approaches. In nature, there exists a limited palette of biopolymer building blocks, which gain multifunctional behaviors according to their material structuring when powered by environmental stimuli. In contrast, human- engineered systems rely on the myriad of artificial materials, purposely synthesized for specific properties, that are assembled into mechanisms which consume fossil fuel energy to operate.

This article presents the conceptual framework of material programming and a series of case studies using biobased cellulosic materials in bioinspired architected mesostructures for hygromorphic responsive systems. The key challenge in developing such systems is managing their interactions across scales – from the properties of materials at the microscale and how they affect printed structures at the mesoscale to their adaptive motion at the macroscale in response to environmental humidity.

Computational 4d-Printing

Extrusion-based additive manufacturing processes result in mesoscale anisotropic features according to the direction of material deposition. The developed computational design and 4D-printing framework (Cheng, et al., 2020) is based on this feature as well as the hygromorphic property of cellulose-based filaments, which swell and shrink perpendicularly to the anisotropic paths upon changes in moisture levels. Fusing two printed layers of opposing anisotropies and hygromorphic properties leads to an overall bending effect of the bilayer structure. By controlling the print paths and thereby tailoring the mesostructure of each layer, the bending radius can be modulated to a wide range.

This bilayer building block can be combined in various configurations to achieve a variety of shapes. Figure 1 shows a 4D-printed self-shaping aperture that opens when dry and closes when wet. Among other programmed structures are surfaces that transform from flat to doubly curved and kirigami-inspired structures that expand substantially in volume. The principle of curved crease origami can also be translated to 4D-printing (Tahouni Y. C., 2020), where opposing bilayers are connected by a flexible curved hinge.

Robotic Upscaling

To prove the transferability and spatial scalability of the computational 4D-printing workflow, the method initially developed using hobbyist FFF 3D- printers and off-the-shelf filaments is adjusted for an industrial robotic platform and a hybrid materials system (Cheng, et al., 2021). A 6-axis robot arm equipped with multiple end effectors is used to integrate wood bilayers and tailored cellulosic metamaterial structures in the flat state of fabrication, resulting in large-scale biocomposite structures that self-shape to changes in relative humidity, as shown in ***Figure 2***.

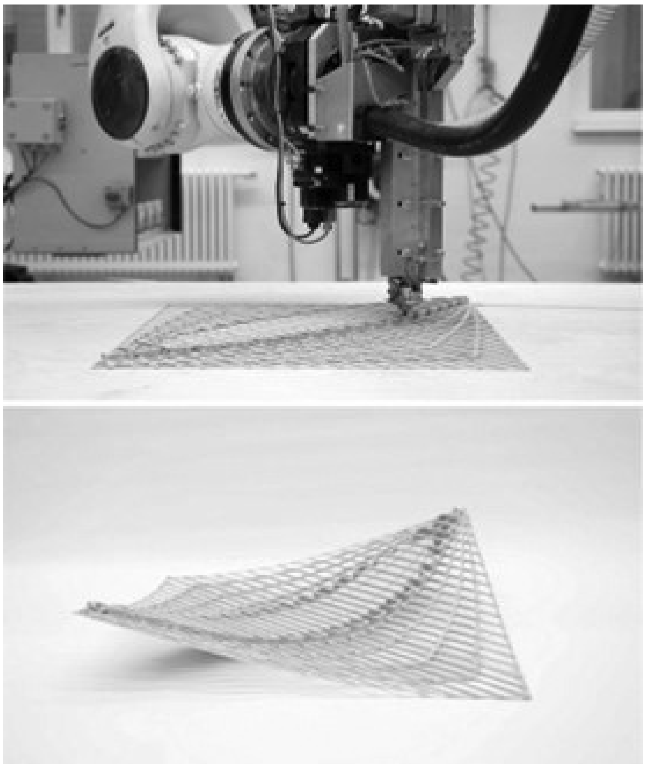

Figure 2. An industrial robot platform is used for the large-scale additive fabrication of hybrid materials systems (top). After being fabricated flat, the biocomposite structure self-shapes by drying (bottom). (Image © Tiffany Cheng, ICD University of Stuttgart)

The mechanical properties of the metamaterial structures can be customized to a high resolution of detail. As such, the unique properties of bending- active auxetic metamaterials are exploited for tuning the Gaussiain curvature, resulting in the transformation of a flat fabricated surface that self- formed into a doubly curved shell structure (Özdemir, et al., 2021).

Bioinspired Adaptive Wearable

There is immense potential for 4D-printing in medical and sports applications. Proper fitting is especially important in order to provide adequate support in orthotic casts; however, muscular atrophy often occurs during immobilization, necessitating frequent cast removal and reapplications. An adaptive orthotic splint is prototyped using the material programming and 4D-printing approach (Cheng, et al., 2021). *Dioscorea bulbifera* has been observed to generate high squeezing forces on its host structure, allowing it to climb without slipping (Isnard, 2009). The working principle of D. *bulbifera* is abstracted as two motion steps: first, the loose coiling of the stem helix around an existing support, and second, the expansion of outgrowths called stipules that tension the stem helix. The shape changes of the stem helix and stipules are translated to 4D-printed mechanisms referred to as the helix mechanism and the pocket mechanism, respectively.

