COLORFUL BITS

EXPLORING STIMULUS-RESPONSIVE MATERIALS FOR TANGIBLE USER INTERFACES THROUGH MULTI-MATERIAL 3D PRINTING

INGO VERSLUIJS

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AUTHOR

INGO VERSLUIJS
MSC INTEGRATED PRODUCT DESIGN
FACULTY OF INDUSTRIAL DESIGN ENGINEERING
DELFT UNIVERSITY OF TECHNOLOGY

CHAIR

DR.IR. E.L. DOUBROVSKI

MENTOR

DR.IR. W.S. ELKHUIZEN

ABSTRACT

Recent advancements in Additive Manufacturing (AM) suggest that Multi-Material Jetting (MMJ) could create materials with interactive properties that encode digital information readable by computers. However, it remains unclear if these opportunities are compatible and how they could integrate effectively in designs for tangible interaction and Extended Reality (XR).

Building on the concept of Radical Atoms (Ishii et al., 2012), this research explores how MMJ might connect physical interactions with digital information through materialization. A literature study was performed to examine how multi-material 3D printing could enable XR systems to capture and interpret physical manipulation, particularly addressing challenges in XR and Tangible User Interfaces (TUIs). A unique solution space for MMJ was identified, envisioning Stimulus-Responsive materials capable of converting physical stimuli into fiducial responses for computer vision.
To assess the feasibility of this embodied approach for TUIs and explore potential interactions that can be achieved, a "Research through Design" methodology was applied. The proceedings document the design and development of Colorful Bits: a Stimulus-Responsive material for kinetic interaction.

Colorful Bits present a configurable Stimulus-Responsive material which captures kinetic interactions as a dynamic fiducial color response. By interlinking mechanical and optical properties through material and structure, a mechanical metamaterial is designed which transforms movement, orientation, and kinetic deformation of objects to color-encoded information.

Through the physics principle of superposition, the applied stimuli that cause the movements and deformation can be obtained, allowing for force-, stress-, and pressure-sensitive interactions. By applying this process, designers are enabled to design kinetic materials for XR that provide virtual feedback in response to applied kinetic deformation.

Evaluations of Colorful Bits reveal promising insights into the viability of Stimulus-Responsive materials for TUIs, though current gaps between digital models and real-world behaviors limit full application. While Colorful Bits focuses on kinetic interactions, future applications are envisioned that expand fiducial Stimulus-Responsive materials to respond to environmental stimuli such as temperature, light, and moisture, positioning MMJ as a versatile platform for XR applications.

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ABBREVIATIONS

This section serves as a brief overview of concepts frequently addressed within the current work. The definitions are often extensive, nuanced, or dependent on context. Therefore, they are further explained in the relevant chapters.

Human-Computer Interaction (HCI)

Extended Reality (XR)

Virtual Reality (VR)

Augmented reality (AR)

Mixed reality (MR)

Tangible User Interfaces (TUI)

Smart Material Interfaces (SMI)

Stimulus-Responsive Material (SRM)

Additive Manufacturing (AM)

Computer aided Design (CAD)

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CHAPTER 1. INTRODUCTION

1.1 RESEARCH AIM

Within the vision of ubiquitous computing, extensive efforts have been devoted to explore the various approaches in Human-Computer Interaction (HCI) design, with a primary focus on bridging the divide between the virtual and physical domains. Tangible User Interfaces (TUIs) and Extended Reality (XR) research have emerged as prominent directions in this pursuit.

The convergence of these fields suggests a world where physical objects can be digitally enhanced, and interaction with these objects can in turn interact with digital information. 'Radical Atoms' (Ishii et al., 2012) envision interactables between physical and digital properties to achieve tangible and dynamic interactions. In the work, hypothetical materials are proposed which are malleable and reconfigurable and can be described by real-time digital models. Subsequently, dynamic changes in digital information can be reflected by a dynamic change in physical state and vice versa.

This paves the way for future products that seamlessly connect tangible interaction and digital information by establishing intuitive and engaging connections between physical interaction and virtual feedback. Through XR, TUIs could be recontextualized and repurposed to different use cases entirely. This could greatly increase the modularity, versatility and longevity of tangible interfaces, which currently is a major drawback compared to conventional Graphical User Interfaces (GUI) (Holmquist, 2023). However, to explore the interactive affordances laid out by these concepts, the vision of Radical Atoms (Ishii et al., 2012). has to be materialized beyond the hypothetical.

Advancements in digital fabrication over the past decade, particularly in the form of Multi-Material Jetting (MMJ), offer a promising avenue for connecting the physical and virtual realms. MMJ has demonstrated its capacity to leverage material properties to embed digital information within physical designs, thereby facilitating XR systems with essential contextual information (Dogan et al., 2022; Dogan et al., 2023; Mann & Fryazinov, 2019).

Furthermore, another capability of MMJ is the ability to modulate material properties at the voxel-level, enabling material properties like elasticity (e.g. Kaweesa et al., 2022; Schumacher et al., 2015) and color (Yuan et al., 2021) to be controlled locally at voxel-states. The programmable nature of these materials provide designers with unique tools including control over physical behavior, shape-changing effects, physical movement, and manipulation of material properties such as stiffness and flexibility (Morovič et al., 2019).

These developments indicate the potential for MMJ to create materials that embody interactive properties and encoded digital information interpretable by the computer. However, it is currently not known if these opportunities are compatible with one another and how these could be integrated in design to become relevant for both tangible interaction and XR.

To expand upon the vision of Radical Atoms, this research aims to explore potential avenues for MMJ to interconnect physical interactions with digital information within the process of materialization. Moreover, to evaluate the relevance of materialization within HCI, the interactive opportunities and challenges that arise in the translation from hypothetical to actual materials are examined through the design of a conceptual demonstrator.

1.2 PROJECT SCOPE

PRINTING SYSTEM

There are a number of Multi-Material Jetting (MMJ) systems available, for this work the Stratasys J735 printer is used. This printer has the ability to print up to 6 different materials in a singular print at layer resolution of 14 microns and accuracy between 20-85 microns (Appendix A).

MATERIALS

For the purpose of this project, interest lies in varying the properties of stiffness, transparency and color. Therefore, the Agilus family, VeroUltra family, and VeroClear were chosen, providing a diversity in mechanical and optical properties.

It is important to note that the VarioUltra (CMYK colors) and the VeroClear (transparent) family share near identical mechanical properties, but the materials have different optical properties. This partial overlap provides sufficient diversity to explore material interfaces which manipulate optical and mechanical properties while limiting the complexity that comes with each additional material.

To investigate the opportunities of MMJ for tangible interaction, the current work explores the ways it can affect the mechanical properties and subsequent physical behavior. Mechanical properties are strongly and directly interconnected with physical behavior.

IMAGING

Extended Reality (XR) systems can be implemented through various technologies including IoT, Lidar, and Thermal Sensing, among others. Within the project, it was chosen to focus on RGB camera imaging. RGB cameras are currently ubiquitous among smartphones, computers, and MR electronics and therefore provide an easily accessible and relevant medium to demonstrate potential applications.

The primary focus of this project is to establish a feasible connection between physical interaction and digital information afforded by the technology of MMJ, and motivate the future applications and opportunities within Human-Computer Interaction (HCI) through a conceptual design demonstrator. This demonstrator aims to highlight the transformative benefits afforded digital fabrication and MMJ in the design Tangible User Interfaces (TUIs) for Extended Reality (XR).

1.3 BACKGROUND

This subchapter serves as a brief introduction into the topics at hand and the relationships between the fields of research that sparked the motivation of the research aim.

EXTENDED REALITY

Extended Reality (XR) is an umbrella term that encompasses various forms of computer-altered environments and interactions. It includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), each of which offers different levels of immersion and interactivity. Within the scope of this project, AR and MR are particularly relevant.

AR enhances real-world scenarios by overlaying digital content, serving educational, entertainment, and immersive purposes. It enriches a user's perception by augmenting their sensory experience.

MR, as a bridge between the physical and virtual, describes the two-way interaction between digital content and physical environments. It can create digital elements within the user's surroundings, blurring the line between what is real and computer-generated. This fusion of real and virtual worlds deliver a unified experience that seamlessly integrates the physical and digital realms.

XR has demonstrated to be a versatile medium to provide rich, multi-modal experiences for digital applications to be interwoven into everyday tasks (Figure 1), and highly specialized professional settings (Figure 2). Similar to popular Graphical User Interfaces (GUIs), XR allows its content to be updated, adapted, and transformed over time. The envisioned ubiquity of digital content to enhance the physical world, anywhere at any time, highlights a great potential to create novel Human-Computer Interactions and applications.

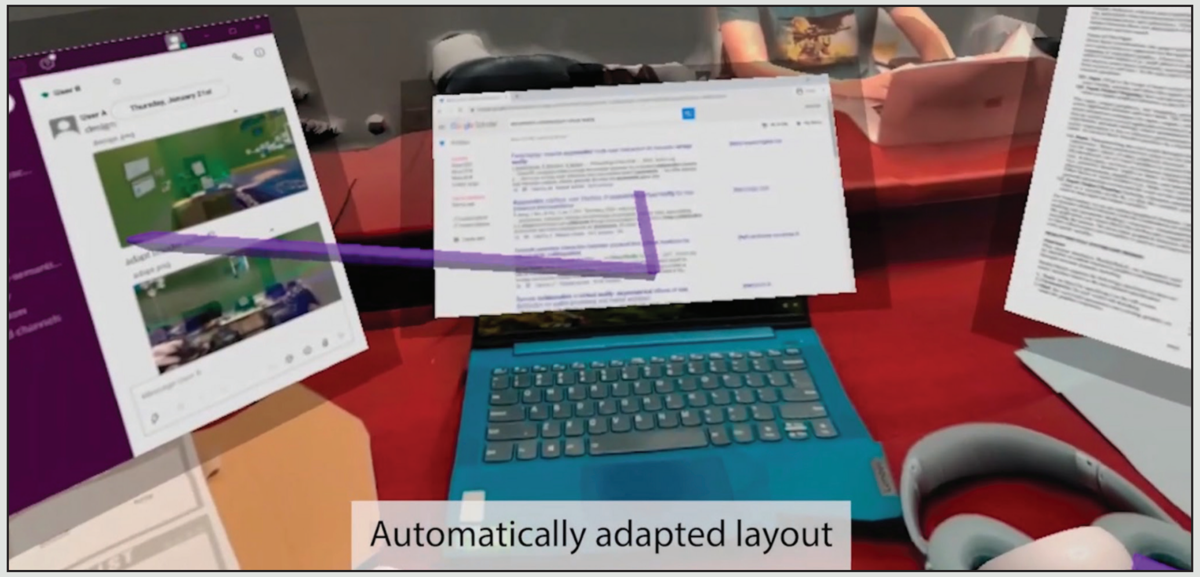


Fig 1 Digital content is automatically displayed at the related physical object (Cheng et al., 2021).

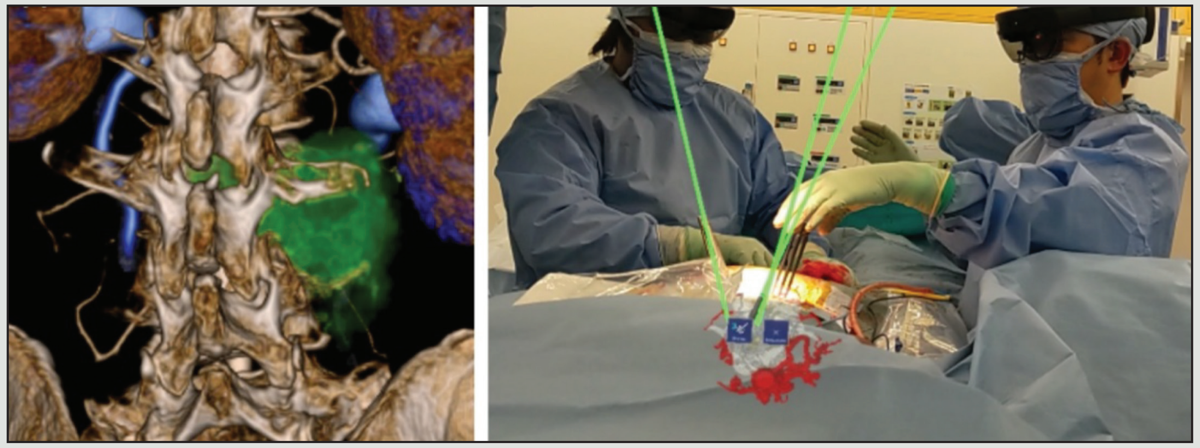


Fig 2 Three-adimensional virtual models are used for pre surgery planning and real time surgery assistance (Morimoto et al., 2022).

TANGIBLE INTERACTION

Tangible User Interfaces (TUIs), form a Human-Computer Interaction (HCI) paradigm that envisions computational, physical objects, and 'smart' environments to bridge the digital and physical worlds. They enable users to interact with digital information through the manipulation of physical objects, effectively turning physical objects and environments into an interactive medium.

Research into tangible HCI explores how the affordances of physical interaction can change the way people understand, appreciate, and interact with digital content. Research in this area often focuses on how tangible objects and physical interactions can transform how we interface with digital content/environments. Notable characteristics associated with tangible interaction include:

Direct Manipulation: Users interact directly with digital data by handling physical objects
Spatial Interaction: The physical layout and spatial arrangement of objects influence the; interaction
Multi-sensory Engagement: TUIs often engage multiple senses, including touch, sight, and sometimes sound.

Through these distinct characteristics, physical interaction has the potential to reconceptualize how we interact with digital information, offering alternative mediums for interaction and enabling new ways to engage with digital content.

Figure 3 and 4 shows an impression of the aforementioned.

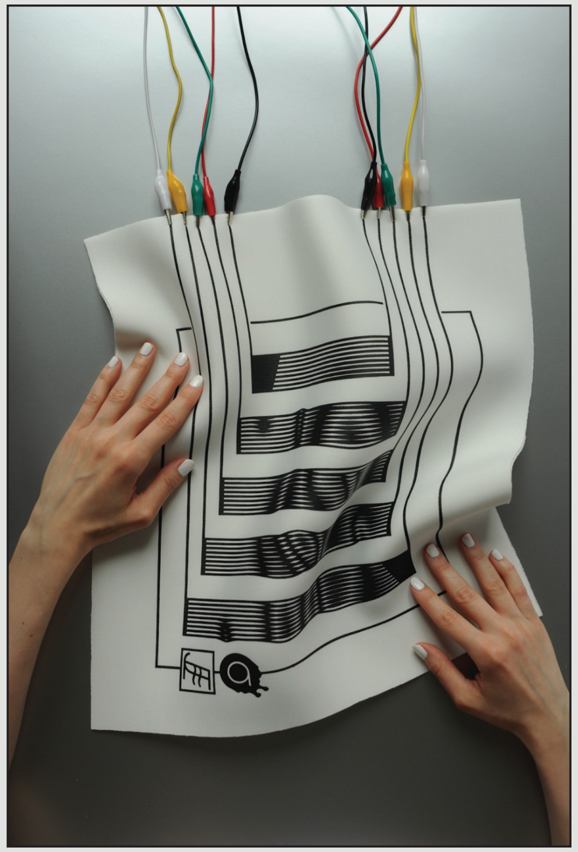


Fig 3 Liquid Midi: a textile interface for sonic interaction (Liquid Midi: Making Sound Matter, 2017).

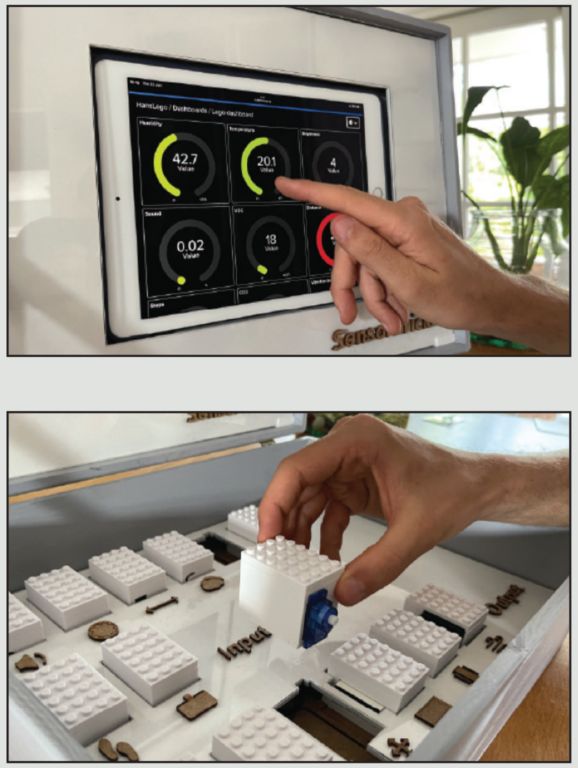


Fig 4 Steps of building a tangible sensor toolkit for learning and collaborative environments (Brombacher et al., 2024).

DIGITAL FABRICATION: MULTI-MATERIAL JETTING

Multi-Material Jetting (MMJ) is an advanced Additive Manufacturing (AM) technology that enables the simultaneous deposition of multiple materials to create intricate, multi-material parts. Similar to an inkjet printer, MMJ deposits thin layers of material on a plane. However, unlike a regular printer, these layers are stacked upon each other to form a 3D object.

In AM, the construction of these layers to form a three-dimensional object can be described by voxels. Analogous to pixels in two-dimensional (2D) space, voxels are the fundamental units of three-dimensional (3D) space. What makes MMJ particularly intriguing is its ability to create high-resolution, multi-material, three-dimensional structures.

The combination of these three properties unlocks novel design applications. By employing specific dispersal patterns of selected materials at micro and/or macro scale, research has demonstrated that the mechanical properties, aesthetics, and interactive behavior of materials can be precisely controlled. This adds a new layer of dimensionality to design compared to conventional 3D printing techniques.

Voxel printing, with its added dimensionality, enables unique design opportunities for complex, adaptive products where material properties, aesthetics (Figure 5), and behavior can be tailored to specific use cases. While this dimensionality allows for intricate and specialized functionalities, there is still much to learn about how these functionalities can enhance and enrich the design of user interactions and experiences.

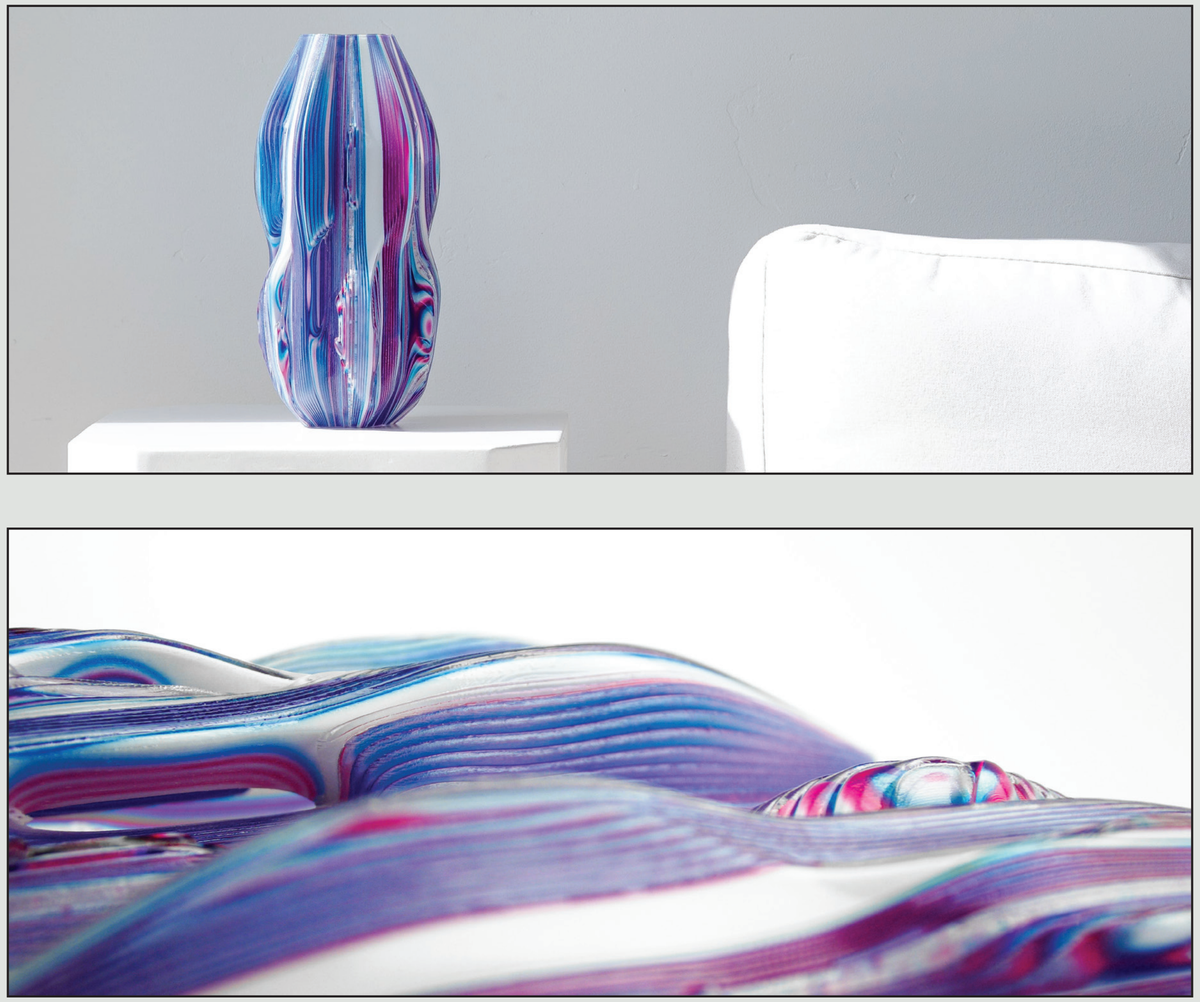


Fig 5 Multi-Material Jetting can create complex three-dimensional material structures (Illusory Material, 2020).

1.4 RESEARCH STRUCTURE

LITERATURE STUDY

This chapter aims to highlight the unique challenges associated with Extended Reality (XR) and Tangible User Interfaces (TUIs) and examines potential avenues of Multi-Material Jetting (MMJ) to address these challenges in design. The chapter identifies and proposes Stimulus-Responsive materials as a potential solution space for MMJ to interconnect physical interaction and digital information.

DESIGN EXPLORATION

The design exploration illustrates how this paradigm may support novel forms of interaction through the design and development of a conceptual demonstrator: Colorful Bits. A research through Design (RtD) approach is employed to evaluate both feasibility and viability of the proposed solution space, revealing opportunities and limitations of MMJ through the process of design.

Furthermore, potential research avenues that are required for further validation of proposed solution space are explained, as well as potential avenues to expand upon the described applications (e.g. other forms of interaction that have been experimented with).

DISCUSSION

The discussion reflects upon the potential applications and limitations of Colorful Bits in the proposed solution space. The degree to which Colorful Bits embody the vision of Radical Atoms (Ishii et al., 2012), seamlessly connecting physical interactions and digital models, is discussed. Finally, the opportunities and limitations of MMJ are addressed.

CONCLUSION

This research concludes by summarizing the prospects and limitations of MMJ and the envisioned solution space at large. Here, contributions to HCI, TUIs, and XR are summarized.

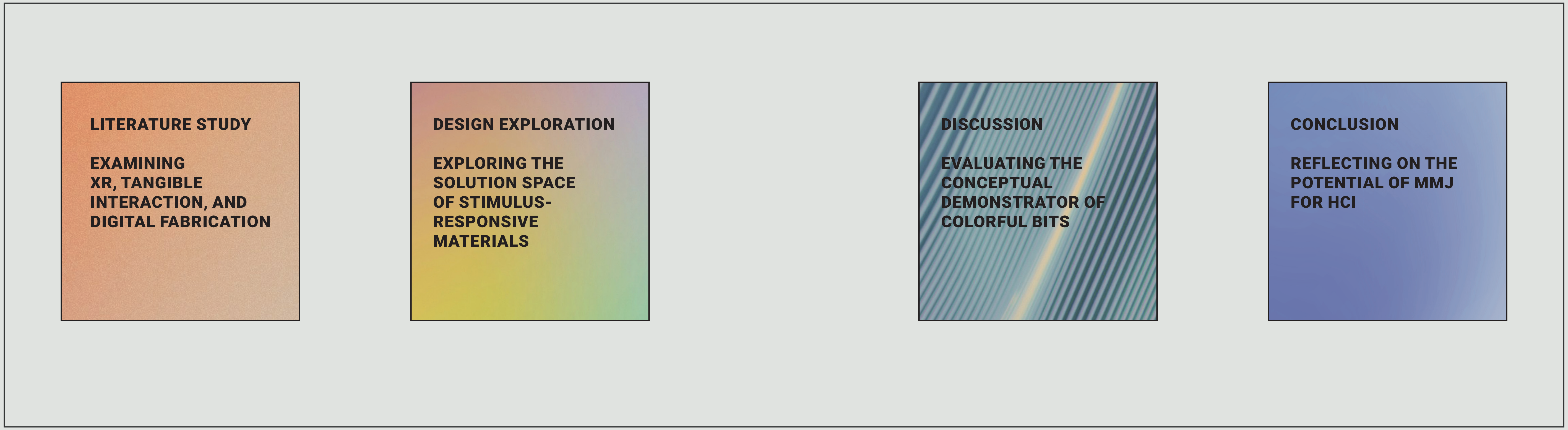


Fig 6 Research structure.

CHAPTER 2. LITERATURE STUDY

2.1 INTRODUCTION

Within the realm of Human-Computer Interaction (HCI), Extended Reality (XR) and Tangible User Interfaces (TUIs) address the manner in which humans and computers are able to exchange information. Despite their thematic similarity, the parameters of design that contribute to the human experience and computer interpretation of interactive events propose unique challenges.

This chapter aims to highlight the unique challenges associated with XR and TUIs, and examines potential avenues of Multi-Material Jetting (MMJ) to address these challenges in design. The chapter concludes by establishing a relationship between these opportunities and presents a possible solution space for MMJ to connect tangible interaction and XR for HCI.

2.2 HUMAN-COMPUTER INTERACTION

2.2.1 EXTENDED REALITY

Despite Augmented Reality (AR), Virtual Reality (VR), and Extended Reality (XR) systems and technologies being decades old, there has not yet been any standardized language or systemic approach to interaction

An important requirement of any XR system is to acquire an understanding of the real world environment/context. This dimension of design was named "Extend of real world knowledge" (EWK) in the seminal work of Milgram and Kishino (Milgram & Kishino, 1994).

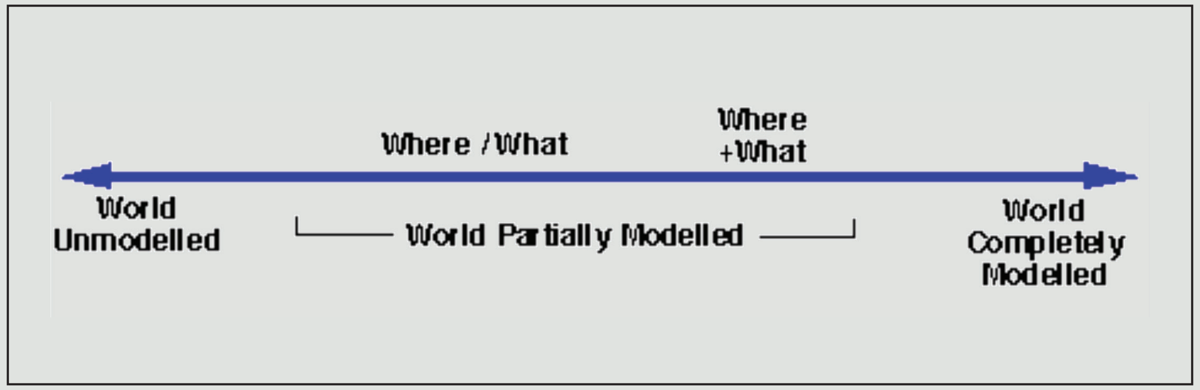


Fig 7 Extent of World Knowledge (EWK) (Milgram & Kishino, 1994).

EWK describes the quality of information computers have available to model and understand the physical world. This has remained a crucial parameter for a functional XR system in order to understand the user's environment, compute an appropriate response and provide feedback.

Within the context of Human-Computer Interaction (HCI), XR systems require various steps to understand the user's position, orientation, and actions to provide relevant and contextually appropriate information. First, localization of objects and estimating pose and orientation is important to register information. Accurate and consistent Pose estimation allows the tracking of objects through 3D space, which is particularly for the alignment and registration of virtual graphics in physical environments (Salhi et al., 2019).

Considering computer vision, singular sensing often can not generate enough information. For example, it is extremely difficult for a regular camera that produces a 2D color image to differentiate a real human from a human depicted in an advertising billboard. Similarly, a single camera would have a difficult time tracking objects through a three-dimensional space. Consequently, computers become prone to misinterpretation and are unable to provide adequate feedback.

MULTI-MODAL UNDERSTANDING

Multi-modal scene understanding is an approach to address this challenge by combining multiple types of data to generate more reliable, accurate, and complete understanding of the interactive environment. This approach relies on the concept to utilize the synergistic effects of multi-sensor fusion to achieve better operation of the system. As described in "Multimodal localization for embedded Systems: A survey" (Salhi et al., 2019), there are various mechanisms sensory information can be fused to improve systemic information generation;

Through these architectures, multi-sensory information can be used to enhance the performance of generic high-level vision tasks, such as object recognition, semantic segmentation, localization, and scene reconstruction, and empower new applications (Chandrasekaran et al., 2017).

For example, combining RGB camera data with thermal cameras enables computers to more reliably and accurately recognize and localize pedestrians during the day and at night (Guan et al., 2019). Referring back to the earlier example of a billboard, this could reduce false positives and false negatives as thermal imaging would easily differentiate a human from a billboard.

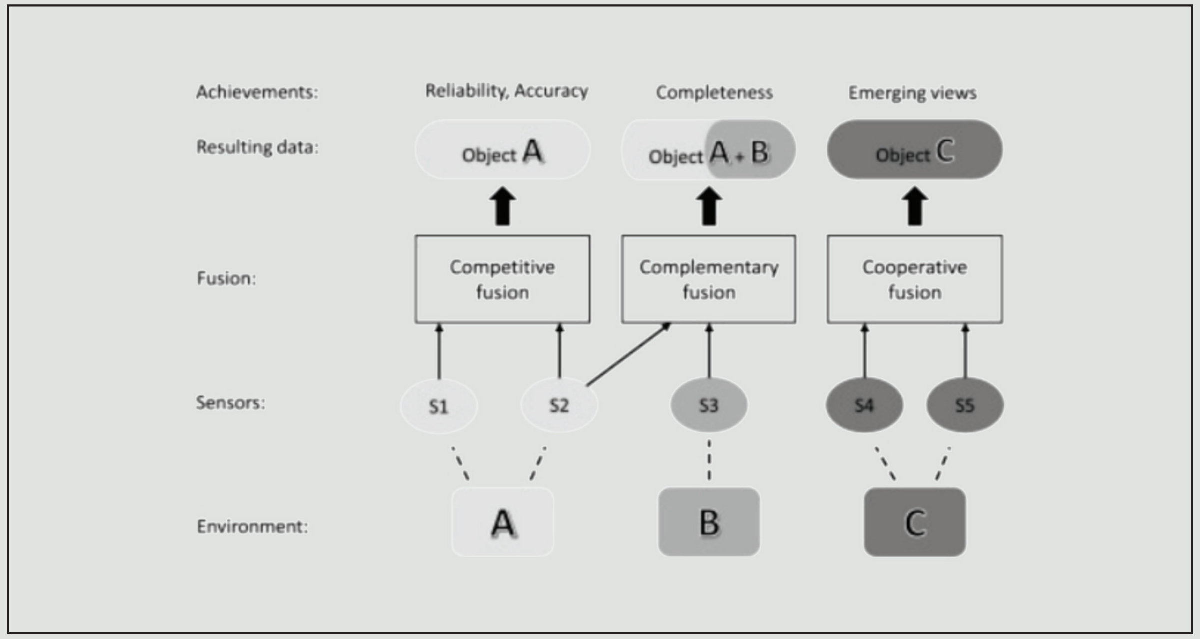


Fig 8 Competitive, complementary and cooperative fusion (Salhi et al., 2019).

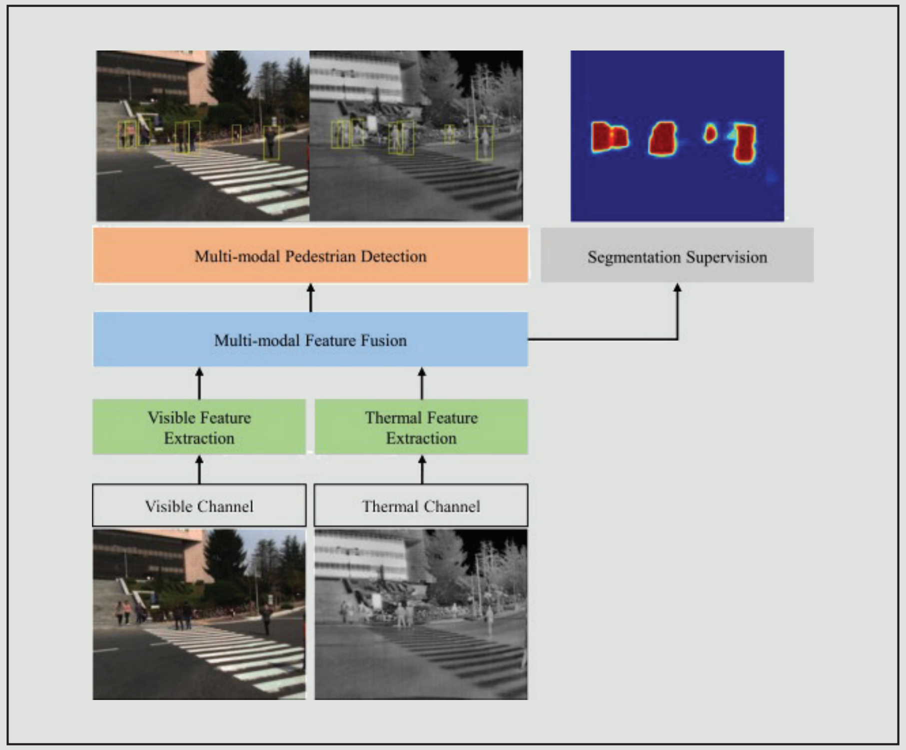


Fig 9 The architecture of a multi-modal fusion framework (Guan et al., 2019).

UNDERSTANDING HARDWARE ARCHITECTURES

It is apparent the concept of multi-sensor fusion and multi-modal scene understanding is widely adopted in VR, MR and XR systems. Contemporary Head mounted displays like the Apple Vision Pro and Quest 3 are equipped with a plethora of high resolution color cameras and Depth sensing LIDAR cameras (Figure 10). Moreover, peripheral hardware solutions for physical interaction often include a plethora of sensing and connectivity technologies for communication (Figure 11).

While the hardware systems provide a significant data stream from which many applications and features can be built, its complexity comes at a significant cost. As described by Salhi et al., (2019) Synergetic Data fusion requires precise and accurate measurements and tightly connected data streams. To achieve this, both vertical and horizontal integration is required between hardware and software. This makes it challenging for third party developers to develop applications or systems for existing ecosystems. Moreover, the aforementioned hardware requires manufacturing, tuning and calibration, which is inherently costly to develop and maintain.

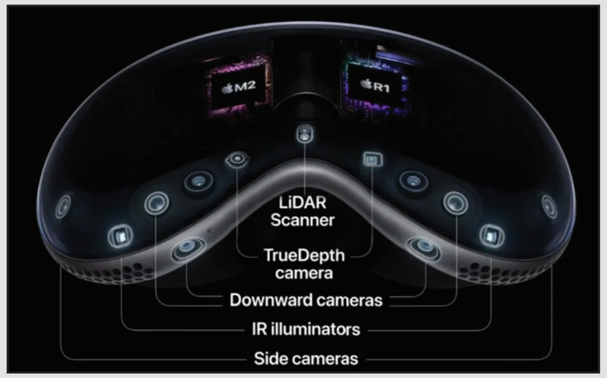


Fig 10 Apple Vision Pro hardware configuration including multi-modal sensors (For Data Sensing and AI Infrastructure, 2023).

Fig 11 SenseGlove implements an array of pressure sensing techniques to enable physical feedback for XR (SenseGlove, 2023).

FIDUCIAL SYSTEMS FOR EXTENDED REALITY APPLICATIONS

Another solution space currently studied to facilitate Extended Reality (XR) experiences with low hardware requirements involves the embedding of digital references in physical environments through embedding information in physical objects.

Fiducial objects are specifically designed markers/objects that are placed in the field of view of an imaging system for use as a point of reference or a measure. Moreover, fiducial markers are characterized by their ability to provide robust and cost-effective solutions for XR applications and are easily accessible by developers to implement (Jurado-Rodriguez et al., 2023).

As summarized by Getschmann and Echtler (2021), there is a plethora of visual fiducial markers available (Figure 12). These markers are often optimized for technical performance, each designed with a specific functionality (Jurado-Rodriguez et al., 2023).

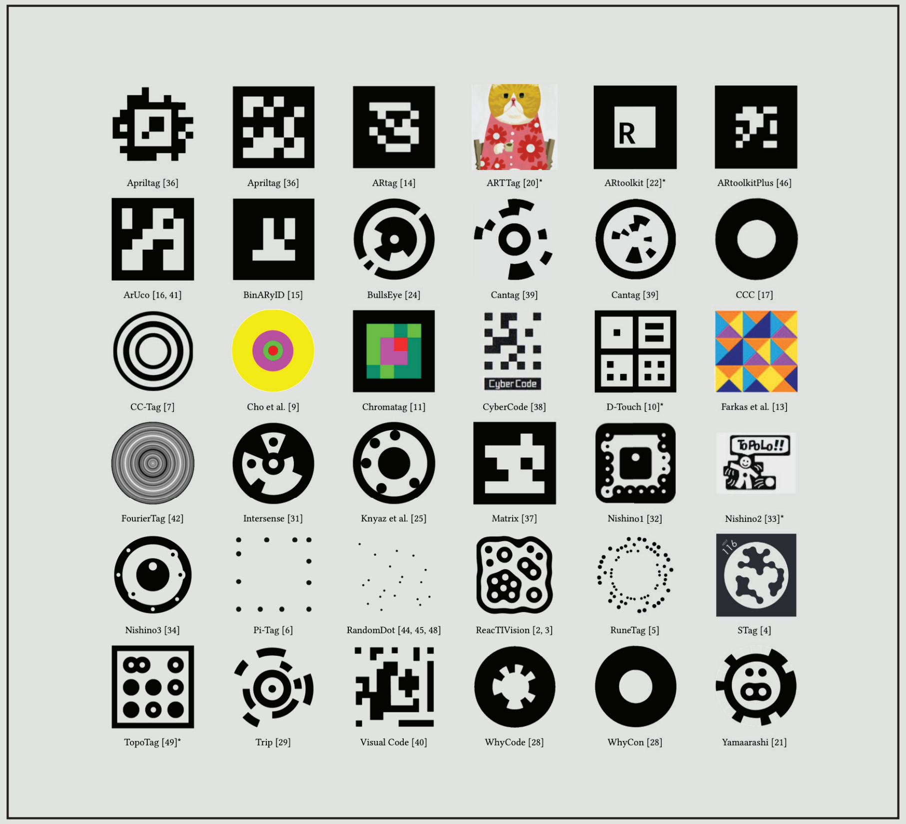


Fig 12 Examples of available fiducial markers (Getschmann and Echtler, 2021).

While each fiducial marker may have its own benefits and limitations, they are generally used to provide relevant information for XR systems. QR codes for example are able to provide object information as well as orientation information, which can both be valuable information for interpretation of the physical environment.

Recent studies have found a myriad of ways fiducial markers can be integrated in design to support XR applications. Dogan et al. (2023) proposed a novel marker approach using infrared-sensitive 3D printed materials, enabling the embedding of markers in everyday objects and wearables without affecting the visual aesthetics (Dogan et al., 2023). This research highlights several interesting aspects of fiducial markers within the context of digital fabrication. Through the embedding of markers in a wearable, it demonstrated a hand can be localized and tracked by simply wearing an unobtrusive wearable (Figure 13). Additionally, the use of 3D printing enables the markers to be seamlessly integrated anywhere in physical designs. Finally, it demonstrates how the use of multi-material 3D printing can unlock new features for fiducial markers. In this instance, the material discrepancies in infrared reflectivity between materials was exploited to serve the visual preferences of humans while providing the contrast technically required for localization.

Although embedded markers showcase the ability to track designated objects, researchers have investigated how physical markers can obtain information of the surrounding external context. Notably, Hsueh et al. (2021) developed an application that enables physical environments to be mapped by users with a physical fiducial marker named “AR Token” (Figure 14).

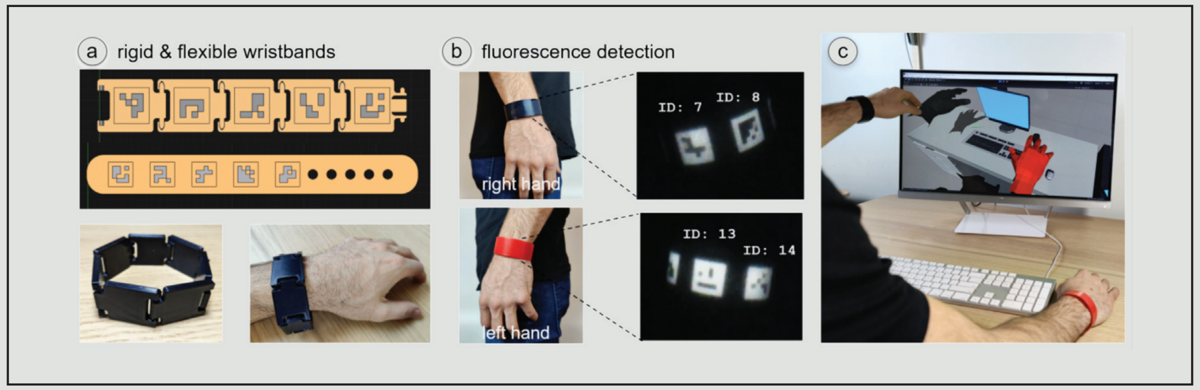


Fig 13 Embedded markers in wearable for localization and tracking (Dogan et al., 2023).

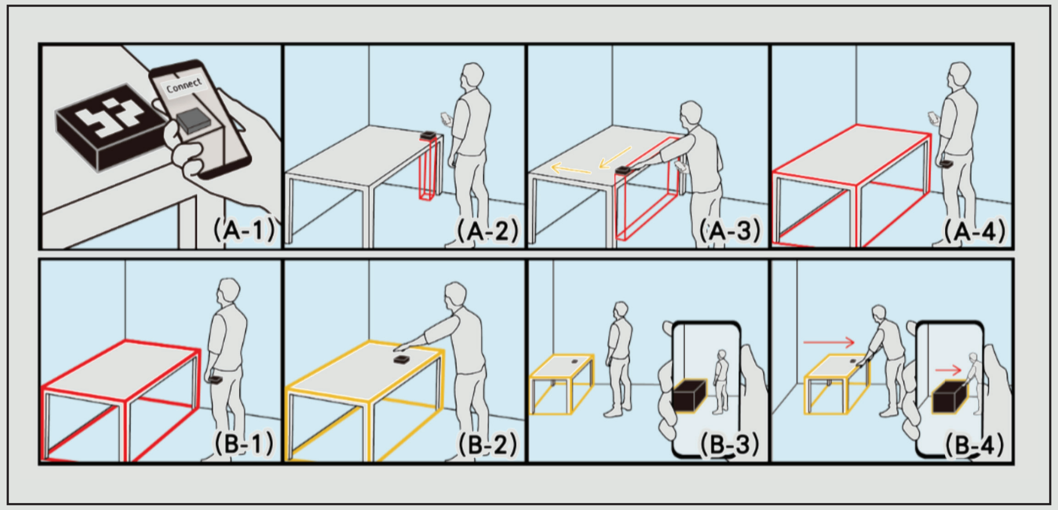


Fig 14 AR token used to map a physical environment (Hsueh et al., 2021).

Hsuesh et al. (2021) demonstrate how fiducial markers can be used not only in integrated product solutions, but can also be used as a tool to interface with physical environments to support mixed reality applications.

It is also possible to exploit multiple modalities of a single sensor to create a multi-modal approach to capture information. For example, while most conventional fiducial imaging techniques use only luminance differences for object recognition, localization and pose estimation, Kyriakoulis and Gasteratos (2010) have shown that using color segmentation can yield significant improvements for pose estimation in low light conditions (Figure 15).

Through utilizing the HSV (hue, saturation, value) color space and isolating colors on the chromaticity plane, a color space where luminosity and value have no effect, Kyriakoulis and Gasteratos (2010) were able to achieve a more robust pose estimation system for against extreme lighting conditions (Figure 16). This was achieved by combining colors on the chromaticity plane for light invariant readability with a classical distance transform pose estimation.

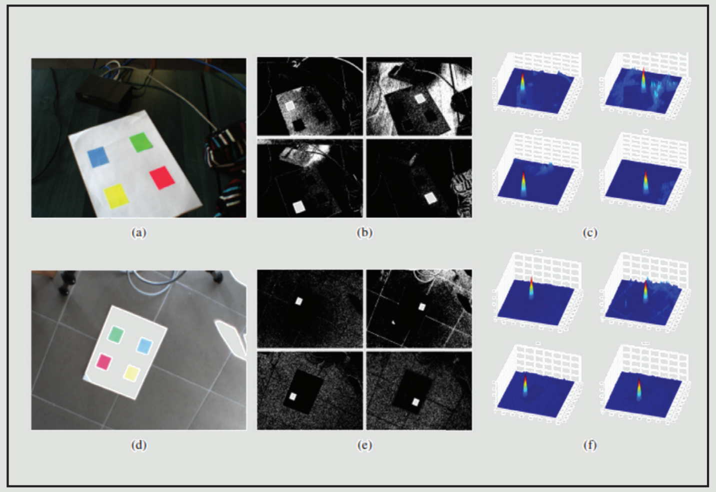


Fig 15 Color channels of the camera can be separated and utilized to facilitate novel multi-modal approaches to obtain data (Kyriakoulis and Gasteratos, 2010).

This highlights the possibility to leverage unique material properties to optimize the fiducial properties for computer vision. It displays how fiducial markers can be optimized for specific applications by tuning the physical design parameters for its intended function/feature.

In conclusion, high quality interactive information (localization, recognition and tracking) is required for XR systems and applications. To operate properly, computers need to understand the user context in order to provide adequate feedback. In contrast to hardware based multi-sensory approaches, fiducial systems potentially provide an accurate, robust and low-cost alternative. Moreover, through strategic design implementations high quality information can be achieved through a singular sensor.

The physical design and materialization of fiducial markers can potentially play an important role to achieve higher level contextual information. Within the process of materialization, material properties can be optimized for specific sensory technologies and to serve and improve particular functionalities.

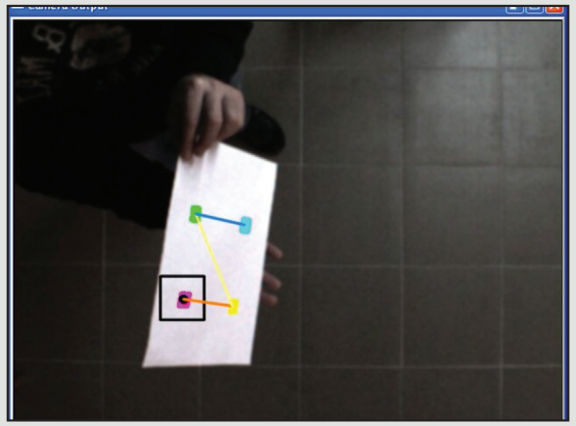


Fig 16 Color based pose estimation for extreme lighting conditions (Kyriakoulis and Gasteratos, 2010).

2.2.2 TANGIBLE INTERACTION

Strongly intertwined with the domain of Extended Reality (XR), research in the field of tangible interaction has explored the ways multi-modal physical interaction can change and improve the way we are able to engage with digital content and environments. Specifically, the benefits of interaction through interlinked modalities of physical inputs and digital feedback has been studied extensively.

Tangible User Interfaces (TUI) have however faced similar challenges as the previously discussed bottlenecks of XR; current approaches have struggled to capture physical inputs reliably and accurately for digital interpretation. Current approaches to facilitate mediation between physical inputs and digital feedback often require electronic sensors, transmitters, batteries and other electronics. Associated with these embedded electronic hardware configurations come concerns (Holmquist, 2023). Electronics are prone to break down, difficult to repair and costly to maintain. As one part breaks down, the entire interface could become uneconomical to repair, ensuring to add to the ever growing stream of electronic waste. Consequently, the paradigm of tangible interaction has been critiqued for its lack of consideration of viability; especially concerning the economic feasibility and environmental sustainability (Holmquist, 2023).

Recognizing the need for data that is dynamic and able to express a change of state , as well as the need for robust, inexpensive and easy employment, Scheirer and Harrison (2022) explored an alternative fiducial approach. The objective of their work was to develop a fiducial system that retains the simple, low-cost nature of printed markers, yet has some of the expressive capabilities of dynamic tags.

In their work, Scheirer and Harrison were able to demonstrate their concept of DynaTags, a paper printed fiducial marker system that is capable of various dynamic payload techniques. It is demonstrated through simple window-, abutting-, and reveal/conceal mechanisms that can enable tangible interactions like pushing, pulling, moving and objects could be translated into accurate and robust data transformations (Figure 17).

Moreover, Scheirer and Harrison demonstrate through various design demonstrators the capabilities of dynamic fiducial markers to translate physical interactions into digital information to support XR applications. For example, a virtually enhanced card game is showcased that provides adaptive feedback depending on the cards that are stacked (Figure 18). Another example includes a medical Covid-19 test kit that provides real time assistance and instructions for self testing (Figure 18).