In evaluating the force generation of the 4D-printed material system, results show that the bioinspired design combining both helix and pocket mechanisms yielded higher forces than the helix mechanism on its own. Moreover, delaying the actuation of pocket mechanisms through material programming resulted in the highest forces. ***Figure 3*** shows a personalized splint worn by the user as well as the programmed self-tightening provided by the many pocket mechanisms.

Beyond wearable assistive technologies, 4D- printing is also useful for facilitating the study of complex deformations in new plant role models whose underlying cellular processes are not fully understood, such as that of the large-flowered butterwort (Sahin, et al., 2023).

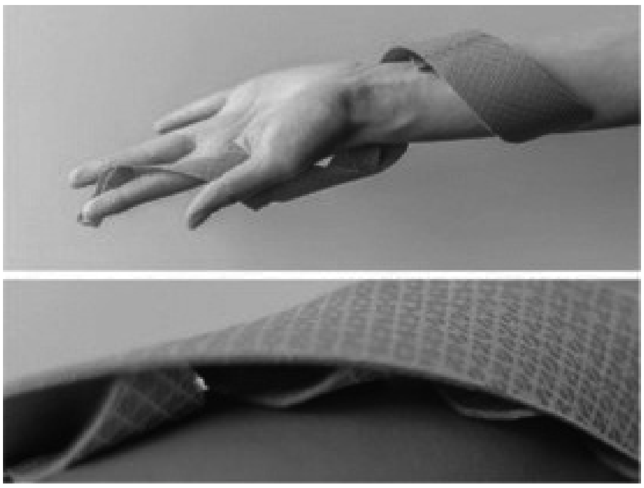

Figure 3. A prototype of the personalized 4D- printed adaptive wearable (top). A close-up of the many bioinspired tensioning mechanisms (bottom). (Image © Tiffany Cheng, ICD University of Stuttgart)

Figure 4. The 4D-printed shading elements open to let in sunlight during a cool morning (top) and close to block heat during a warm afternoon. (Image © Tiffany Cheng, ICD University of Stuttgart)

From Biology To Buildings

As buildings account for a significant portion of carbon emissions due to active heating and cooling for maintaining occupant comfort, weather- responsive building skins could assist in regulating the indoor climate without consuming any operating energy.

The *liv*MatS Biomimetic Shell serves as a case study for the architectural integration of 4D-printed self-shaping mechanisms, which are situated across the 10m2 upper façade of the building. A total of

424 unique self-shaping shading elements have been physically programmed via 4D-printing in the context of environmental and site conditions (Cheng, et al.). The 4D-printed shading elements are designed to shield the building's interior from high heat loads during summer and hot days while allowing thermal energy to penetrate during winter and cold days, as shown in ***Figure 4.***

Since March of 2023, these 4D-printed mechanisms have been self-shaping in response to changes in daily and seasonal weather cycles without using any operating energy at all. As the first truly weather-responsive 4D-printed adaptive building façade, this project proves the production scalability of 4D-printing and marks a step towards an energy-autonomous solution for solar shading in buildings.

Toward A Sustainable Future

Architects have been conceptualizing responsive and future-proof buildings and cities for decades, from Yona Friedman's *L'architecture mobile* to Archigram's *Instant City,* but few instances have been built. Although the Nakagin Capsule Tower was designed for its configuration to be customized as needed, none of the 140 modules were ever replaced until the building's demolition. The Villa Girasole, a house designed to follow the sun by rotating its 1500-ton mass, is at risk of suffering the same fate due to the complexity and cost of maintenance. Similarly, the kinetic façade of the Institut du Monde Arabe no longer functions as intended, as one broken part within the interdependent mechanism renders the entire assembly immovable.

The work presented in this article shows an alternative approach to these highly mechanized interpretations of adaptive structures. The integration of cellulosic materials, architected mesostructures, and hygromorphic motions through material programming has enabled 4D-printed systems to respond to environmental humidity with a variety of shapes and properties. Their functions are completely energy-autonomous and powered by the natural ebbs and flows of the environment.

Necessary for democratization of the technology, the methods used do not require any exotic materials or specialized equipment (in fact, FFF 3D-printers proved to be indispensable for manufacturing medical devices and isolation wards during the COVID-19 pandemic due to their availability). Yet, the developed methods are transferable to industrial robot platforms and familiar construction materials, critical for wide adoption across spatial and production scales as well as application domains.

To achieve the bioinspired vision of an adaptive and resilient built environment (Poppinga S. Z., 2018), further work must consider the material system's end-of-life. The most sustainable type of building or city is one that is used in perpetuity through adaptation; however, some societal shifts and user needs cannot be predicted. In such a case, the life cycle of the biobased material system should be improved by ensuring its recyclability through monomaterial 4D-printing (Sahin, et al., 2023), biodegradation through developing new materials (Tahouni, et al., 2023), and the re-programmability of its adaptive functionality through designing hierarchical mechanism (Chen, 2021).

There are still many lessons from nature, still from the conifer cone – fossil cone scales have been observed to retain full functionality of hygromorphic motion even after millions of years (Poppinga, et al., 2017), while other species have evolved specialized mechanisms to respond only after a wildfire (Warren, 1978). By learning from nature, we may forge a sustainable pathway that overcomes the competing resources between nature and technology.

Acknowledgments

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