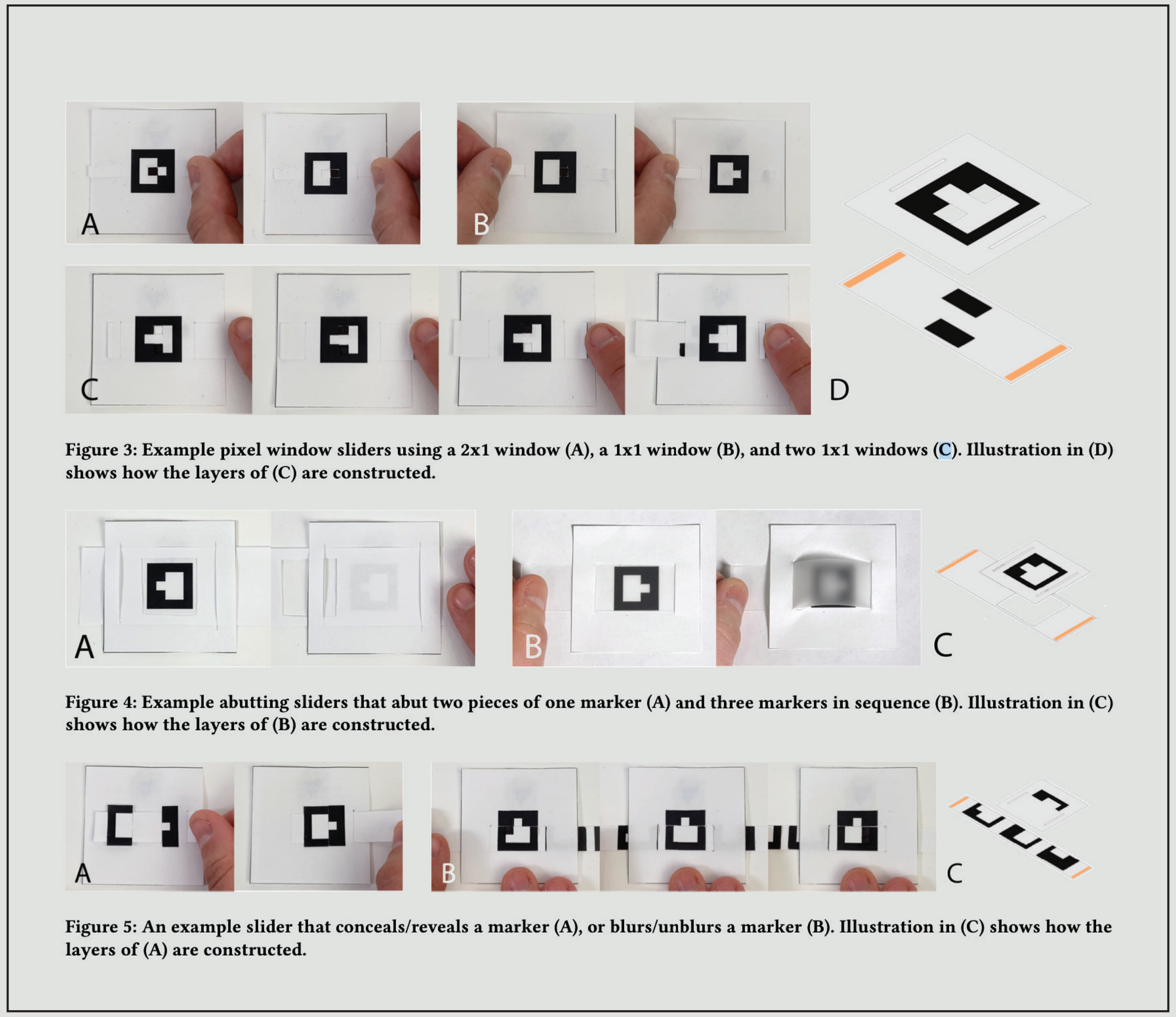


Fig 17 DynaTags: Physically reconfigurable dynamic markers (Scheirer & Harrison, 2022).

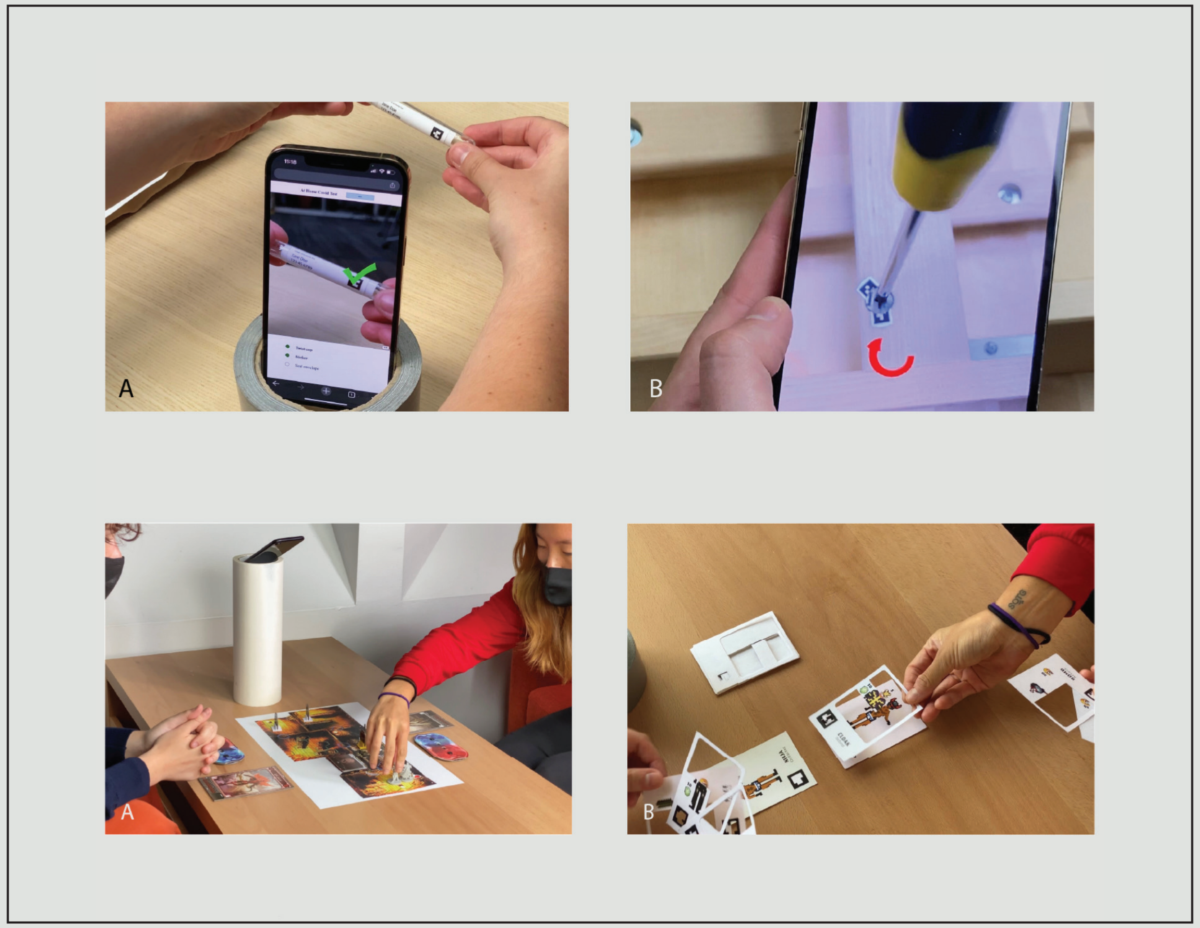


Fig 18 A) Real time assistance for Covid-19 testing kit through augmented reality. B) Interactive game where digital content is adaptive to the stacking of cards (Scheirer & Harrison, 2022).

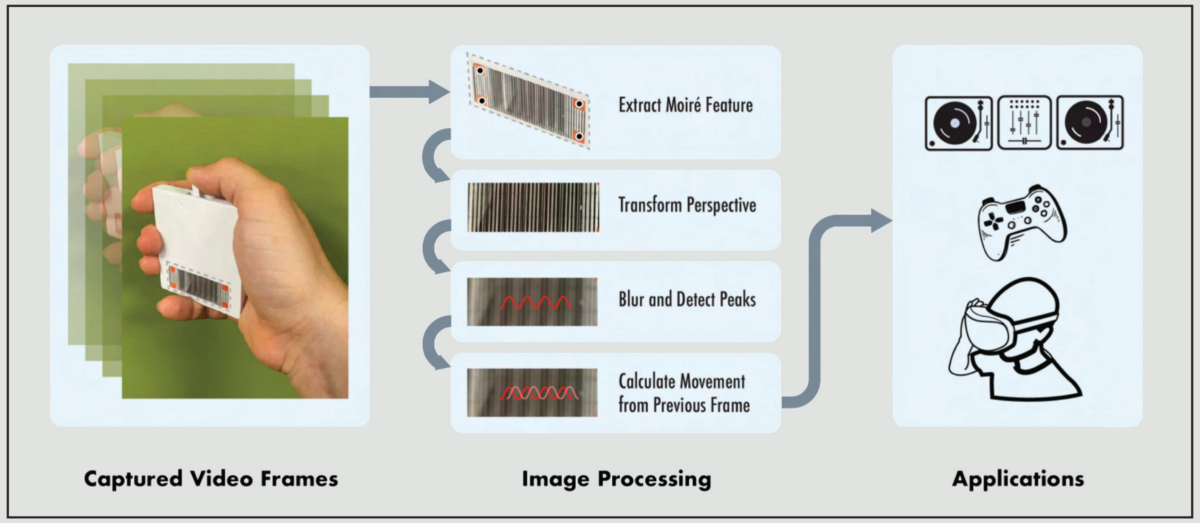


Fig 19 MoiréWidgets (Zamora et al., 2024).

DynaTags (Scheirer and Harrison, 2022) demonstrate the possibility and utility of dynamic fiducial data within the realm of XR and Human-Computer Interaction (HCI). However, the fidelity and resolution of the data remains quite limited. The DynaTags system is based on conventional Augmented Reality (AR) markers which are originally designed to be static and robust rather than dynamic.

Zamora et al. (2024) have developed an alternative approach named "MoiréWidgets" to obtain high resolution sensing of physical interaction through the optical phenomenon of Moiré. Moiré are patterns generated by overlapping two textures creating a pattern of interference. In their design of MoiréWidgets, the authors analyze the optical patterns generated as a result from physical interactions (Figure 19).

In contrast to AR markers which are statically pre-defined, the pattern of Moiré is dependent on the designed Moiré pattern. Designers can control and calibrate the sensitivity of these patterns to physical interactions to suit the specified use case. For example, Zamora et al. (2024) showcase the design of a rotatable volume knob that enables users precise control over the auditory feedback (Figure 20).

This approach highlights an opportunity for designers to not only implement dynamic data in tangible designs - but to control the type fidelity and sensitivity of data as a response to the physical input. This provides significantly more control and freedom to design fiducial systems to suit the specific needs of desired applications, and potentially unlocks more responsive and representative feedback to the users.

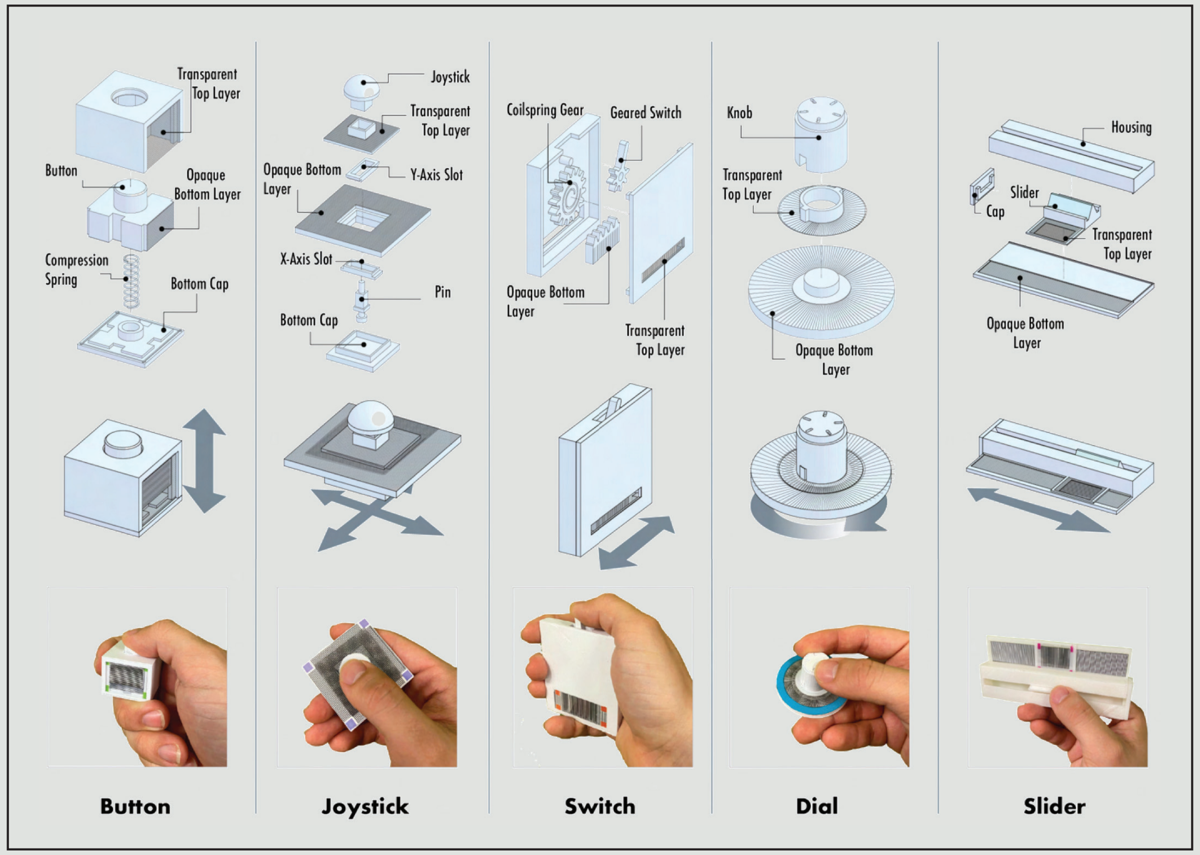


Fig 20 Virtual sound interface controlled through Physical MoiréWidgets (Zamora et al., 2024).

While the aforementioned work has predominantly focused on physical interaction as an input for XR, other researchers have studied approaches that maintain physical form as part of the experience.

In 2019, Mann and Fryazinov have explored the possibility of adapting virtual models to tangible objects, to enable users to interact with the actual object. By mapping a fiducial texture on an existing geometry of a meteoroid (Figure 21), and training a computer vision model afterwards to recognize the fiducial object, they were able to create an approach to adapt a digital model to any physical shape/geometry.

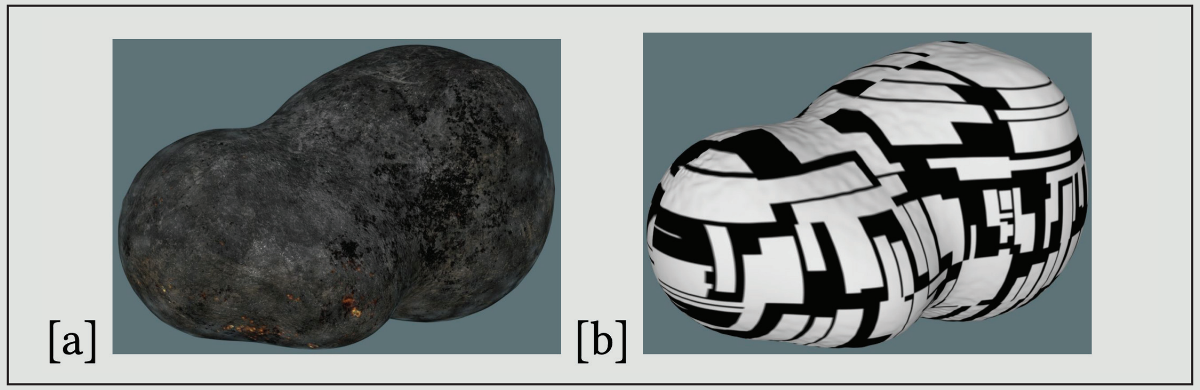


Fig 21 Mapping a fiducial texture on an existing geometry of a meteoroid (Mann & Fryazinov, 2019).

This is particularly relevant to tangible interaction, as it enables the physical form of the object to serve its designated purpose. In his case, it enables museum visitors to handle, interact and inspect museum artifacts otherwise not available to the public. Moreover, it could be used to better serve the modality or fidelity of the interaction itself. For example, the physical shape can support a better grip, handling and control over spatial movement.

The prototype also demonstrates interesting qualities that are afforded by Additive Manufacturing (AM) and Multi-Material Jetting (MMJ). As discussed in the paper, the prototype was produced by a multi-material FDM printer. The complex three-dimensional patterns and the optical contrast of materials used for pattern recognition highlight affordances in materialization that can create novel approaches to create and support fiducial systems. Considering MMJ's capability of offering more materials and higher significantly higher resolution, this could be an interesting avenue to explore.

These studies highlight AM's and MMJ's ability to replicate and enhance existing fiducial approaches to enable tangible interactions. However, their reliance on existing systems which have not been developed with digital fabrication in mind potentially fail to capture the broader capacity of MMJ to support Human-Computer Interaction (HCI).

A paradigm that has emerged to move beyond the static interfaces associated with computers are Smart Material Interfaces (SMIs). SMIs consider the unique properties afforded by smart material composites and explore the implementation of digital logic to the physical world of objects to create novel interactions (Vyas et al., 2012).

For instance, EJtech has developed Liquid MIDI (Liquid Midi: Making Sound Matter, 2017): an experimental textile interface for sonic interactions which explores how aesthetics and morphology affects interactive design (see Figure 22). The technology involves the printing of a conductive paint applied directly onto a flexible textile surface. Sensors are able to capture user manipulations of form and shape by the changes in electric resistances. The digital response is a product of the designed patterns and physical manipulations.

Liquid Midi (2017) highlights how distinct material properties can be combined to serve a generative function for digital information. As the designer Kárpáti (2015) stated in a blogpost "..the medium becomes part of the message, where the interface becomes part of the process of creation itself." Liquid Midi (2017) demonstrates how SMIs can create more "natural" modalities for interaction and a rich sensorial satisfaction for users.

While this particular approach has used electronic components, the broader concept of leveraging unique material properties in combination with a digital logic to enable novel interactions is an interesting paradigm for MMJ. MMJ provides a rich variety in materials from which novel and unique interactions can be generated.

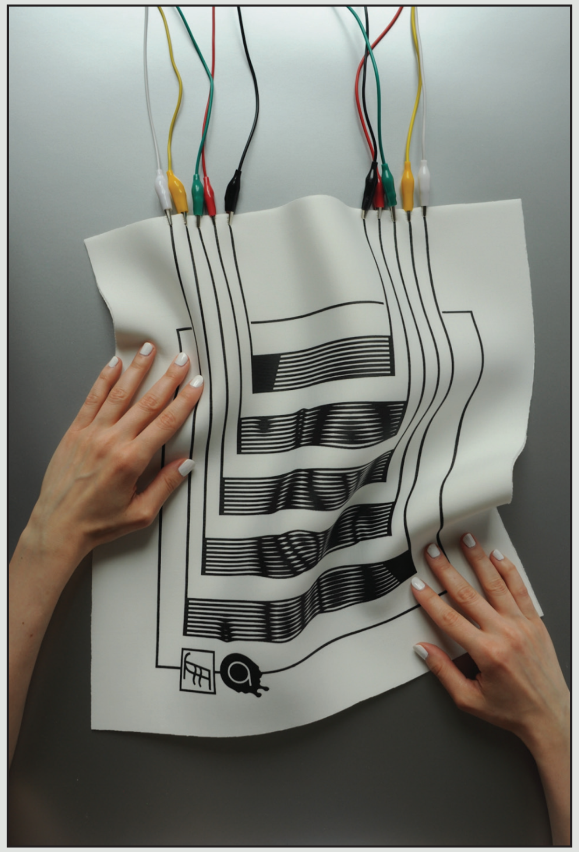
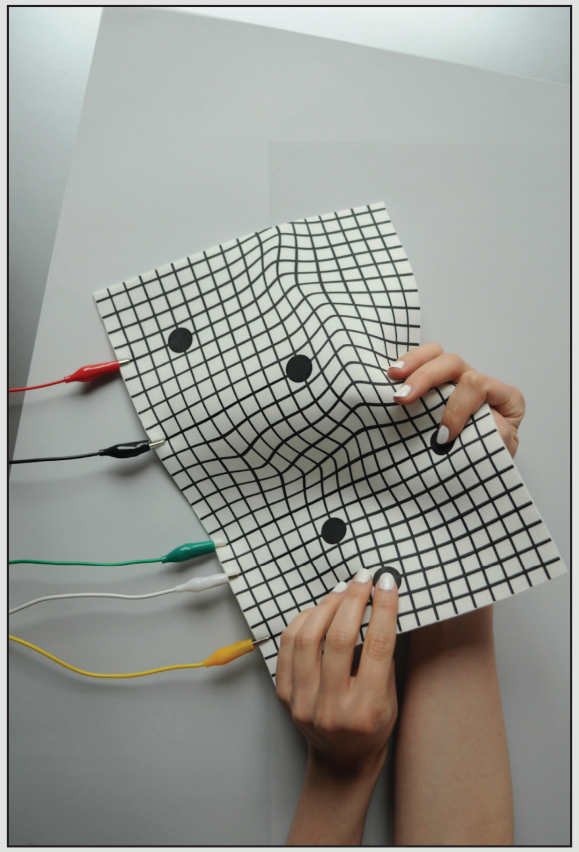


Fig 22 Liquid Midi: a textile interface for sonic interaction (Liquid Midi: Making Sound Matter, 2017).



2.3 DIGITAL FABRICATION: MULTI-MATERIAL JETTING

2.3.1 MULTI-MATERIAL STRUCTURES

To consider how materials behave physically, there are two important parameters to consider for Multi-Material Jetting (MMJ); which materials are selected and the structure in which they are configured. To understand how each parameter affects the physical behavior of materials, it is important to understand how these parameters interact with one another.

First, before introducing the complexity of multi-material structures, it is important to consider how mono-material microstructures have already been able to influence material behavior. Studies have shown that micro-material structures are able to manipulate mechanical behavior through the design of lattice structures, 3D geometries, and localized material density.

Notably, Schumacher et al. (2015) have demonstrated how numerical optimization could be used to design families of related microstructures that can be interpolated to smoothly manipulate the material properties over a wide range (Figure 23). Through their developed framework, given objects with specified elastic material parameters can automatically be converted into a fabricable representation that resembles the desired elastic deformation behavior.

Within the context of physical interaction, a unique feature that can be achieved through this process is the ability to control desired elasticity and subsequent behavior dynamically throughout an object. From a design perspective this enables mechanical behavior to be manipulated to

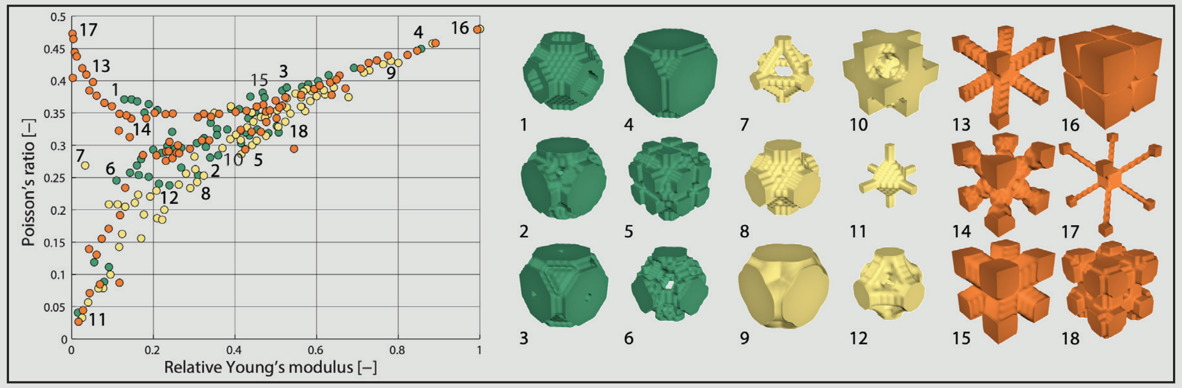


Fig 23 Micro-material structures families (Schumacher et al., 2015).

control physical movement, resistance and associated interactive modalities.

Moreover, micro structures enable designers to control and manipulate behavior given a predetermined shape or volume. The ability to optimize mechanical behavior through microstructures in material rather than macro-structural topology is especially interesting considering the design of physical interfaces, where shape and form can strongly improve the functionality and ergonomics of physical designs.

The discussed qualities of mono-material structures reveal a new dimension in design that enable designers to implement unique properties and applications in design for Additive Manufacturing (AM). It gives designers the freedom to design geometries and shapes that best serve the given application for physical interaction while simultaneously manipulating and controlling the physical properties and subsequent desired interactive behavior. Consequently, Micro structures vastly expands the diversity in material properties that can be achieved through the process of AM.

The introduction of multi-material printed structures offers new avenues to increase variety, functionality and performance of material structures. In their review of 3D printed Lattices, Mora et al. (2022) describe how distribution of materials with vastly different mechanical and thermal properties can create tunable mechanical properties. For instance, the combination of stiff and flexible materials to control the distribution of rigid and rubbery phases has allowed the tunability of elastic modulus and Poisson's ratio (Mirzaali et al., 2018), (Bossart et al., 2021) or the control of instabilities and buckling modes (Janbaz et al., 2018) (Figure 24).

Mora et al. (2022) highlight the MMJ process particularly interesting for the future development of tunable materials and functional structures. AM processes have had challenges dealing with imperfections, defects and anisotropy. These inconsistencies have made it difficult to accurately predict material behavior. However, Material Jetting's (MJ) high printing resolution and reduced anisotropy have improved the predictability of material behavior. Mora et al. (2022) contribute these features to an increasing number of tunable structures.

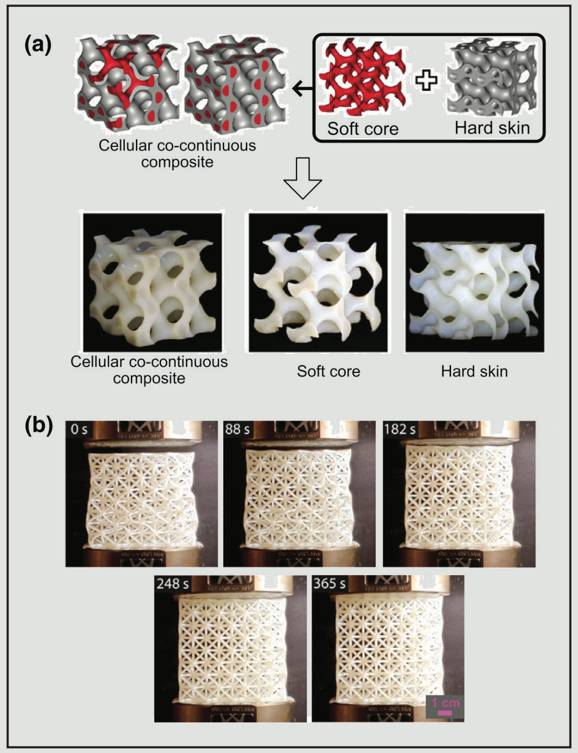


Fig 24 Soft-hard material interfaces control buckling (Mora et al., 2022).

Given these features, researchers have investigated the mechanisms by which MMJ can influence and control the mechanical properties of composite materials. Kaweesa et al. (2022) highlighted the tunability of composite mechanical properties achieved through voxel-based microstructural design in MMJ. The study examined the effects of various material properties leading to the development of a model that accurately predicts the mechanical behavior of particle-reinforced composites.

Their experiments identified key parameters that describe the behavior of multi-material composites. First, the mechanical properties of particle-reinforced composites are influenced by the microstructural representation of the orientation, size, and aspect ratio of rigid particles (Figure 25). Secondly, the composite properties mostly lie between the mechanical properties of the two constituent materials, regardless of the microstructural design.

In the context of Multi-Material Jetting (MMJ), these findings, along with those of Schumacher et al. (2015), suggest that material selection determines the range of mechanical properties and physical behaviors that composite materials can exhibit. Meanwhile, the form and structure dictate the specific point within this range at which the mechanical properties will manifest. Through precise control of the microstructures, composite materials can be engineered to dynamically exhibit desired mechanical behaviors within the boundaries set by their constituent materials (see Figure 26).

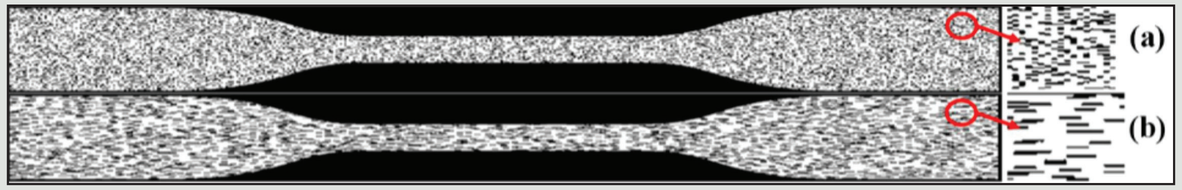


Fig 25 Cross section material variants in orientation size, orientation and aspect ratio (Kaweesa et al., 2022).

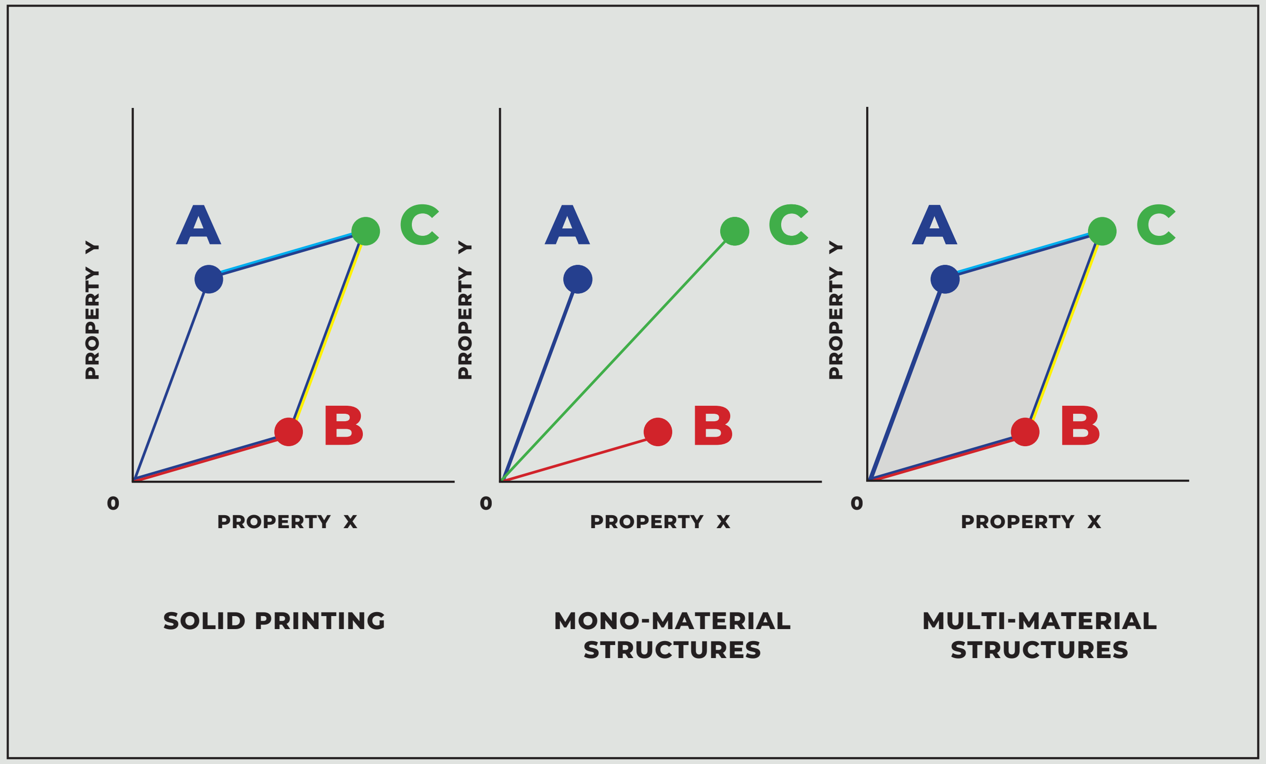


Fig 26 Showcase: design parameters of material and structure.

2.3.2 STIMULUS-RESPONSE MATERIALS

Beyond the ability to control mechanical properties and physical behavior locally, Multi-Material Jetting (MMJ) is recognized for its ability to create complex three-dimensional macro structures. The combination of micro- and macro-structures can significantly affect the way materials behave and respond to external circumstances. Certain unique behavior that can be achieved can be described having unique properties are described in literature as metamaterials;

"Metamaterials are artificially structured materials used to control and manipulate light, sound, and many other physical phenomena. The properties of metamaterials are derived both from the inherent properties of their constituent materials, as well as from the geometrical arrangement of those materials..." https://metamaterials.duke.edu/definition

A particularly relevant subset of metamaterials is Stimulus-Response Materials; these materials are designed to react in a specific and predictable manner to external stimuli. For instance, materials have been developed that exhibit shape morphing and/or shape-memory effects when exposed to particular temperatures (Yuan et al., 2021) (Figure 27). Described by Ayushi et al. (2021), the controlled behavior of Stimulus-Response Materials has been recognized as a potential feature to develop sensing technologies and actuation systems.

A notable Stimulus-Response effect within the context of computer vision and tangible interaction is the technology of lenticular surfaces. Lenticular surfaces are structures utilizing micro-lenses that redirect light project light to an image circle, enabling different images to be seen dependent on the relative viewpoint of the observer.

In 2021(a), Zeng et al. demonstrated how MMJ can replicate the mechanism of lenticular surfaces, allowing these typically 2D features to be easily printed and applied to 3D geometries. This capability enables the creation of three-dimensional objects with viewpoint-based visual representations.

Their work showcases that existing structural mechanisms like lenticular surfaces can be reimagined and innovatively implemented through the capabilities of MMJ, opening up new design opportunities. For example, they provided a demonstrator showing how lenticular surfacing can be applied to exercise kettlebells to offer real-time feedback to users on proper technique (see Figure 28).

Their work highlights that it is valuable to consider that MMJ can not only replicate existing applications, but the added affordances of digital fabrication can significantly recontextualize the meaning of adopted technology. When replicating or adopting existing metamaterial mechanisms, it is therefore important to consider how the differences in manufacturing technologies open up opportunities for novel interactions.

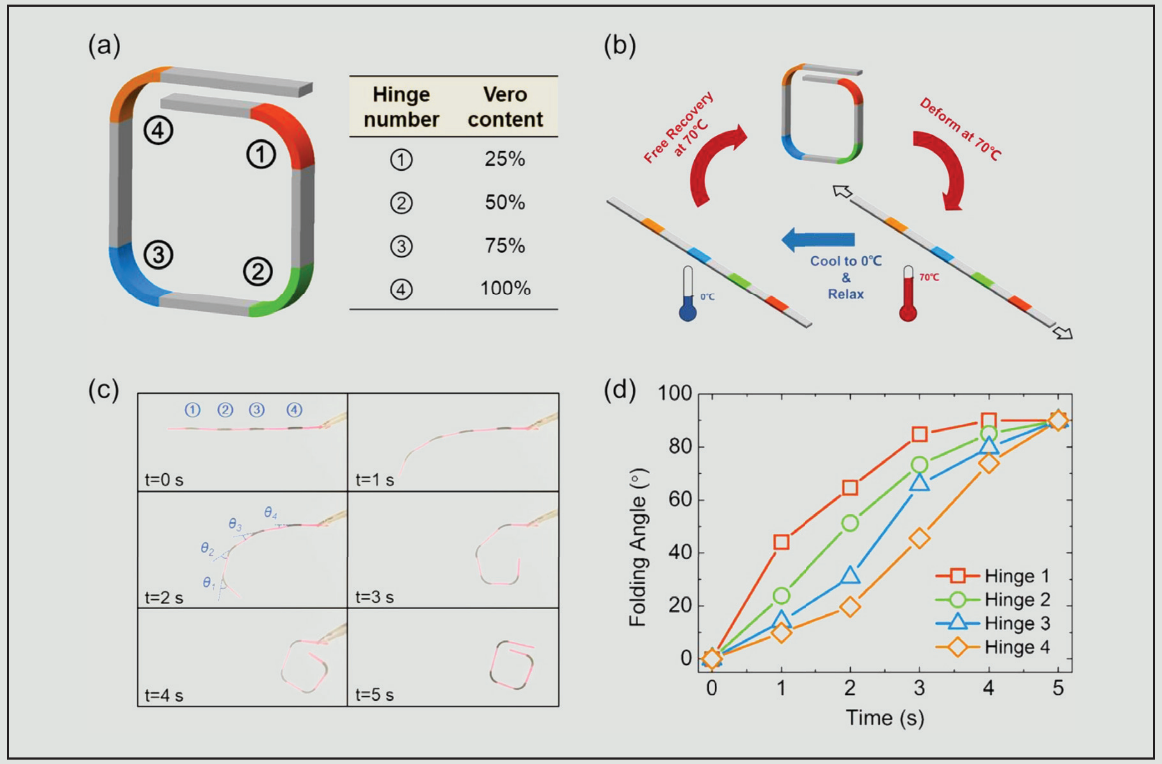
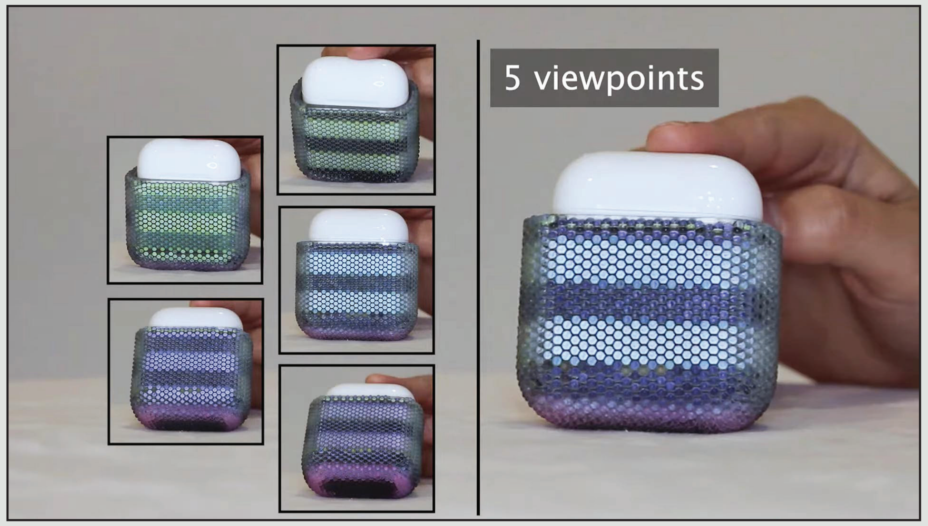


Fig 27 Temperature-actuated shape morphing materials (Yuan et al., 2021).



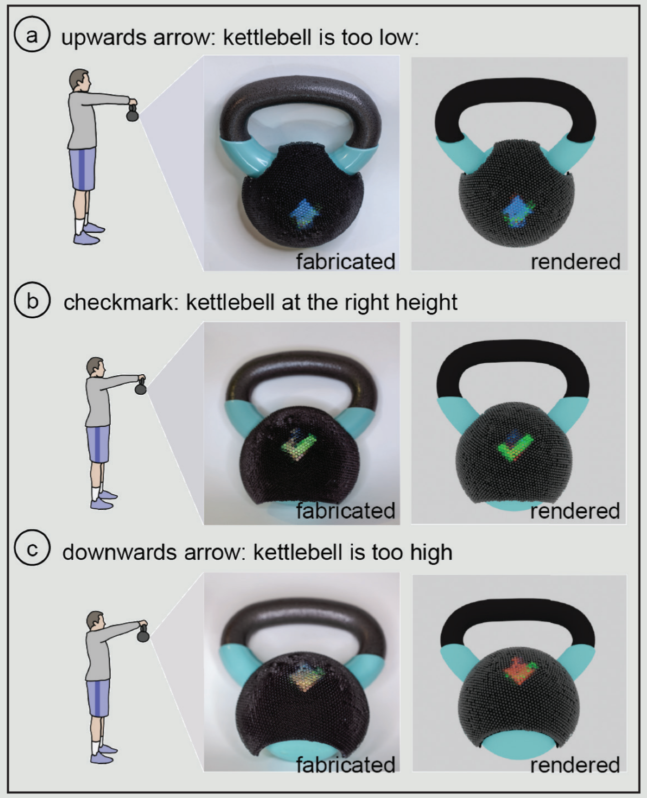


Fig 28 Lenticular surfaces and dynamic feedback (Zeng et al., 2021b; Zeng et al., 2021a).

Within the context of Extended Reality (XR), the ability to reconfigure and combine these technologies could potentially transform them in a way that supports novel ways to obtain or embed digital information in physical design. In the blogpost "Internet of Towels", Reddy (2019) has demonstrated how lenticular QR codes could be embedded in everyday objects to spatially connect digital data with the point of view of observers (Figure 29).

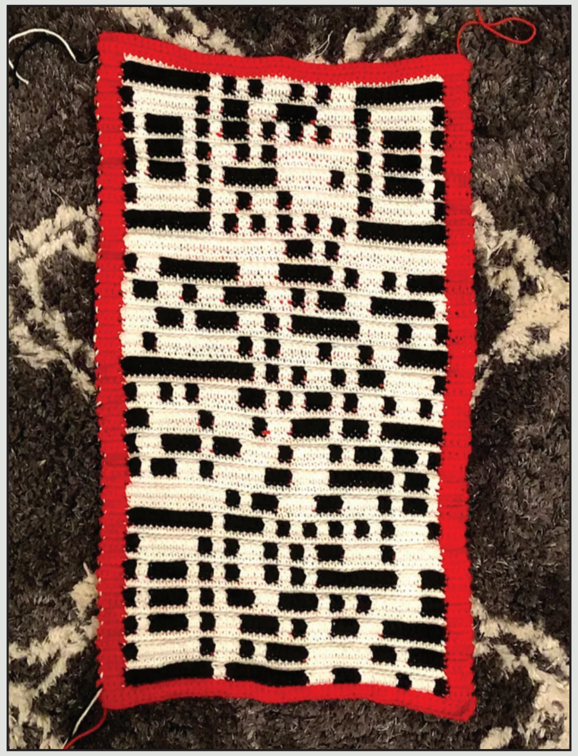


Fig 29 Internet of towels: A Lenticular QR Code only readable from a specific 45 degree angle (Reddy, 2021).

Similar to DynaTags (Schumacher et al., 2015), Reddy (2021) demonstrates the potential of "computational" objects that reflect dynamic information based on physical interactions between users and objects. In this process, it is shown materialization can play an interesting transformative role to interconnect interaction with digital information.

Moreover, it has also been shown that the paradigm of obtaining digital information from material properties described by Smart Material Interfaces (SMIs) can be applied to metabehavior of multi-material structures. In 2023, Meng et al. demonstrated a mechanical metamaterial which has utilized material-based encoding that enables storage and manipulation of digital information within the structure of material.

A temperature-responsive metamaterial was presented that provides temperature tunable responses. For example, to spell out particular letters at different temperatures as seen in Figure 30.

The mechanical metamaterial presented by Meng et al. (2023) suggests pathways to creating stimulus-responsive materials that can achieve multi-function; Stimulus-Response Materials are envisioned that encode information and allow users and environments to manipulate and interact with digital information.

Utilizing the dimensionality of mechanical and optical properties afforded by MMJ, smart material interfaces could potentially be generated that translate physical stimuli into dynamic fiducial responses. This

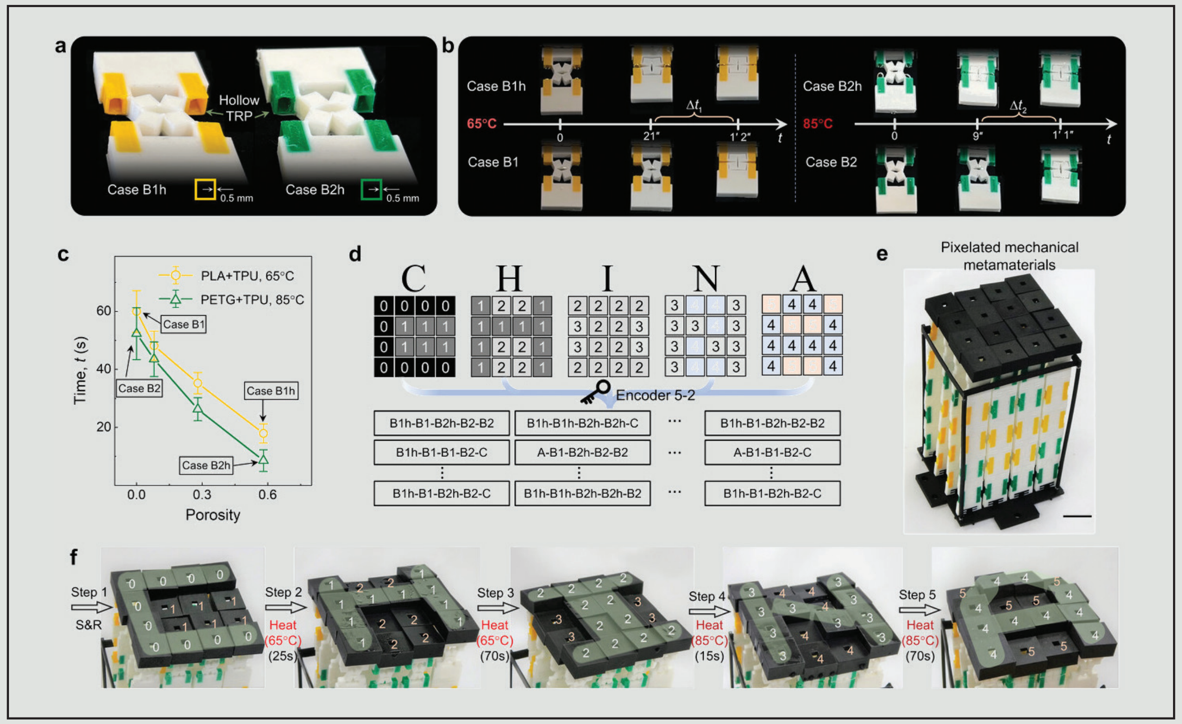


Fig 30 Temperature-responsive mechanical metamaterial (Meng et al., 2023).

would allow for smart material interfaces which do not require the use of embedded electronics (Figure 31).

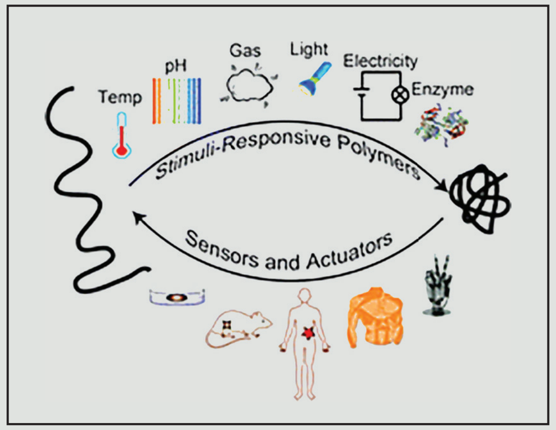


Fig 31 Stimulus-Response interface (Ayushi, 2021).

2.3.3 COMPUTER-AIDED DESIGN

The metabehavior and shape morphing effects that can be achieved by Multi-Material Jetting (MMJ) are recognized as unique design opportunities for Human-Computer Interaction (HCI). However, its added layer complexity and dimensionality to design has made implementations challenging. The digital and programmable nature associated with discrete material deposition has led to researchers exploring Computer-Aided Design (CAD) approaches.

The domain of Computer-Aided Design (CAD) has emerged as an approach to integrate the unique properties of metamaterials in the process of design. Through the utilization of digital algorithms and definition of desired parameters, design solutions can be generated that integrate digital fabrication affordances in a manner that optimizes materials' form and structure to support functionality and performance of objects in a meaningful way.

For instance, various approaches have been described to control and predict mechanical behavior of micro material structures (Schumacher et al., 2015; Kaweesa et al., 2022). However, while these studies demonstrate that materials can be created and subsequent behavior can be predicted, a functional or hierarchical approach where structure and behavior is generated to support predetermined desired design parameters would enable fabrication to optimize material behavior for their desired function.

Through an hierarchical optimization of structure and material, it has been shown that both material structure and local material properties can be co-optimized for mechanical elements (Rodrigues et al., 2002). This approach has demonstrated the possibility of controlling mechanical properties and subsequent desired physical behavior given pre-defined structural parameters of the shape.

The ability to optimize mechanical behavior hierarchically for a given geometry through material and structure is especially noteworthy considering the design of physical interfaces, where topology of shape and size can strongly inform the interactive modalities and ergonomics of physical designs. Consequently, it enables physical form and mechanical behavior to be optimized for different functional parameters.

This potential utility has shown the ability to transform the process of design and achieve desired mechanical properties through CAD. In 2023, Saldívar et al. presented a design approach towards environment and performance-driven form generation and material mapping, which was demonstrated in the design of a customized prosthesis socket.

Conventional socket designs are associated with tedious and labor intensive development processes that ultimately deliver sockets that do not fit properly, causing pain and discomfort. To overcome these limitations, Saldívar et al. (2023) have developed a CAD workflow that includes the ability to allocate material properties at a voxel scale to introduce function graded materials.

Based on a pre-determined geometry and allocated desired properties, a combination of material form and structure is generated to achieve desired properties (Figure 32). This has enabled the design of prosthesis where form, material and structure co-evolve, optimizing functionality and comfort.

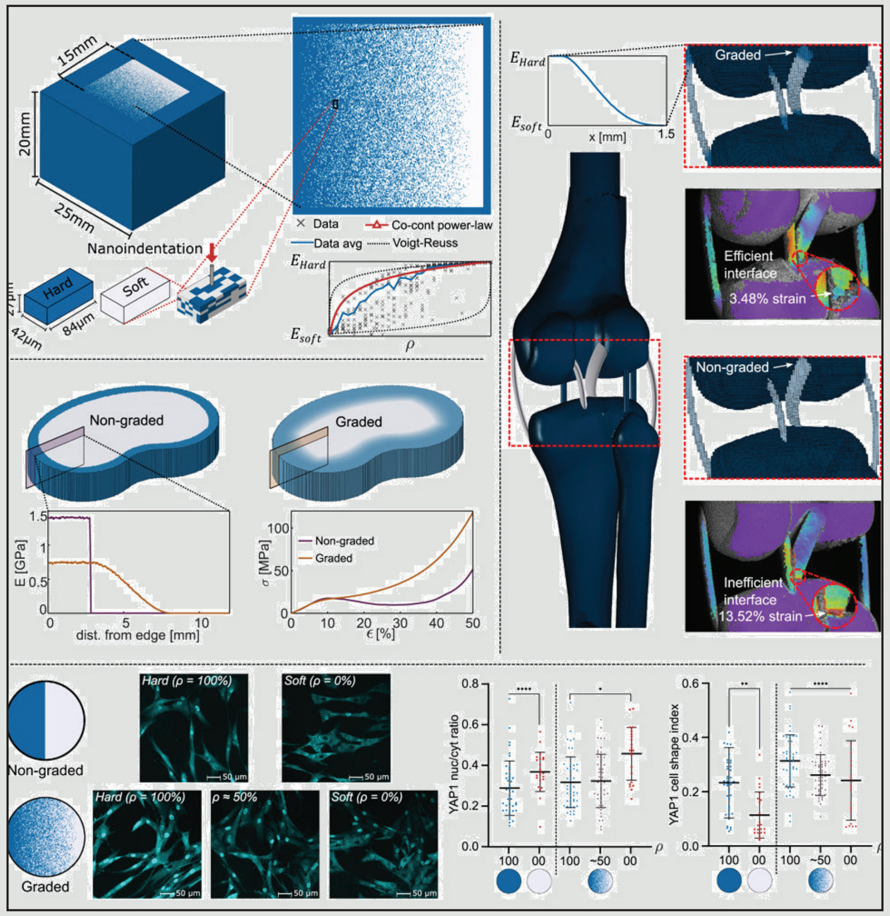


Fig 32 Physical behavior of prosthesis controlled through material structure allocation (Saldívar et al., 2023).

This study demonstrates a level of control over material properties achieved by allocating material and structure at voxel states which cannot be achieved using traditional CAD tools and volume-based Additive Manufacturing (AM) workflows. Moreover, it highlights an ability (and necessity) of CAD approaches to leverage this control in order to support functionality and performance.

Besides mechanical properties, researchers have developed CAD approaches to optimize the optical properties of multi-material 3D printing. In a recent review on full color reproduction, various approaches which enable designers to create complex visualizations and implement these in designs through automated digitized pipelines were described (Yuan et al., (2021). Yuan et al. (2021) concluded that computer-aided coloring methods show the greatest potential for achieving accurate full-color 3D printing with many types of printing materials.

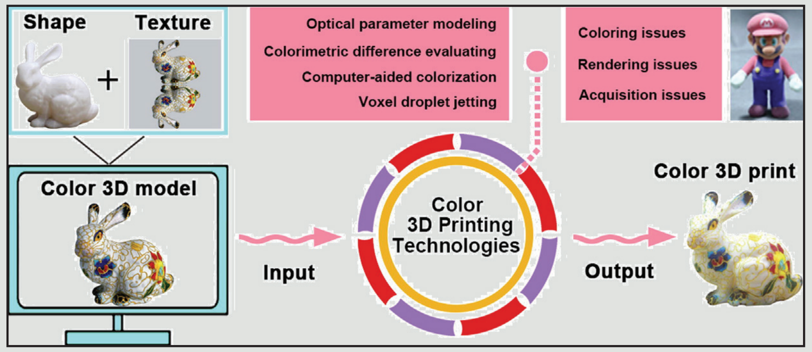


Fig 33 (Yuan et al., 2021).

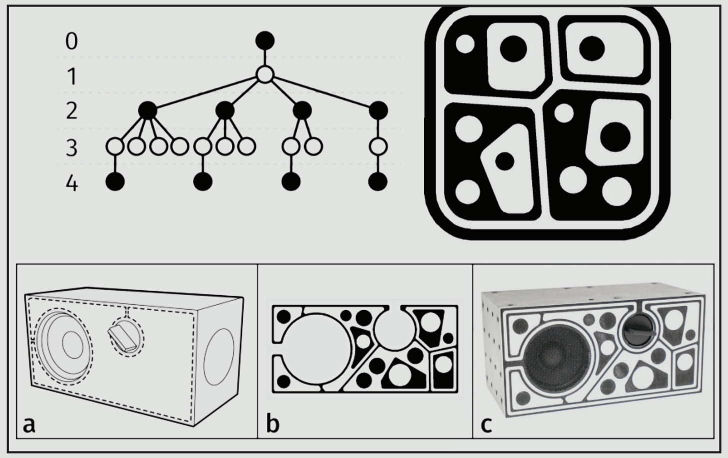


Fig 34 Fiducial marker CAD generated for specific geometry (Getschmann and Echtler, 2021).

These computer-aided coloring methods enable designers to utilize hierarchical optimization for optical properties to support desired applications. Getschmann and Echtler (2021) have explored how fiducial markers for tangible interfaces could be more seamlessly integrated in the design of physical objects. They proposed Seeedmarkers, a novel CAD approach to generate shape-independent fiducial markers that can be implemented in Additive Manufacturing (AM).

While their work focused primarily on the aesthetic perception of merging shape and topology of markers with physical objects, it has demonstrated hierarchical optimization can be applied to the design and generation of fiducial markers. Their generative approach prioritizes desired properties like shape and aesthetics where computational design bridges the conventional gap between function and form through material-structure generation (Figure 35).

The results demonstrate an ability to co-optimize aesthetics of physical form and shape and the embedding of digital information for Extended Reality (XR) applications concurrently within physical designs.

In addition to the ability to optimize physical and optical properties independently, Morovič et al. (2019) have demonstrated the possibility to co-optimize both physical and optical properties within a singular part.

Their work presented a general approach to characterizing the properties resulting from the various material combinations of a printing system, followed by the use of that characterization for controlling color and mechanical properties separately as well as jointly.

Through this approach, Morovič et al. (2019) were able to produce physical objects which met both desired optical and mechanical

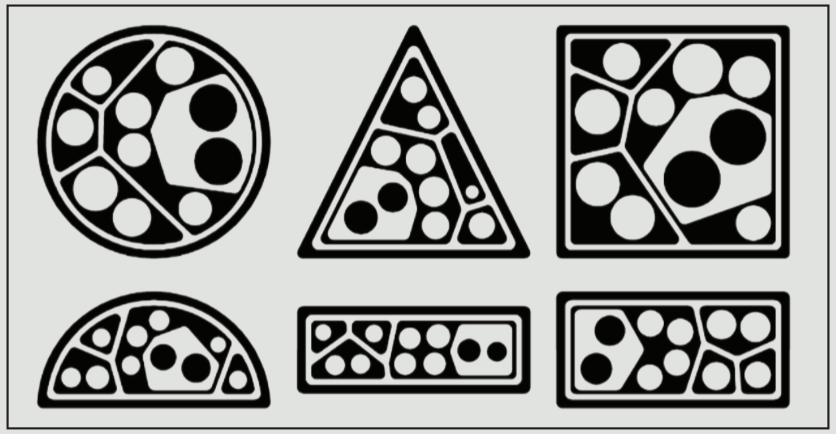


Fig 35 Fiducial markers generated for various two dimensional geometries (Getschmann and Echtler, 2021).

properties. For instance, they were able to control the center of mass and mechanical breaking point concurrently with color imaging within a single print (Figure 36).

The independent ability of CAD form generation of material and structure to support physical interaction and computer understanding, combined with the ability to co-optimize mechanical and optical properties within a singular part present a unique opportunity. It suggests a potential for MMJ to optimize both physical and digital properties within the process of materialization which are crucial for enabling physical interaction and interpretation of digital information (Figure 37).

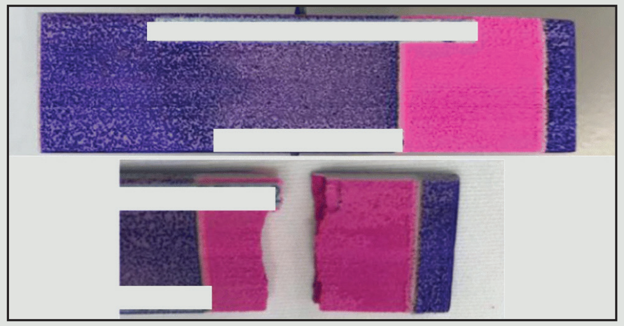
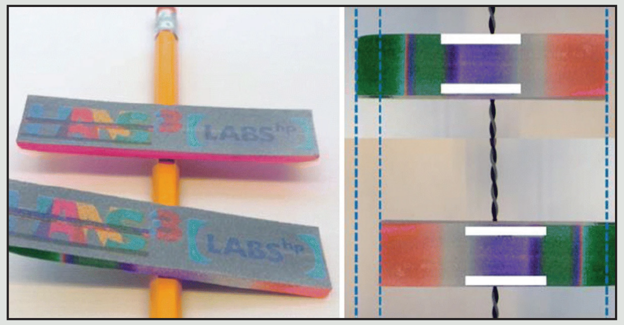


Fig 36 Various demonstrators of mechanical-optical co-optimization: Left: Breaking point, Right: center of mass (Morovič et al., 2019).



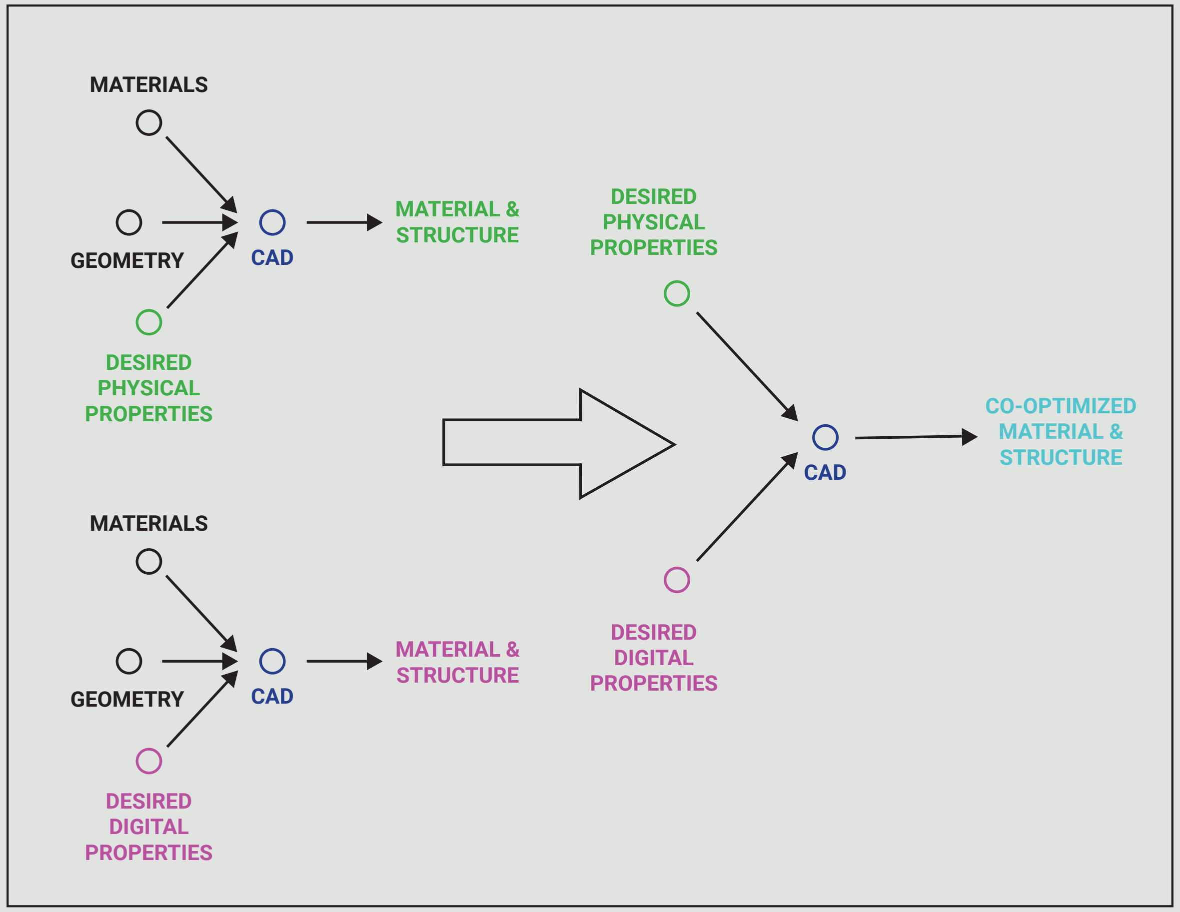


Fig 37 CAD + MMJ enables co-optimization of physical and digital properties within the generation material and structure.

2.4 OPPORTUNITIES AND ENVISIONED SOLUTION SPACE

STIMULUS-RESPONSIVE MATERIALS

Extended Reality (XR) and Tangible User Interfaces (TUIs) provide a strong synergy within the realm of Human-Computer Interaction (HCI). TUIs enable users to physically interact with virtual environments, which has been shown to improve understanding, usability and experience of HCI. On the other hand, the ability of XR to virtually recontextualize physical interactions has been shown to greatly increase the versatility and functionality of physical interfaces.

However, a major challenge persists in the area of Extent of Real-World Knowledge (EWK). In order for TUIs and XR systems to connect user interactions with appropriate feedback, the interactive environment has to be captured reliably and accurately. High quality information has to be generated in real time in order to support applications for HCI.

In literature, both XR and TUIs have often utilized electronics and hardware to acquire this information. While multi-modal hardware approaches have shown the ability to support HCI, their employment has significant limitations. As summarized by Holmquist (2023), the implementation of electronics in TUI is accompanied with poor reliability and repairability, as well as high development and maintenance cost. By extension, Holmquist (2023) concluded that while TUIs are desirable, they may not be economically viable nor environmentally sustainable.

To address these limitations, alternative information systems that minimize hardware use have been explored. Fiducial approaches, for instance, offer a promising solution for HCI. Fiducial markers are inexpensive, easy to implement, and provide robust, accurate data. For XR, applications fiducial approaches have been shown to support high levels of functionality. Moreover, dynamic fiducials have demonstrated the potential to create interaction systems that support robust and accurate digital information for XR which can be manipulated through physical interactions (Scheirer & Harrison, 2022).

While conventional fiducial designs have been considered limiting and restrictive in the past, materialization has shown various avenues to improve information accuracy, reliability and resolution. It has been shown how fiducial designs can be optimized through consideration of the intended sensory modalities and desired interactive elements to be captured. For instance, colors on the chromaticity plane have been used to create lumination invariant markers (Kyriakoulis and Gasteratos 2010), and MoiréWidgets (Zamora et al., 2024). showcase an ability to tune resolution and robustness of information for specific applications (Zamora et al, 2024).

Furthermore, the paradigm of Smart Material Interfaces (SMIs) reveals materialization itself as a potent avenue to generate digital information. By linking the unique and predictable behaviors of smart materials to a digital logic system, materials can be designed to translate physical interactions into digital data (Vyas et al., 2012). This embodied approach provides a promising avenue for seamlessly interconnecting physical interactions with digital information, enabling more natural and innovative interaction modalities (Liquid Midi: Making Sound Matter, 2017).

Examining materialization as an avenue to improve TUIs for XR, the paradigms of digital fabrication and Additive Manufacturing (AM) were explored for potential intervention opportunities. Multi-Material Jetting (MMJ) has shown a myriad of qualities and affordances that show a potential to interconnect the respective physical and digital needs in the process of design.

MMJ can be characterized by its high dimensional control over material and structure (Mora et al., 2023). Through this precise control over material and structure, composite materials can be engineered to dynamically exhibit desired mechanical behaviors within the boundaries set by their constituent materials (Schumacher et al, 2015; Kaweesa et al., 2022).

Regarding physical interaction, MMJ shows considerable promise in accurately predicting and controlling the mechanical properties and physical behavior of composite materials (Kaweesa et al., 2022). Through manipulating material and structure, MMJ can dynamically adjust the interactive behavior of materials locally across different areas of a physical design to serve interactive purposes (Schumacher et al., 2015). By leveraging Computer-Aided Design (CAD) approaches, this capability can be used to develop solutions that support and optimize for the desired modalities of physical interaction (Doubrovski et al., 2015).

Similarly, combining MMJ with CAD has proven effective in controlling and optimizing optical and fiducial properties during materialization (Yuan et al., 2021). This capability has enabled innovative methods for embedding digital information within physical designs, including the optimization of fiducial markers for various shapes (Getschmann & Echtler, 2021) and geometries (Mann & Fryazino, 2019).

A particulary relevant feature afforded by the ability to allocate material properties at voxel states is the ability to co-optimize both mechanical and optical properties at once. It has been shown both optical and mechanical properties can be co-optimized within the generation of form, enabling designs that embody both desired physical behavior and visual representation (Morovič et al., 2019).

Another feature which shows promise to interconnect the physical and digital trough material and structure is MMJ's ability to produce stimulus response materials (Ayushi et al., 2021). Stimulus-Responsive Materials are understood as a subset of smart materials specifically designed to undergo significant and predictable changes in their physical properties or physical form in response to a specific external stimulus.

By applying the digital logic associated with smart material interfaces to stimulus response materials, it has been shown that these aforementioned transformations can interlink physical interactions with dynamic fiducial information (Ayushi et al., 2021). For instance, the mechanical metamaterial presented by Meng et al. (2023) and the lenticular QR code presented by Reddy (2019) demonstrate how shape manipulations and spatial interactions can be interlinked to a fiducial system, enabling physical and spatial manipulations to be represent a change in digital information.

The convergence of these capabilities suggests a potential solution space where

MMJ can both optimize and interconnect the physical and digital properties within the generation of form, which are crucial for facilitating tangible interaction and exchange of digital information. Through a careful implementation of digital logic, Stimulus-Response Materials are envisioned that embody the computational processing needed to translate physical interactions into dynamic fiducial responses. Subsequently, computers could interpret these responses to provide virtual feedback that (re)contextualize the physical interactions within XR applications (Figure 38).

Ultimately, MMJ's access to printing parameters that include exceptional control over material and structure outline a potential avenue for CAD approaches that interweave the paradigms of TUI and XR within the process of materialization, representing a transformative approach to HCI.

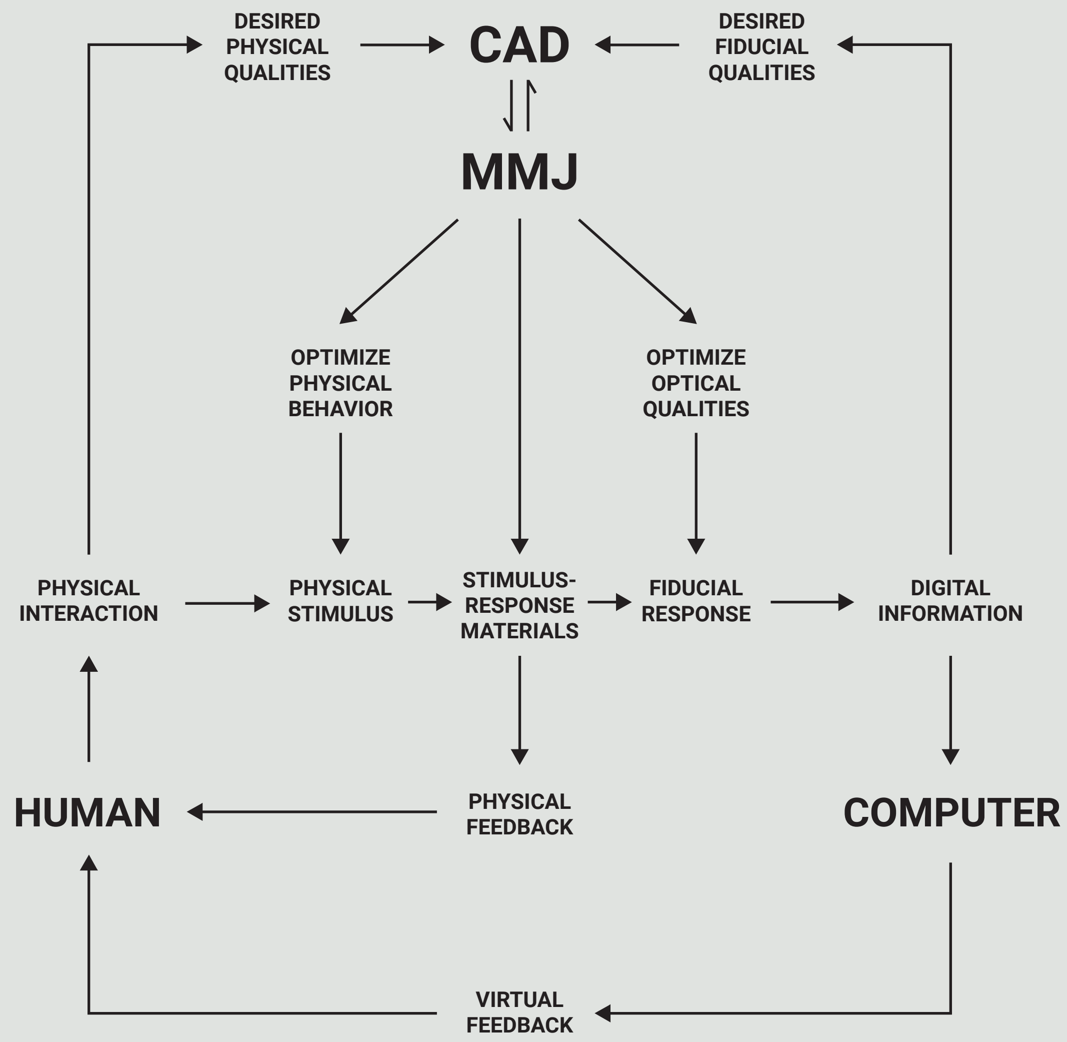


Fig 38 Stimulus-Responsive materials and Multi-Material Jetting as a potential solution space for Tangible User Interfaces and Extended Reality.

2.5 CONCLUSION

This chapter was set out to find possible opportunities of Multi-Material Jetting (MMJ) to address challenges associated with tangible interactions and Extended Reality (XR).

MMJ's exceptional control over material and structure was found particularly promising to bridge and connect physical interactions with digital information.

Through a Computer-Aided Design process (CAD), MMJ has the ability to co-optimize both physical and digital properties within the process of materialization. Through manipulation of material and structure, mechanical properties can be manipulated to allow for certain interactive behavior while optical properties can be optimized for fiducial information systems.

Combined with MMJ's ability to create stimulus response materials, a potential solution space is envisioned for fiducial stimulus-responsive materials that dynamically convert physical interactions into fiducial information.

CHAPTER 3. DESIGN EXPLORATION

3.1 INTRODUCTION

The literature study has explored how multi-material 3D printing may facilitate physical manipulation to be captured and interpreted within Extended Reality (XR) systems. A unique solution space for Multi-Material Jetting (MMJ) has been identified that envision stimulus response materials capable of converting physical stimuli into a fiducial response.

To evaluate feasibility of this embodied approach for Tangible User Interfaces (TUIs) and explore the potential interactions that can be unlocked, a "Research through Design" process was used:

"Research through Design (RtD) is an approach to scientific inquiry that takes advantage of the unique insights gained through design practice to provide a better understanding of complex and future-oriented issues in the design field" (Godin & Zahedi, 2014).

This chapter describes the design and development of Colorful Bits: a Smart Material Interface for kinetic interaction. Opportunities, challenges and limitations for TUIs and XR are demonstrated, revealing the potential relevance of MMJ for Human-Computer Interaction (HCI).

3.2 DESIGN OBJECTIVE

KINETIC INTERACTION

Within current literature, many fiducial approaches have been developed for pose estimation and tracking movement to facilitate user interaction. However, the majority of existing fiducial approaches only consider the spatial aspect of movement, disregarding kinetic properties of motion.

Kinetics describe the relationship between the motion of material bodies and the forces and energy associated therewith. Unlike traditional fiducial approaches that focus only consider spatial movement, Kinetics interfaces propose the relationship between motion and applied physical stimuli to embody and communicate information (Parkes, 2008).

This outlines a potential for fiducial stimulus responsive materials that interconnects kinetic deformation with digital information. Moreover, the malleable nature of kinetic materials are intrinsically interactive. Through such materials, digital interactions can become richer, redefining sensorial and cognitive participation of users (Figure 39 above) (Bengisu and Ferrara, 2015).

To expand interaction design beyond the constraints of spatial tracking alone, this project investigates kinetic interaction that considers kinetic motion as a tangible user input - a future for tangible interaction where a relationship between motion and meaning can be established through kinetic deformation (Figure 39 below).

*"Develop a **Stimulus-Responsive material** that interconnects **kinetic shape transformations** with **dynamic fiducial information**"*

Fig 39 Establishing a relationship between movement and energy could be a powerful tool for expression through physical interactions (Minimalissimo, n.d.).

CHALLENGES

A subset of challenges which are particularly relevant to kinetic interaction have been identified.

Deformation breaks the fundamentals of existing fiducial markers:

Current fiducial marker systems rely on the recognition of static features. For example, In order to localize and detect QR codes, it is assumed that a certain set of feature points are always present within a certain threshold relative to one another. Consequently, existing detection methods assume that markers are printed on ideally planar surfaces (Yaldiz et al., 2021).

The introduction of deformation fundamentally breaks this condition. When objects are deformed, there are theoretically infinite amounts of possible shape variations and superpositions. Consequently, any computer vision approaches that require static proportions between features will not work (Figure 40).

CURRENT FIDUCIAL TRACKING LIMITATIONS

To overcome the aforementioned challenge, current fiducial tracking approaches often employ an array of markers to track movement and deformation. Each fiducial marker is a unique reference point, where the sum of all fiducial markers represents a fiducial system. Though this approach is effective in certain use cases, there are significant limitations.

The size of a message or identification code is limited by the spatial resolution of binary patterns in a marker. Consequently, features of conventional marker based tracking approaches rely on the size of the marker. The size of the markers determines the optimal viewing distance, as well as the resolution of surface tracking. This proposes a design constraint where increasing the tracking resolution by employing small markers inadvertently restricts the viewing distance. Moreover, as each tracking point requires a full marker, the tracking resolution is inherently low (Figure 41).

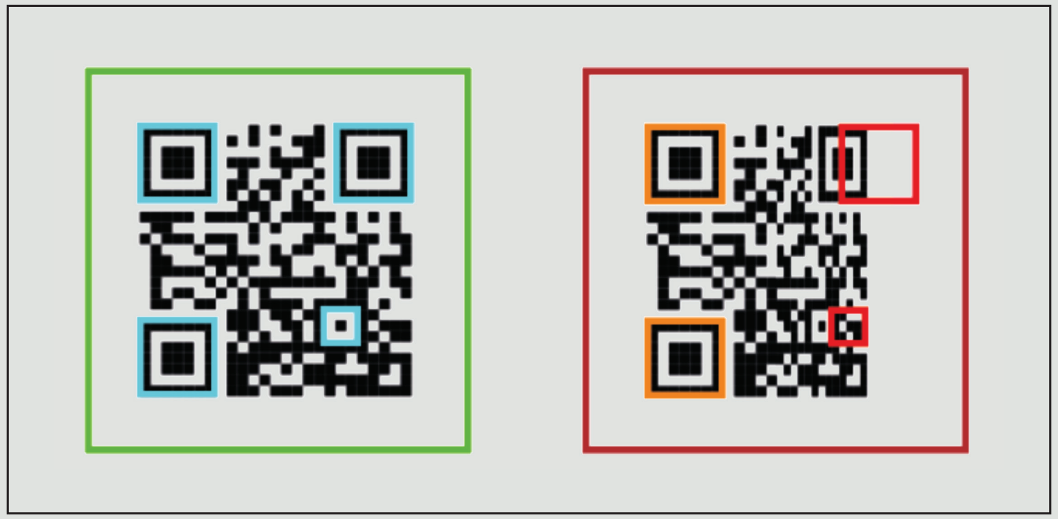


Fig 40 Marker with static reference points B Deformed marker not recognized.

Fig 41 Array of tracking markers to track dynamic shape. Left showcases limitation viewing distance (Liang et al., 2024).

POSE ESTIMATION ERRORS: POSITION AND ORIENTATION

The orientation and position of a fiducial marker relative to the observer is important to consider. Size and perceived resolution of markers decrease as the viewing angle to the observer increases (Figure 42). The size and resolution of the marker is therefore directly related to the relative angle to the observer. Paradoxically, as the angle increases the relative size and resolution within the image decreases, therefore becoming less accurate and consistent for pose estimation. As seen in Figure 43, this results in edges not being recognized.

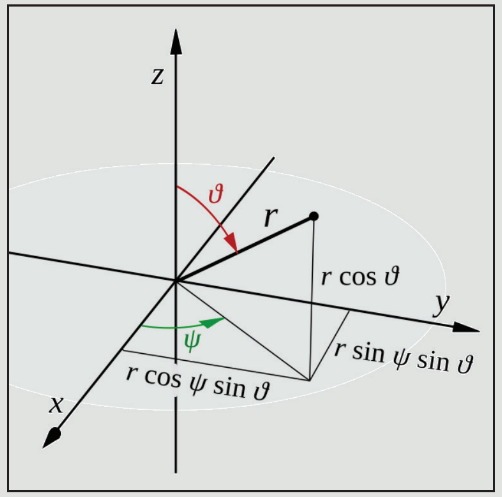


Fig 42 (Math Insight, n.d.)
A projected = cos(a) * Aoriginal
Xres = cos(b) sin(a)
Yres = sin(b) sin(a)

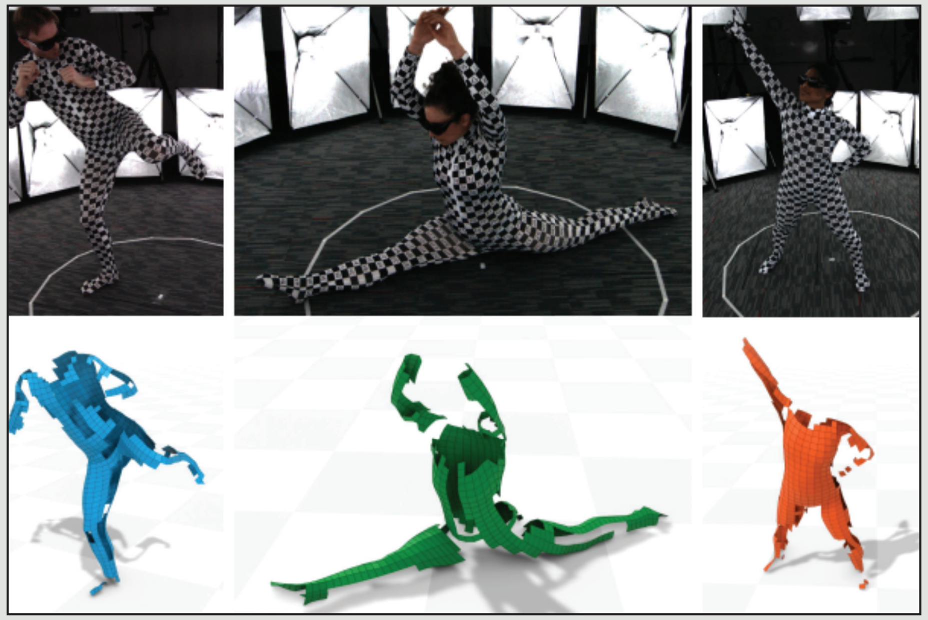


Fig 43 Markers on contouring edges are not recognized as a result of viewpoint distortion (Chen et al., 2021).

When considering a design that deforms, this is especially problematic. Static designs can account for different orientations by strategically placing markers to be viewable from any orientation. Assuming a static object always has the same shape, correctly estimating a single marker is sufficient to know the orientation and position of the entire object. This quality is however not afforded to form-changing objects.

To summarize, current fiducial markers are inherently static by design. Consequently, they are unsuitable for capturing dynamic transformations and deformation, which are crucial for the envisioned facilitation of kinetic interaction as a tangible user input.

3.3 DESIGN SPACE: CHARACTERIZATION OF MATERIAL PROPERTIES

To overcome the aforementioned challenges, it is important to consider how different printing parameters affect the kinetic behavior and fiducial properties. As described in chapter 2.2.1, selected materials define and describe material properties achievable through multi-material structures.

To understand how material and structure can be optimized for kinetic interaction, this chapter describes the mechanical and optical properties that can be achieved and are characterized by their influence on kinetic behavior and fiducial qualities respectively.

MECHANICAL PROPERTIES AND PHYSICAL INTERACTION

The first step of the composite material characterization process consists of the characterization of constituent materials. According to the manufacturer, the Vero materials share mechanical properties, and are therefore considered mechanically identical. From existing literature, the following mechanical properties were obtained (Table 1).

Property	VeroUltra	Agilus 30
Tensile Strength	50-65MPa	2.4 - 3.1 MPa
Elongation at break	15-25%	220-240%
Modulus of elasticity	2000-3000 MPa	LOW

Table 1. Material comparison, retrieved from Stratasys Datasheets (Appendix A).

Material composite boundaries: Rule of Mixtures:

Next, following the approach of Kaweesa et al. (2022), a broad estimation of achievable composite properties was obtained by applying the Rule of Mixtures.

According to the Rule of Mixtures (1), the upper and lower bounds of a composite's expected material properties can be derived from their relative volumetric fraction and associated material properties of the constituent materials. Moreover, utilizing the Inverse Rule of Mixtures (2), the lower bound of material properties can be estimated (Figure 44).

(1) $$E_{High} = f * E_f + (1-f)E_M$$

(2) $$E_c = \left(\frac{f}{E_f} + \frac{1-f}{E_m}\right)^{-1}.$$

Where:

f = Vf / (Vf + Vm)
Ef is the material property of the fiber
Em is the material property of the matrix

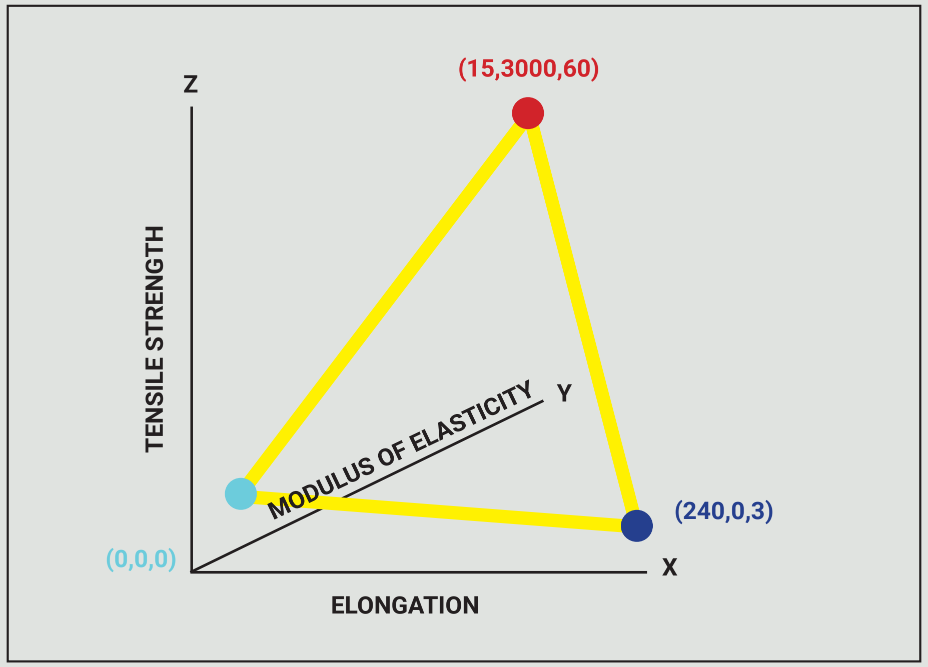


Fig 44 Simplified 3D Representation of material-property volume derived from rules of mixtures and structural topology.

Interactive properties:

Comparing Vero materials with Agilus 30, a stark contrast in mechanical properties is apparent. A notable feature are the inverse proportions of tensile strength to elongation, where Agilus elongates up to 10 times more while having a 10 times while having 10 times less tensile strength.

In practice, Agilus behaves like an elastic rubber that can be easily deformed, stretched and bent, and is soft to the touch. Vero is stiff and strong. It is flexible but hard to bend (see Figure 46).

OPTICAL PROPERTIES AND FIDUCIAL INFORMATION

3D CMYK color printing:

The Vero color materials allow for CMYK printing. CMYK printing is a color printing process that uses four ink colors: Cyan, Magenta, Yellow, and Key (White or black. These inks are layered and combined in various amounts to create a wide range of colors. CMYK is a subtractive color model, meaning that it starts with a white reflective background and subtracts color to create the desired shades (Figure 48). Traditionally it is used for various printing applications such as for magazines, posters, and packaging, as it allows for accurate color reproduction on physical media.

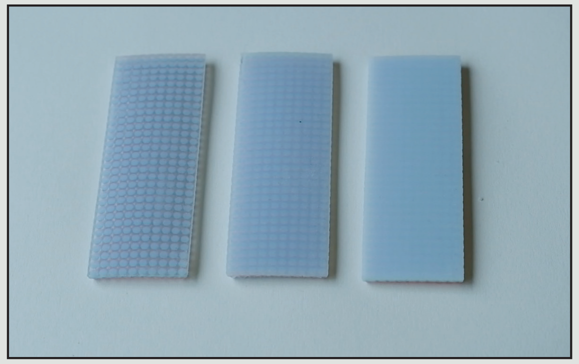


Fig 45 Flatlays.

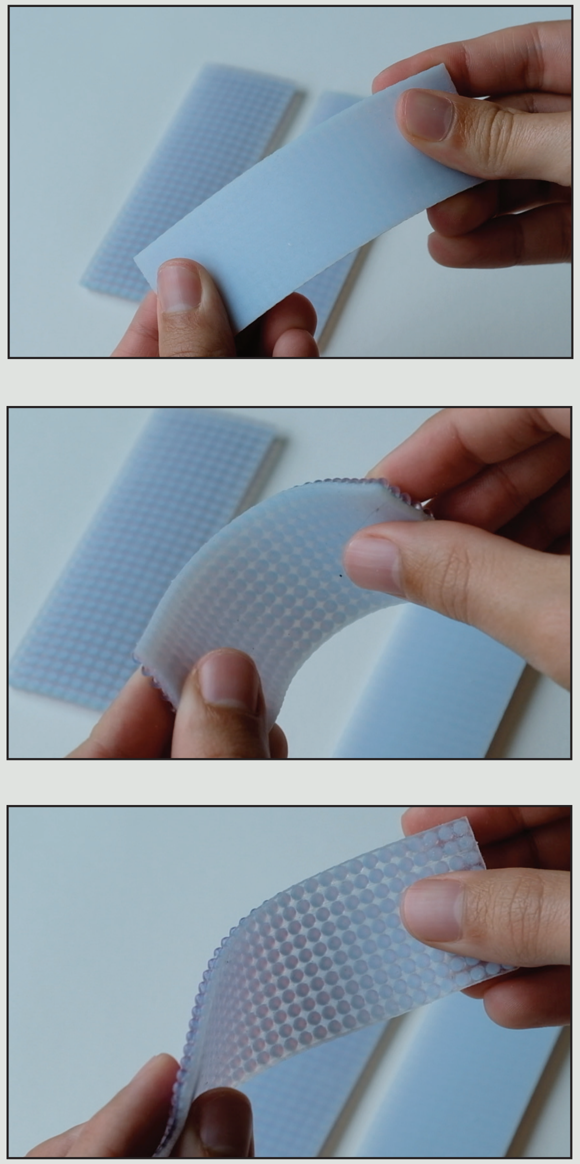


Fig 46 From hard, stiff, and static to soft, flexible, dynamic.

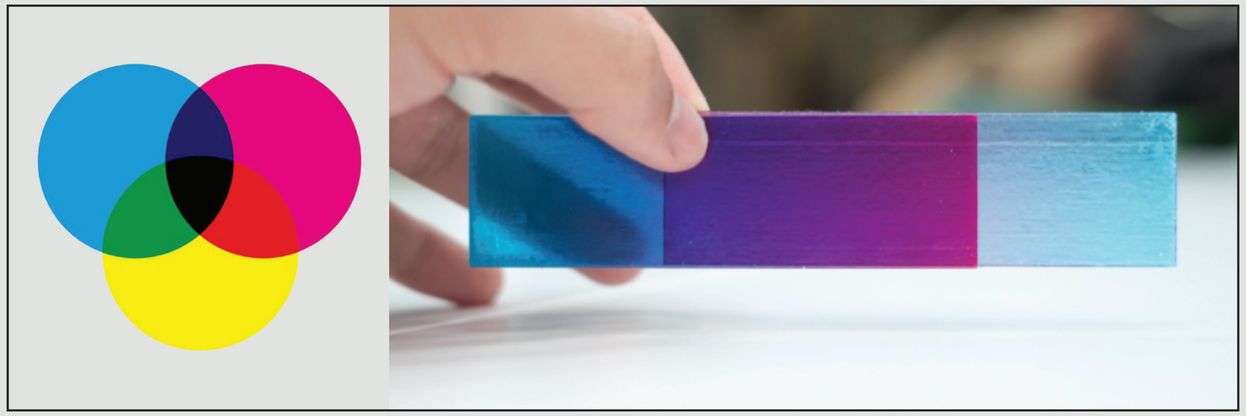


Fig 47 CMYK is a subtractive color model.

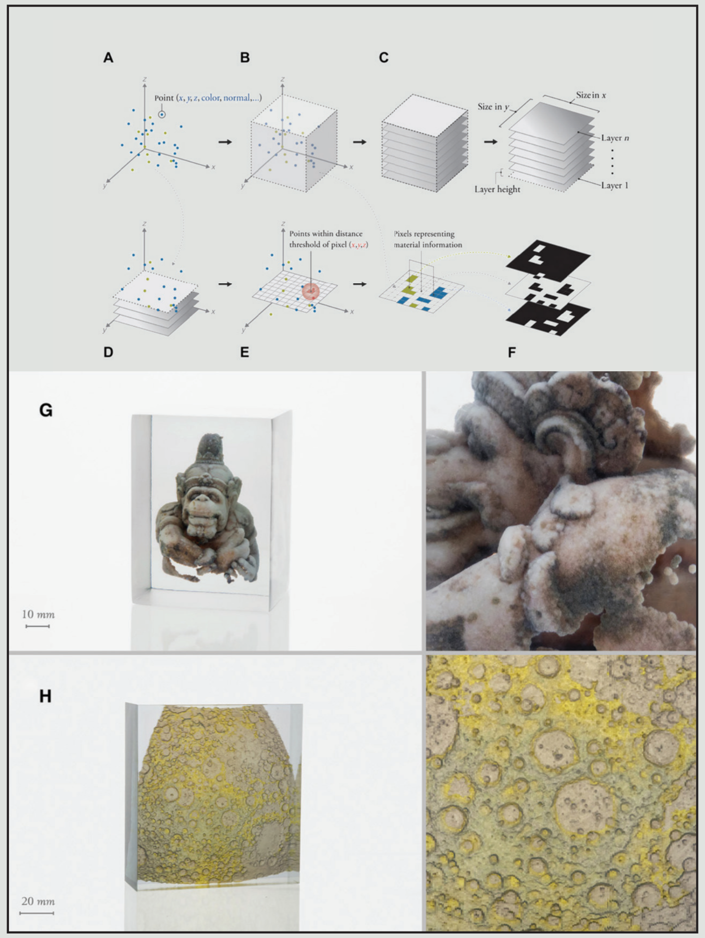


Fig 48 Voxel based bitmapping approach to 3D color printing (Bader et al., 2018).

Fiducial characteristics of full color imaging:

Intensity (grayscale):

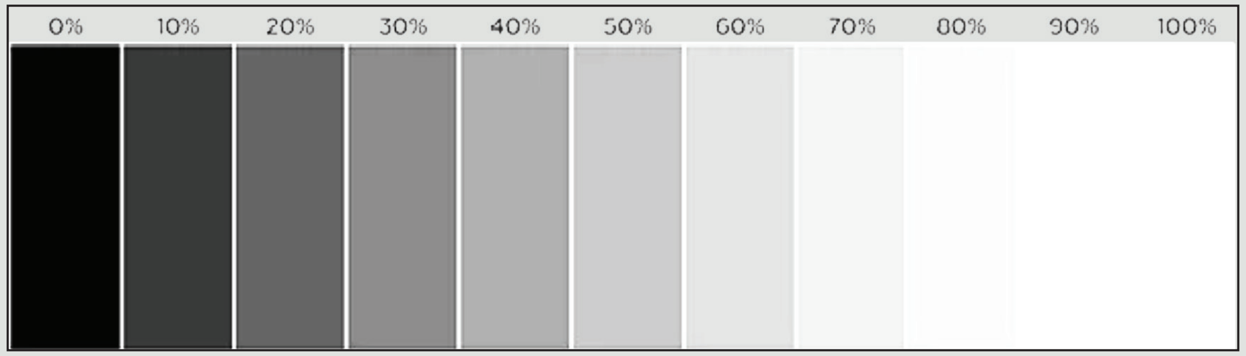


Fig 49 Grayscale.

In certain types of analysis, grayscale images often provide better contrast than color images because the differences in intensity are more pronounced. Grayscale is particularly useful in tasks like edge detection, feature extraction, and object recognition, where distinguishing patterns or identifying objects relies heavily on intensity variations (GeeksforGeeks, 2024).

Benefits of color imaging: hue and saturation
Rather than collapsing the RGB values to obtain a greyscale value, the measured R, G ,B values can be considered separately as well as jointly for image analysis. By converting RGB to the HSI colorspace, this provides certain advantages over grayscale imaging for image analysis.

Provided chromaticity of a color remains consistent under different lighting conditions, it can serve as a reliable reference feature. This differs from grayscale imaging, as it enables the separation of data even when they share the same perceived intensity (Cheng et al., 2001 (see Figure 51).

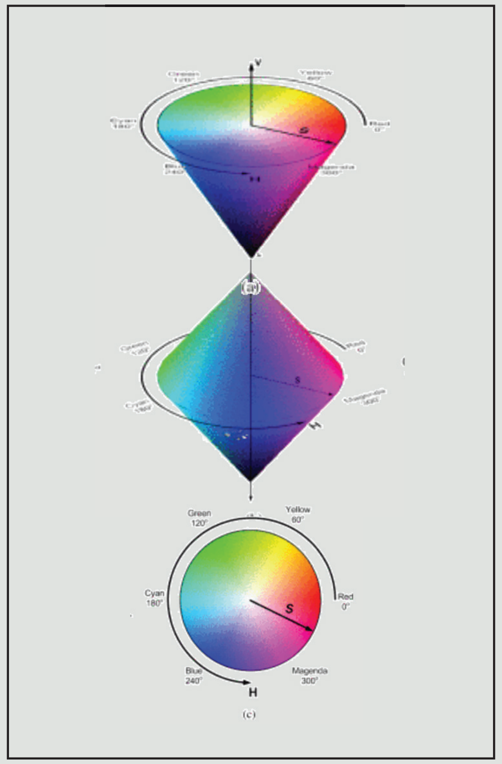


Fig 50 The HSI color model separates Hue (color), Saturation (colorfulness), and intensity (perceived brightness) (Kyriakoulis and Gasteratos, 2010).

Additionally, hue is particularly valuable in situations where the lighting level changes across different areas or between images. Under the condition of integrated white, hue remains invariant to specific types of highlights, shading, and shadows (Cheng et al., 2001) (see Figure 52).

These examples demonstrate that the separation of color can be a valuable tool for the interpretation of physical environments. By considering colors separately, color contrast can be used to evaluate images by considering the hue, saturation, and intensity components respectively. Color and particularly chromaticity holds strong fiducial qualities for digital information.

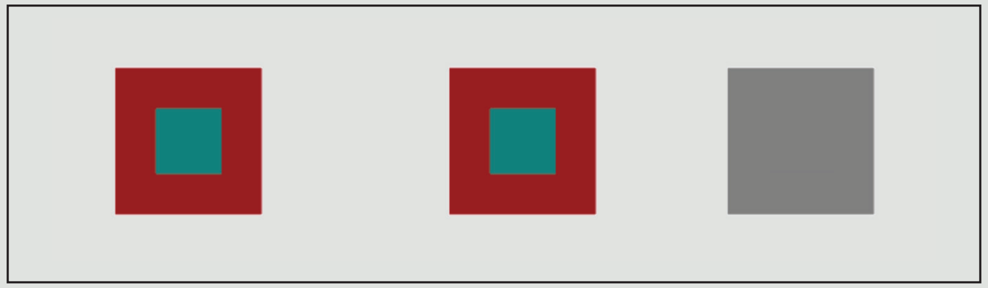


Fig 51 Object - Chromaticity VS. grayscale.

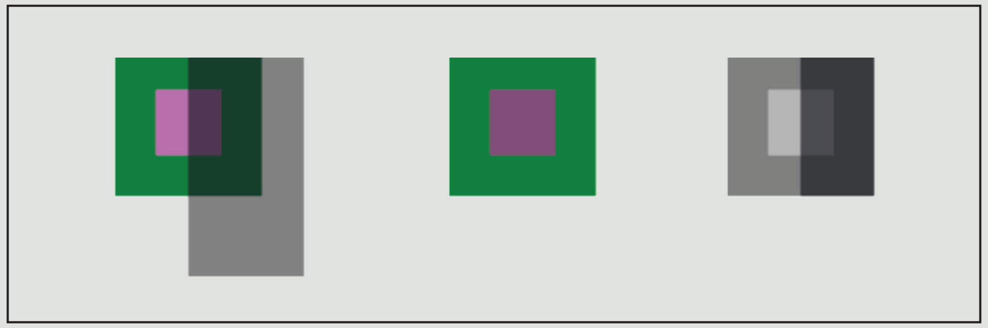


Fig 52 Object, Shadow > Chromaticity vs grayscale.

3.4 EXPLORATIVE PROTOTYPING

KNOWLEDGE GAP

"How can kinetic interaction be linked to dynamic fiducial information?"

APPROACH

To understand how the described mechanical and optical properties can be used to interlink kinetic interaction and digital information, low-fidelity prototyping was employed to explore material behavior, interactions, and uncover potential opportunities. An exploratory and iterative approach was taken to gain insights into material-specific interactions. The prototypes were evaluated for their relevance to either physical interaction or fiducial encoding. Based on the insights gathered, potential pathways for integrating physical and digital properties through material and structure were identified.

ITERATION 1: COLORS AND COMPUTATION

Research question:

"How can colors be used for encoding and computation of information?"

Results and insights:

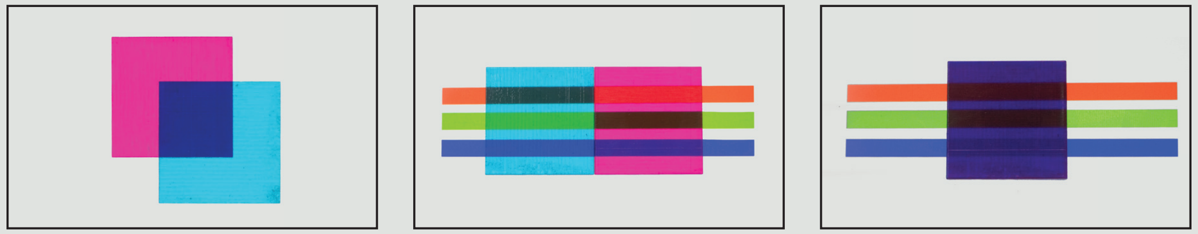


Fig 53 CYM color space can be used to filter information allowing for analog computations.

Through experimenting with various material thicknesses and surface finishes, it was found that the Vero materials effectively operate as a color filter (Figure 53). Each pixel on a camera sensor captures an R, G, and B value. By evaluating each color channel individually, information can be encoded for each channel independently. Provided the printer is capable of full color printing, this enables a myriad of avenues to encode and compute information.

For example, a noteworthy feature is the ability to write to two different channels at the same time. Cyan can be represented in RGB by G and B. By encoding information in cyan, information can only be captured within the green and blue channels.

Alternatively, it can be used to encode multiple layers on top of another. In Figure 55, on the left, a QR code was created by stacking a red, green, and blue QR code on top of each other, each containing their own information payload. Within this configuration, it is possible to encode 3 times more bits within a given surface compared to conventional black and white encoding.

Moreover, the content of the information can be physically manipulated through filtering colors and evaluating the relative luminance of the RGB channels. Taking inspiration from DynaTags, reveal and conceal mechanisms were found to be an effective means to compute information. Color filtering can be used to implement analog computations such as "If..else" and "and" functions. In Figure 55, on the right, it can be seen that magenta allows R + B to pass, while Cyan + Magenta allows only B to pass. This reveals an opportunity for color to not only encode information, but to use colors to interpret and process information based on environmental conditions.

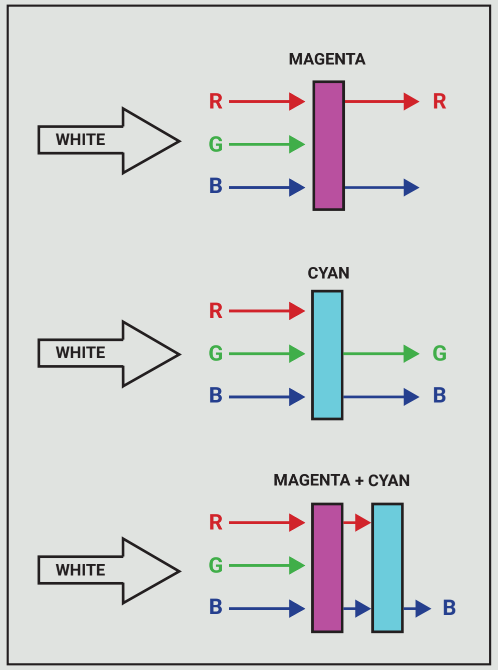


Fig 54 CMYK Color Filtering ("Unit 8: Color Image Processing," n.d.).

Fig 55 Color filtering for computation and information processing.

Summarizing the obtained insights:

> *"Colors can be used to encode data to the RGB color channels of a pixel separately, which allows for the embedding and processing of information that considers the relationship between colors within its output."*

ITERATION 2: COLORS AND DYNAMIC FIDUCIAL INFORMATION

Research question:

> *"How can color encoding and processing be used to facilitate dynamic fiducial information?"*

Results and insights:

Colors can be used to encode dynamic information that presents predetermined designed interactions. For example, colors can be used to filter information as seen in Figure 56, where similar to DynaTags (Scheirer & Harrison, 2022) the content of information can be physically changed.

Fig 56 Color filtering as a reveal-conceal mechanism, allowing for color dependent information payload.

Moreover, colors can also be used to enrich information. In the example shown in Figure 57, the MoiréWidget (Zamora et al., 2024). was reproduced in color. The introduction of color allows the Moiré to represent different information depending on the interacting colors. The blue and red interference could be used for different applications. Compared to black and white, utilizing 3 colors would increase the possible unique outputs of one pattern by 3! = 6, showcasing a vast increase in "dynamic range".

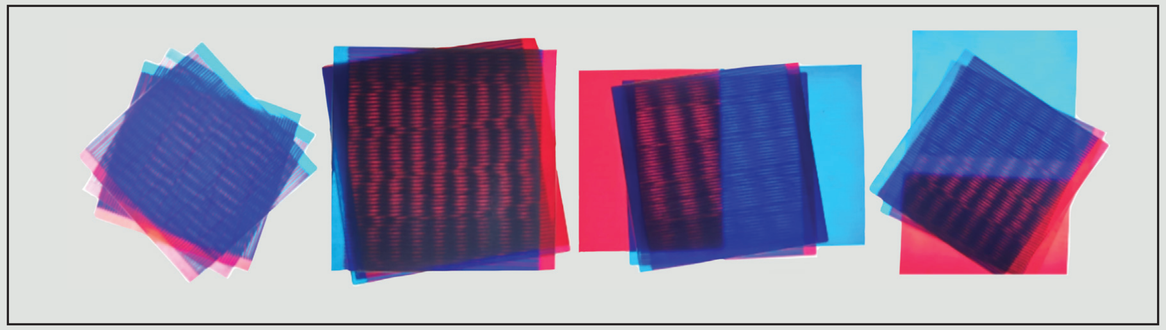


Fig 57 Color sensitive Moiré patterns.

Finally, color information can be used to encode more dynamically. As depicted in Figure 58, the QR code was manipulated through moving gradient plates. By measuring a particular property like hue or saturation, it could be used to manipulate the content of the QR code. For instance, if the QR code represents a particular sound, the slider could manipulate the sound volume. Unlike grayscale imaging where the RGB values are flattened to measure intensity, the independent channels can be used to contextualize the image for image analysis and assign different interpretations based on the separate RGB values.

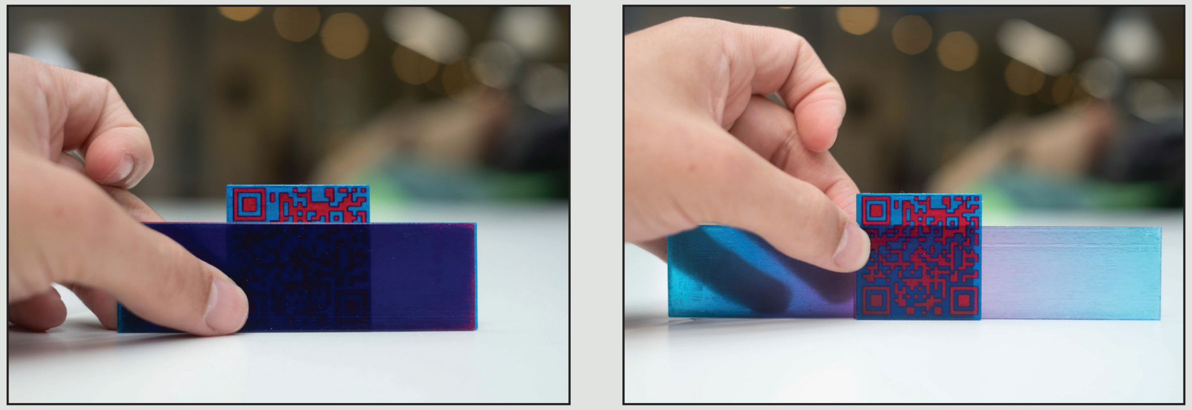


Fig 58 Potentiometer based on luminance contrast between red and blue channels.

To conclude, information can be interpreted in different ways by considering the independent color channels individually, as well as jointly. Through this mechanism, it is possible to create printed materials that can be enriched or manipulated by color interactions.

“A change in color may constitute a change in fiducial information through manipulation of encoded color information.”

ITERATION 3: PHYSICAL INTERACTIONS AND COLOR

Research question:

“Can color encoded information be manipulated by physical interactions?”

Results and insights:

To establish a relationship between physical interaction and color, approaches were explored to change the color representation of an object within an image.This section will briefly go over the most relevant insights that contribute to the final design.

Movement: opposition and orientation
By reproducing the lenticular design of Zeng et al. (2021a), it is possible to represent spatial movement and orientation by color relative to the observer (Figure 59). The lenticular design allows for different colors to be projected depending on the relative position and orientation to the observer. By allocating a unique color to each viewpoint, the color becomes representative of the position and orientation. Compared to conventional pose estimation a couple of unique features were however identified.

With the lenticular design it is possible to calibrate the sensitivity to orientation by adjusting the design of the lenticular lens or the image plane. Similar to MoiréWidgets (Zamora et al., 2024), the fiducial response can be calibrated to be very sensitive relative position and orientation. This allows designers to optimize the accuracy and resolution of pose estimation for the desired application.

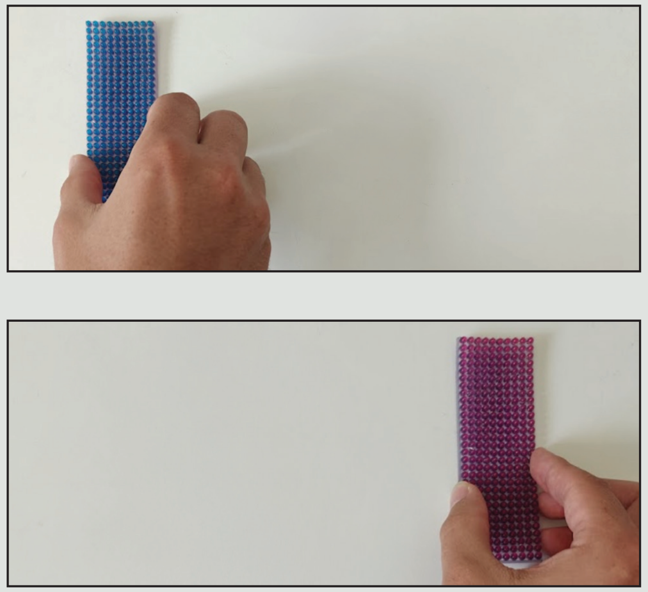


Fig 59 Lenticular surfaces: position and orientation represented by color.

Motion: Deformation
Next, various approaches were explored to capture motion and deformation through color. A notable concept “Voxel Grid” involved the combination of a flexible matrix material with a voxel grid on top Figure 60). The mechanism involved an array of voxels that each had a different color on each side. Once the material plate was deformed, the colors on the side are revealed, allowing for color coded tracking lines that aid in the reconstruction of shape.

A noteworthy feature that was observed involved the ability to interconnect the mechanical behavior of the matrix with the color response. By manipulating the stiffness, the color response could be more or less severe for a given force. Although conceptually promising, the physical prototype revealed major flaws. Because the colors of the side were on the side of the voxels, surfaces were poorly and inconsistently illuminated. Moreover, because of the tight spacing and square design of the voxels, the plate could only be bent around the side of the flexible matrix, limiting the degree of freedom for motion.

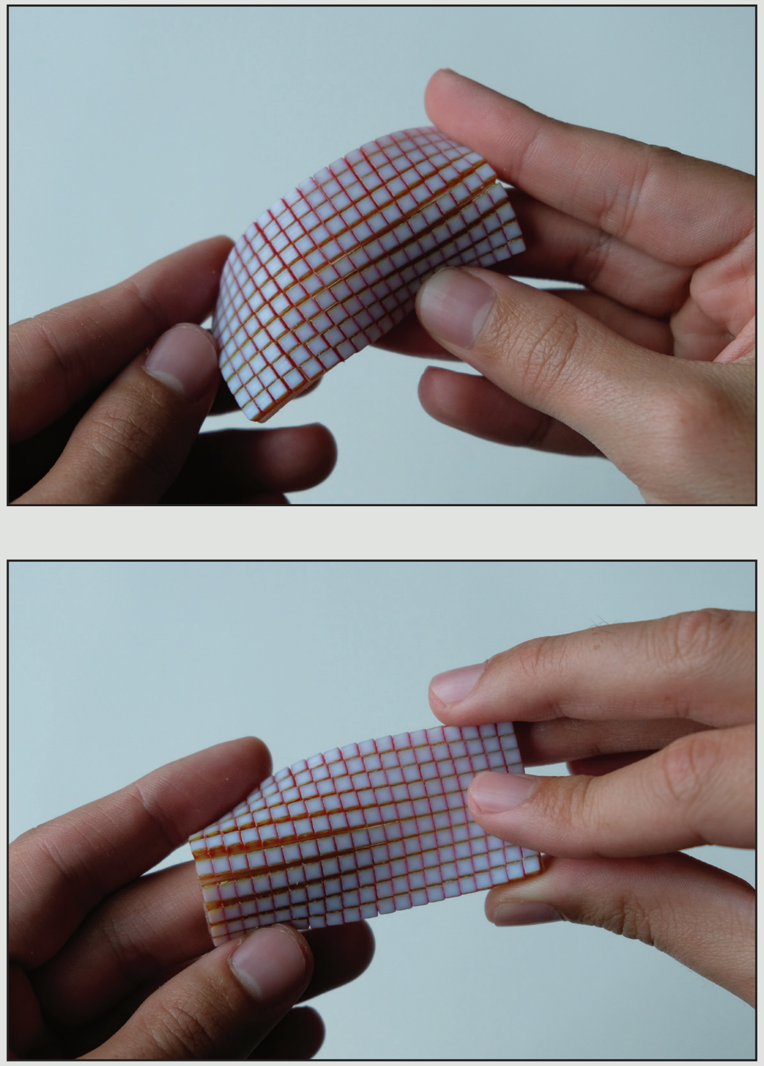


Fig 60 Exploring alternative ways to generate color based information through deformation.

Movement and motion
Combining insights of previous iterations, a concept was envisioned that involved the benefits of both lenticular surfacing and the voxel grid design. Combining the flexible matrix material, grid structure and lenticular design, a flexible lenticular surface was designed that was capable of capturing both movement and motion. This showcased the potential for MMJ to seamlessly connect fiducial mechanisms to create a novel approach to interaction.

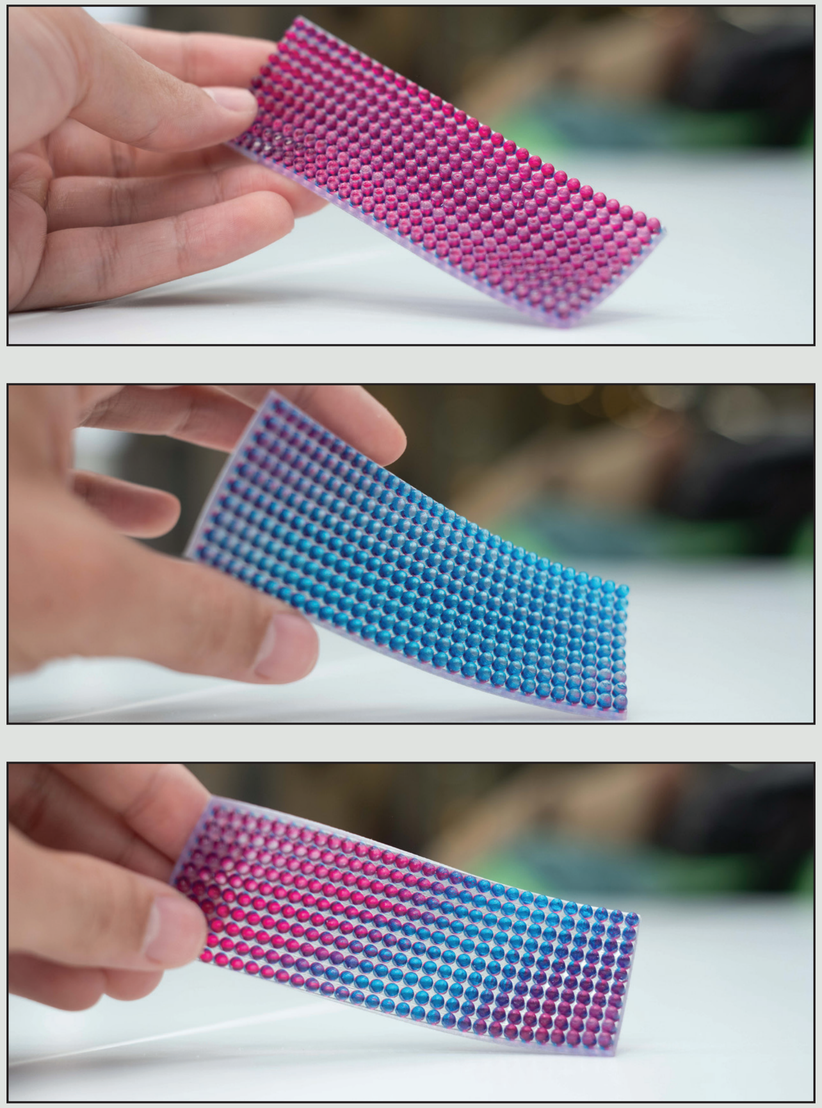


Fig 61 Movement, orientation, and deformation.

CONCLUSION

To summarize and conclude the insights from exploratory prototyping, the following prepositions were established. These prepositions outline a framework for connecting physical interactions with digital information through the use of color.

1 *Colors can be used to encode data to the RGB color channels of a pixel separately, which allows for the embedding and processing of information that considers the relationship between colors within its output.*

2 *A change in observed color may therefore constitute a change in fiducial information.*

3 *Physical Interactions and transformations can be represented by a dynamic change in color.*

4 *Physical Interactions can therefore be coupled to a change in fiducial information.*

3.5 COLORFUL BITS A STIMULUS-RESPONSIVE MATERIAL FOR KINETIC INTERACTION

Colorful Bits present a configurable Stimulus-Responsive Material which captures kinetic interactions as a dynamic fiducial-color response. By interlinking mechanical and optical properties through material and structure, a mechanical metamaterial is designed which transforms movement, orientation, and deformation of objects to color-encoded information.

Through the physics principle of superposition, the constituent forces that cause the movements and deformation can be obtained, allowing for force, stress and pressure sensitive interactions. By applying this process, designers will be able to design kinetic materials for Extended Reality (XR) that provide virtual feedback in response to applied kinetic deformation. (See Figure 62).

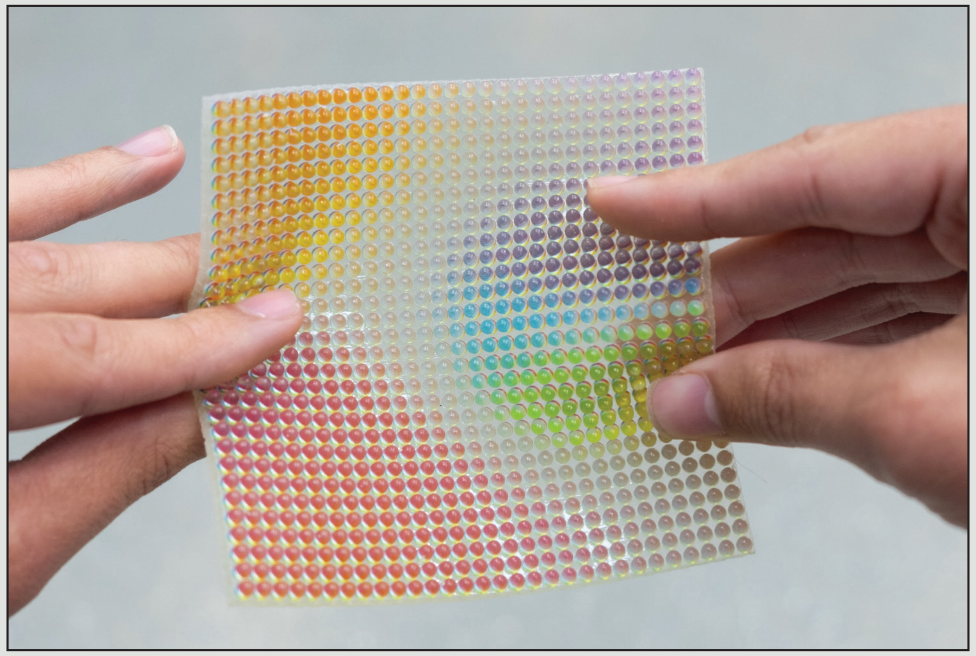


Fig 62 Kinetic deformation.

3.5.1 DESIGN OVERVIEW

Viewpoint
The viewpoint is the position from which the colorful bit is observed.
Lenticular Surface
The lenticular surface consists of an optical lens that projects light from the image plane to the viewpoint
Projected Image
The projected image describes the part of the image plane that is viewed by the user through the lenticular surface.
Image Plane
The image plane contains all possible projected images respective to the viewpoint.
Mechanical Matrix
The mechanical matrix that connects each colorful bit consists of a functional material with configurable mechanical properties. (Figure 63).

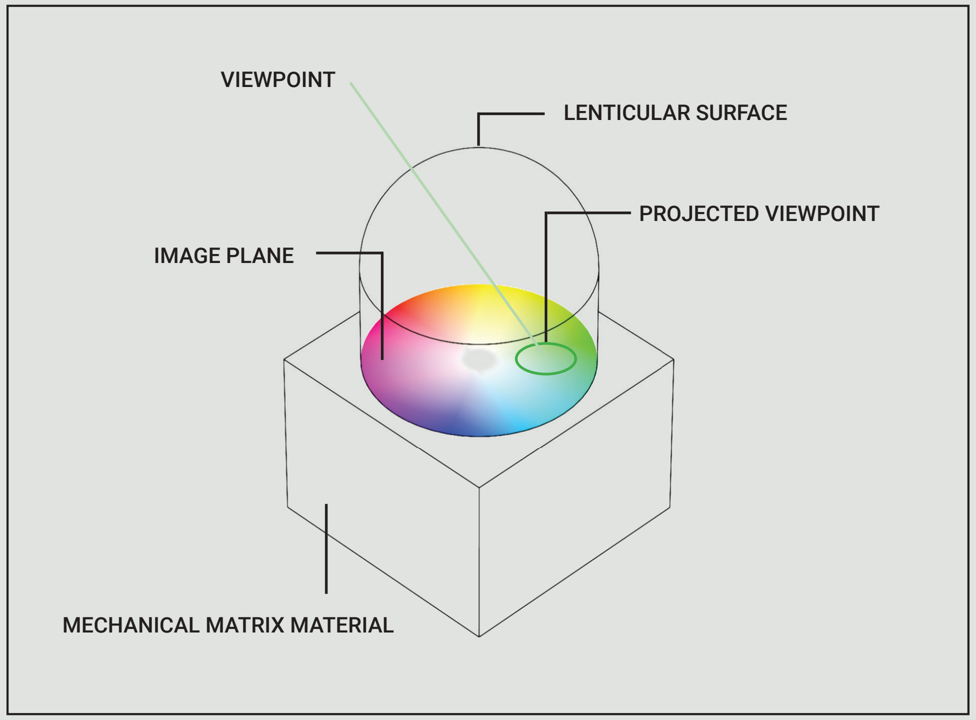


Fig 63 Design overview of Colorful Bits.

3.5.2 FIDUCIAL MECHANISM

COLOR BASED POSE ESTIMATION

For the optical design of the lenticular surface, the proposed optical design by Zeng et al (2021) was adopted (Figure 64). The lenticular design projects an image circle on the image plane respective to the polar orientation of the observing viewpoint. Instead of allocating pre-determined visuals on the image plane for each different viewpoint, Colorful Bits utilize the image plane for a dynamic color response by projecting the HSI colorspace (Figure 64).

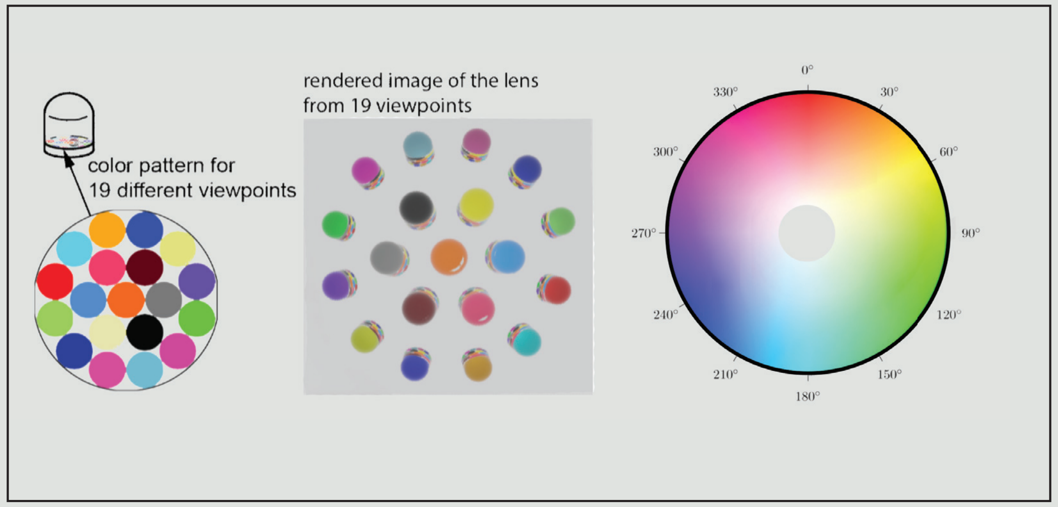


Fig 64 Left: optical design (Zeng et al., 2021), right: HSI color space, (Cycling Through Colors With the Same Brightness, 2016).

Considering hue, saturation, and intensity (HSI) color space provides a circular model for color. Each polar orientation relative to the observer can be mapped to a distinctive hue and saturation. By capturing the color of a bit with a camera, the pose can therefore be estimated by converting the hue and saturation into the respective phi and Theta vectors within a polar coordinate system (Figure 65).

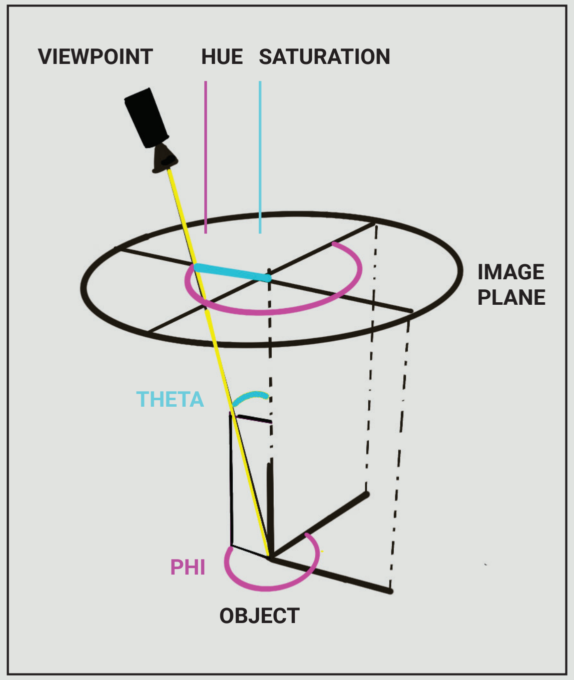


Fig 65 Polar Phi, Theta Mapped to hue and saturation.

Considering the spherical coordinate system for polar orientation, hue can be used to estimate the Phi angle (Figure 66). As hue and Phi are both represented by a range of 360 degrees, hue and Phi values can be linearly mapped to one another.

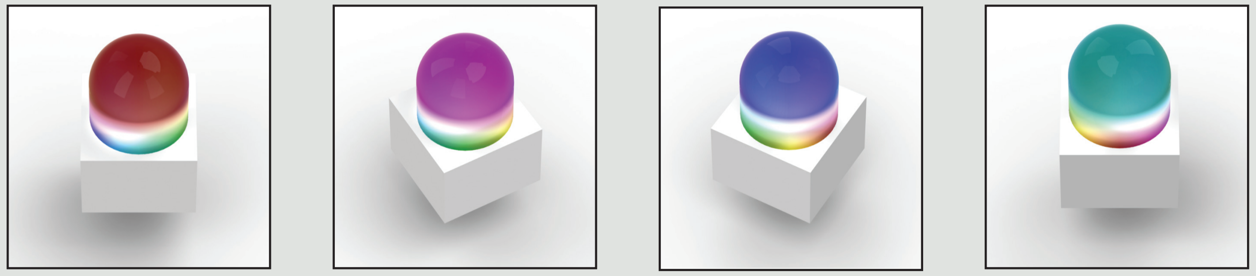


Fig 66 Linear relationship between viewing angle Phi and hue.

Moreover, saturation scales linearly with the viewing angle Theta, saturation can be interpreted to determine the Theta angle (Figure 67). However, unlike Phi mapping between viewing angle Theta and saturation depends on the optical design of the lens. The saturation of a color depends on the purity of color. Considering a projected image circle on the HSI colorspace, the maximum saturation is therefore dependent on the diameter of the projected image circle. The relationship between saturation and Theta can therefore be described as follows:

*Saturation = Theta * (Max Saturation / Max viewing angle)*

Theta = Saturation / (Max saturation / Max viewing angle)

It is important to note that at the maximum angle, the hue and saturation values approach the chromaticity plane, thus theoretically achieving optimal invariance to heterogeneous illumination and noise. Therefore, utilization of the HSI-based color pose estimation provides a unique feature, becoming increasingly resilient in proportion to the critical failure conditions of resolution and noise.

Fig 67 Linear relationship between viewing angle Theta and saturation.

TRACKING DEFORMATION AND DIGITAL RECONSTRUCTION

Tracking deformation:

Each bit color is represented by its own color, enabling pose estimation for each individual bit. In contrast to conventional marker systems, this allows for the tracking of deformation within a singular marker rather than between multiple static markers (Figure 69), significantly increasing the tracking resolution.

Reconstruction of shape:

By evaluating the pose and orientation of each bit relative to the observing viewpoint, the relative viewpoint distortion of each bit can be vectorized. As the pose and orientation of each are all mapped within the same polar point of reference of the observing viewpoint, these vectors can then be used to measure the angular rotation between each bit. By averaging the directional vectors of all bits, a normal plane can be constructed that optimizes for flatness by minimizing the Phi and Theta. Finally, each bit can be projected onto the normalized plane reconstructing the original shape from a distorted image.

In Figure 68, a simplified overview is provided:

1. Original object
2. Physical deformation of form
3. Projection of deformed shape the cameras image plane
4. Color image of deformed object: content is distorted, Color represents Phi and Theta
5. Color image of deformed shape for analysis
6. Color vectorization and reconstruction deformed surface
7. Reconstructed of original shape
8. Reconstructed object: Contains original information ABC + deformation data (color).

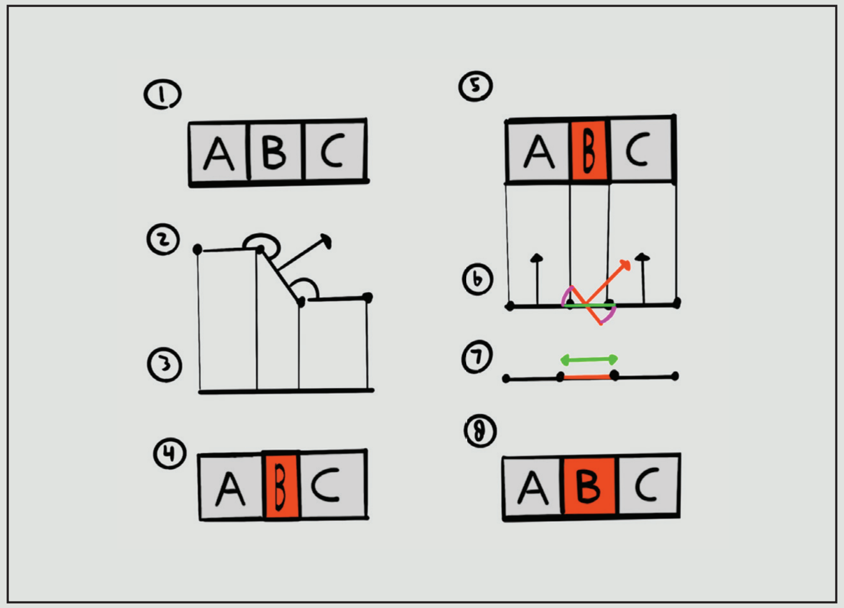
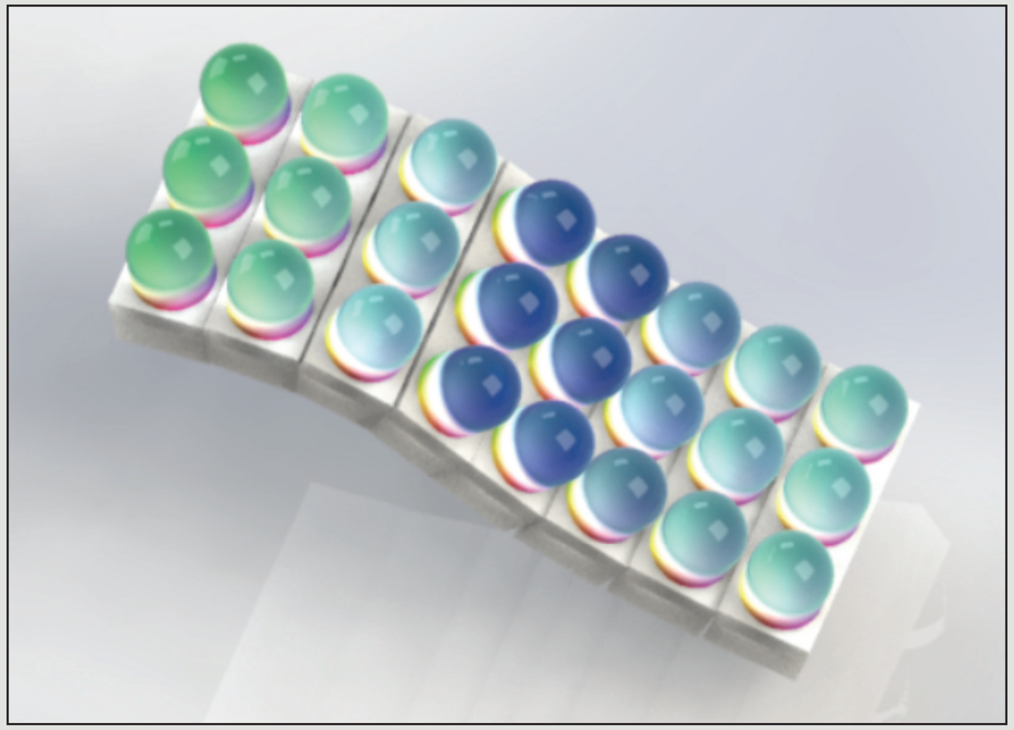


Fig 68 Simplified overview of color vectorization and the reconstruction of original shape



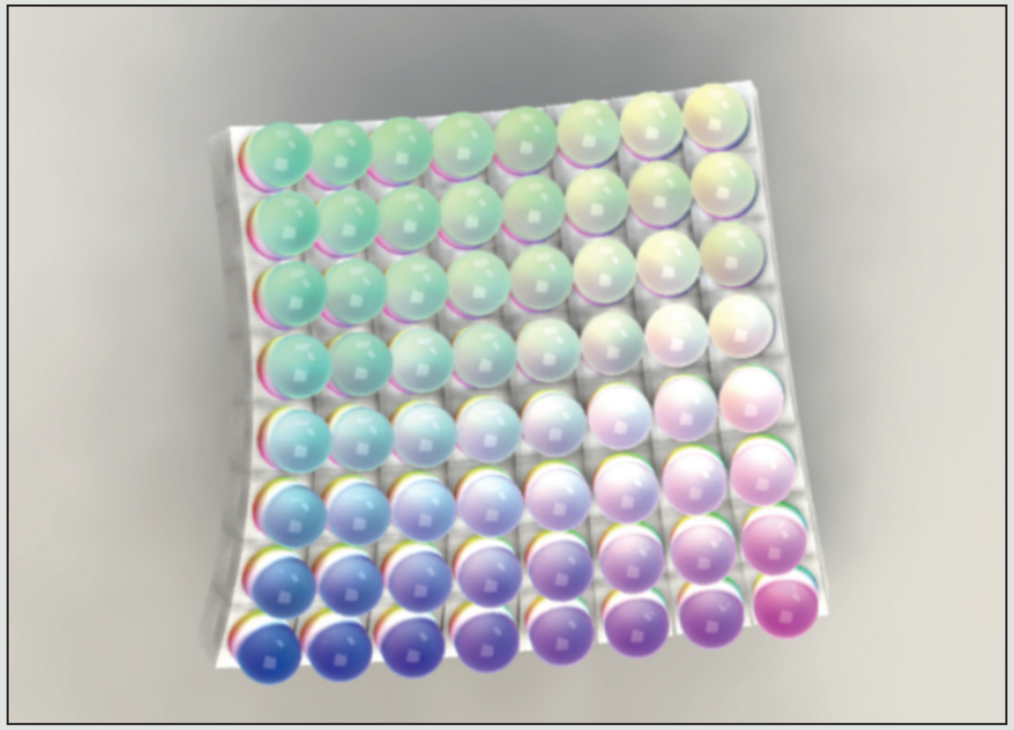


Fig 69 The color of each bit represents its polar orientation relative to the observing viewpoint.

PHYSICAL STIMULUS AND FIDUCIAL RESPONSE

To interlink the physical stimulus and fiducial response, the ability for MMJ to optimize both mechanical and optical properties is utilized. First, a connection between physical stimuli and deformation is established through precise allocation of mechanical properties at voxel states. Through this approach, the kinetic relationship between applied physical stimuli and deformation is mathematically modeled and defined within the process of materialization (Sossou et al., 2019) (see Figure 70).

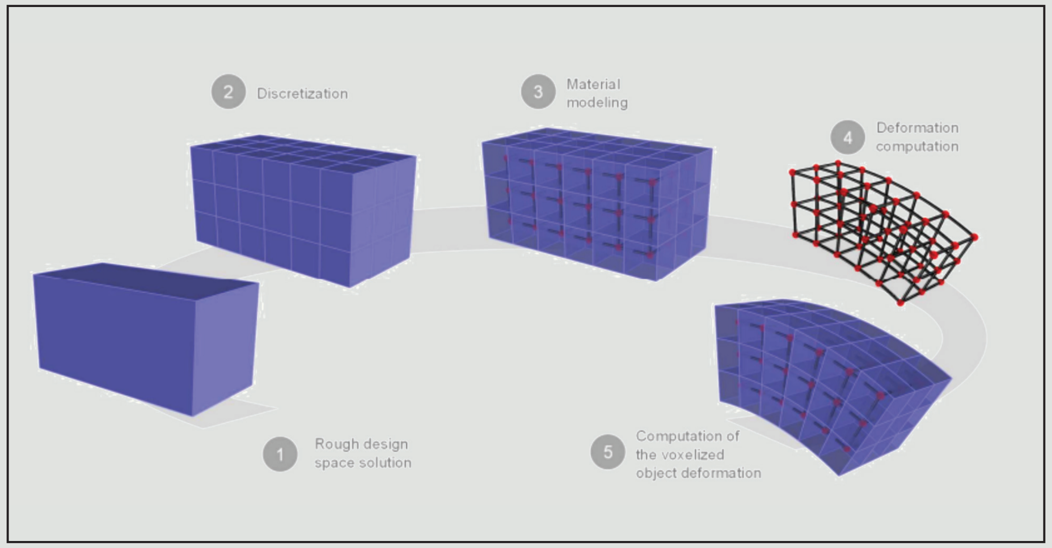


Fig 70 Continuum mechanics modeling setup (Sossou et al., 2019).

Provided the deformed shape can be obtained and reconstructed from the fiducial color response, the applied forces on a deformed shape can be obtained through the physics principle of superposition;

The superposition principle, or superposition property, states that in all linear systems, the combined response to multiple stimuli is the sum of the individual responses each stimulus would produce on its own (Illingworth, 1991). In other words, if input A generates response X, and input B generates response Y, then an input of (A + B) will produce a response of (X + Y). For example, a beam can be treated as a linear system, where the load on the beam serves as the input stimulus and the beam's deflection is the resulting output response. (Figure 71 and 72).

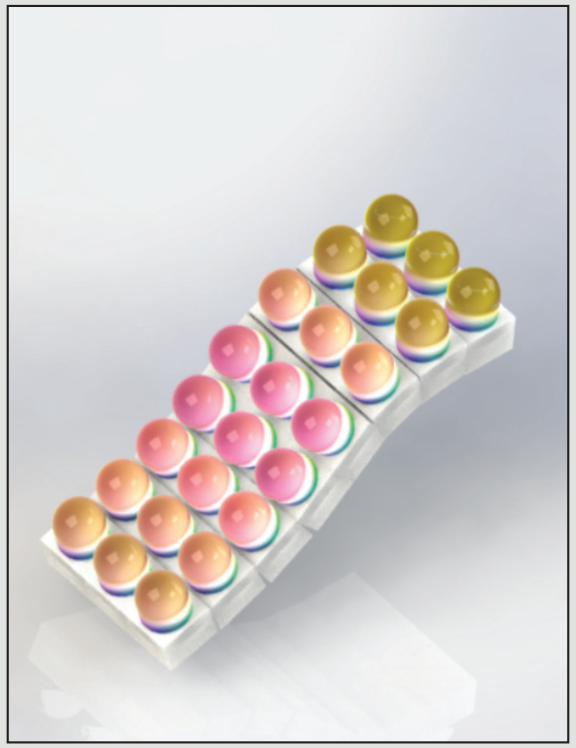
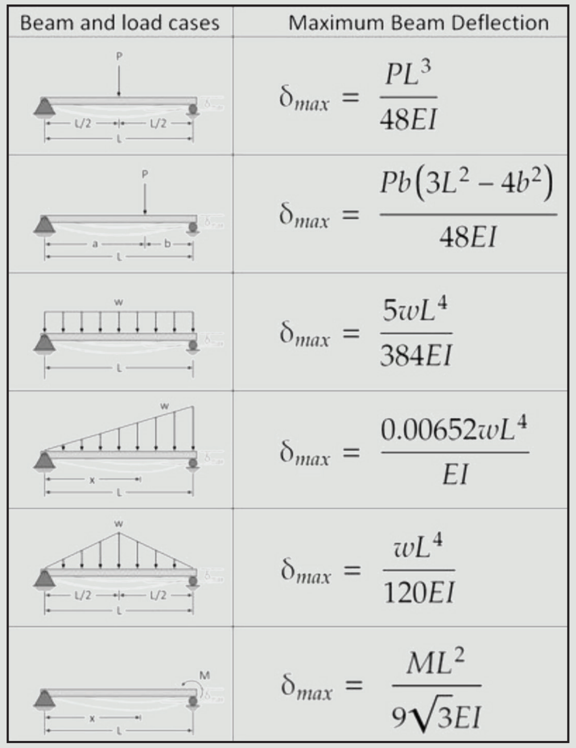


Fig 71 Deflection between each bit represented by difference in color.



Beam and load cases	Maximum Beam Deflection
	$\delta_{max} = \dfrac{PL^3}{48EI}$
	$\delta_{max} = \dfrac{Pb(3L^2 - 4b^2)}{48EI}$
	$\delta_{max} = \dfrac{5wL^4}{384EI}$
	$\delta_{max} = \dfrac{0.00652wL^4}{EI}$
	$\delta_{max} = \dfrac{wL^4}{120EI}$
	$\delta_{max} = \dfrac{ML^2}{9\sqrt{3}EI}$

Fig 72 Deflection (deformation) as a function of stiffness and stimuli (Alambra & Swanson, 2024).

For the envisioned mechanical matrix material where the resistance to deformation is known, capturing deformation therefore represents a reflection of applied physical stimuli. The more accurate a material's behavior can be allocated and captured through the fiducial color response, the more reflective its response becomes of its applied physical stimuli (Figure 73).

Kinetic energy = potential energy
*Force * distance = Distance * R*

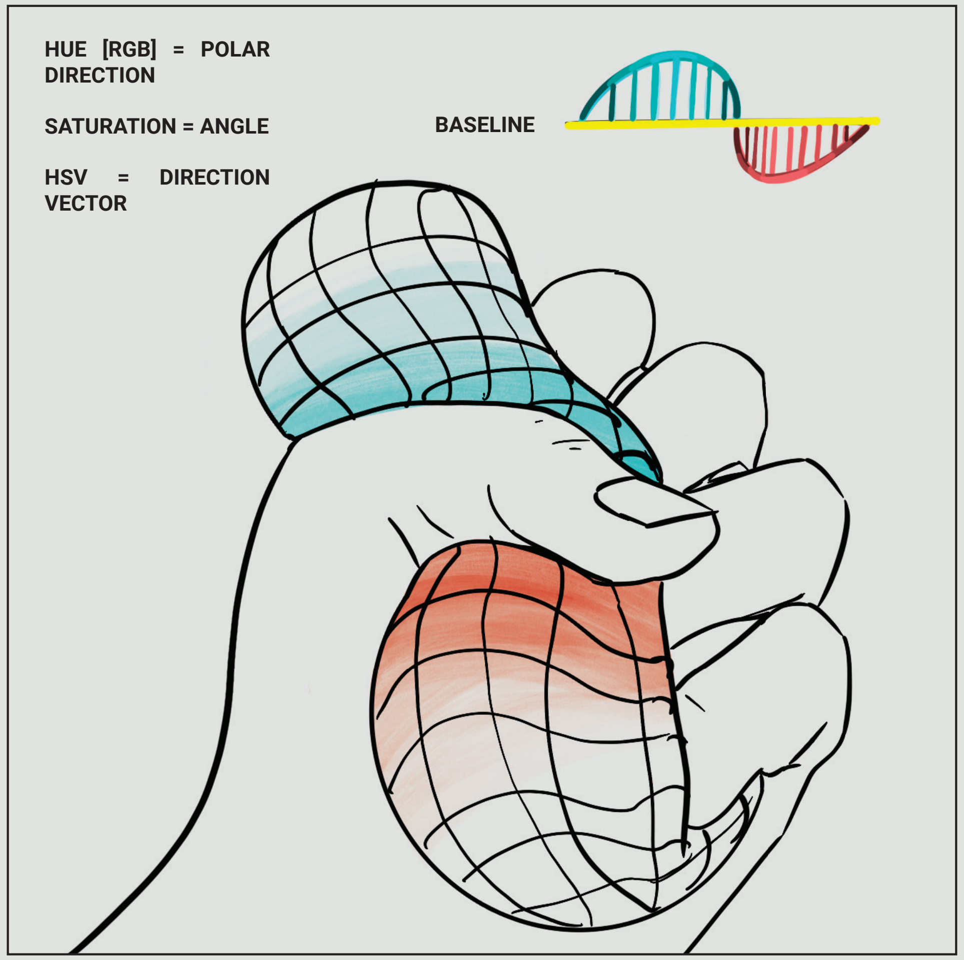


Fig 73 Stimulus-response mechanism.
1. If an object is deformed color is used to reconstruct the original shape.
2. The original shape contains the information that describes 3. the mechanical properties.
4. Through the principle of superposition, the deformation data and mechanical properties can be used to compute and reconstruct the applied physical stimuli.

3.5.3 ENVISIONED APPLICATIONS: MULTI-MODAL INTERACTION

MOVEMENT AND MOTION AS A PHYSICAL INPUT

Movement: Position & orientation:

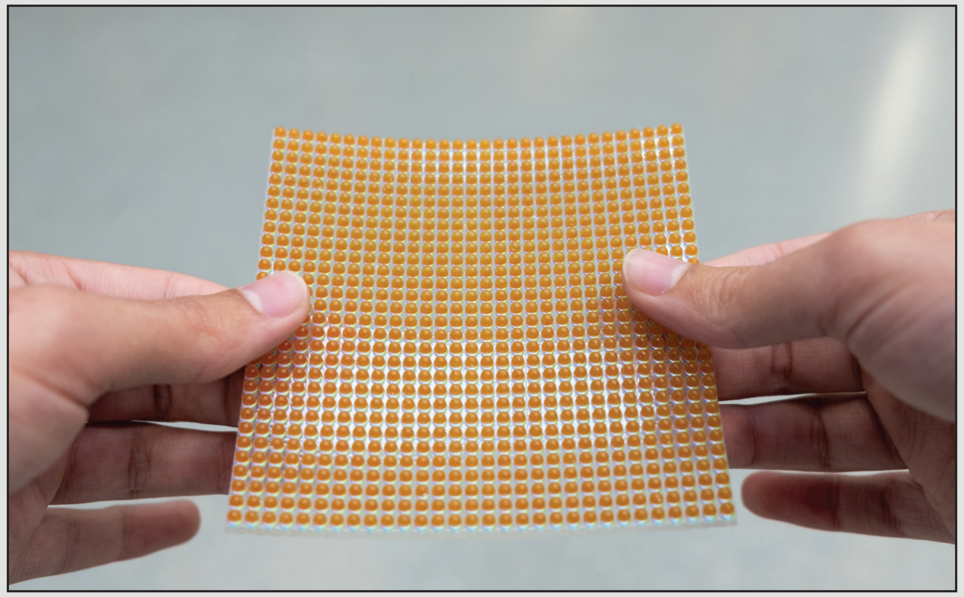
Colorful Bits have outlined an approach for lenticular surfacing to estimate the pose and orientation through measurements of hue and saturation.The information contained within Colorful Bits can be evaluated based on the color in which they are represented.

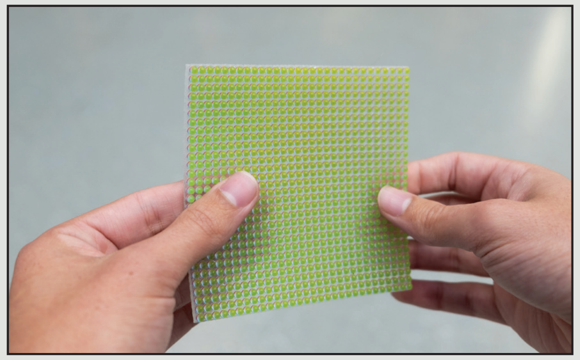
Consequently, the hue and saturation measurements provide dynamic responses that can reflect the polar viewing angles Phi and Theta be used for the interpretation of information in various ways. For instance, the hue of Colorful Bits can be used to encode different information depending on orientation of the observer (Figure 74).

Moreover, saturation and respective Theta can be used to provide an amplitude or magnitude to which it is turned away from the observer. This provides possibilities for saturation as a proportional input, where hue describes the direction and saturation describes the magnitude (Figure 75).

Although the described applications are both derivatives from pose estimation which can be achieved by conventional marker approaches, the utilization of color provides several differences. Unlike conventional marker approaches where accuracy decreases at larger polar angles as a result from reduced resolution, it is expected that Colorful Bits accuracy increases. At larger angles, the measured colors approach the chromaticity plane, at which hue and saturation become illumination and noise.

Considering spatial movement and the polar orientation approach to pose estimation, this feature may provide a unique advantage. Considering all possible orientations an object can have relative to the observer, the positions that face away from the observer far exceed those that are facing the observer. By optimizing pose estimation for larger viewing angles, Colorful Bits may provide better tracking capabilities for spatial movement (Figure 76).





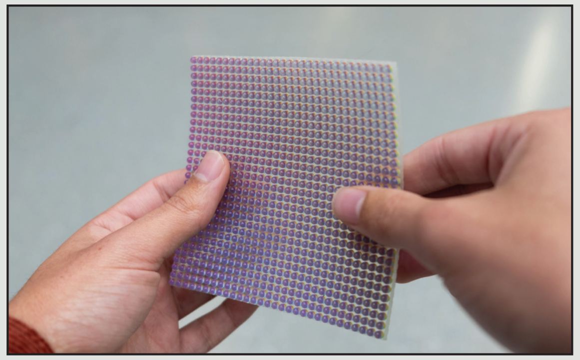


Fig 74 Hue sensitive information.

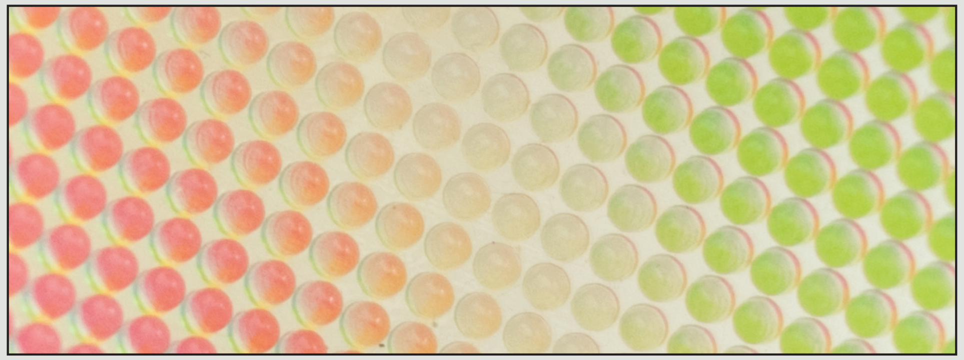
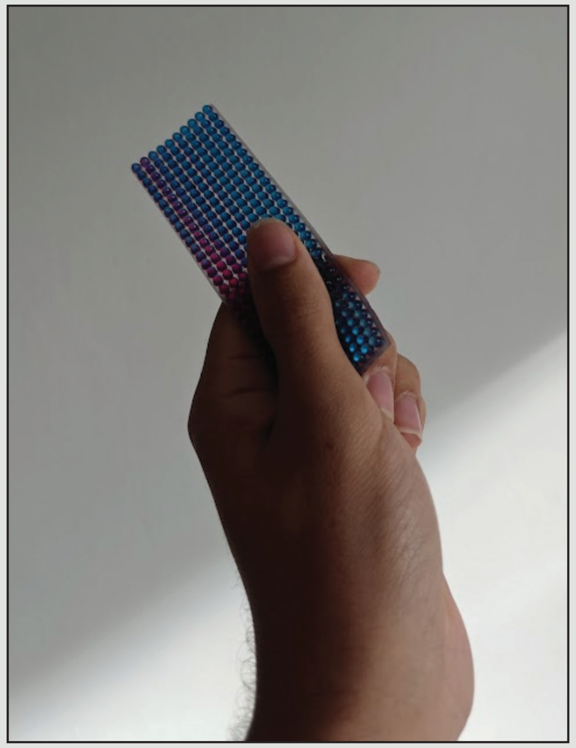


Fig 75 Saturation sensitive information.



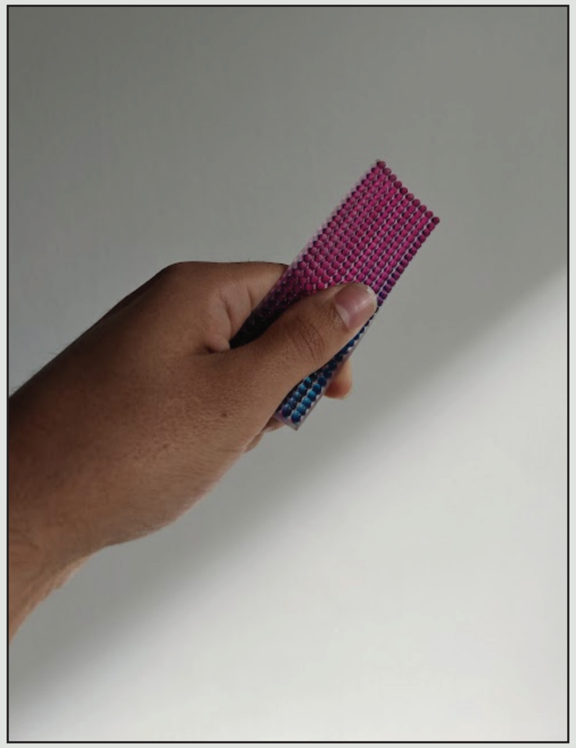


Fig 76 Movement tracking

Motion: Kinetic deformation:

In addition to movement, Colorful Bits implements another dimension to interaction: motion. The ability to capture pose and orientation not only between markers but within a marker itself allows unique tracking capabilities (Figure 77). Consequently, original information can be reconstructed from deformed objects, while maintaining the deformation information. This feature can be leveraged in various ways.

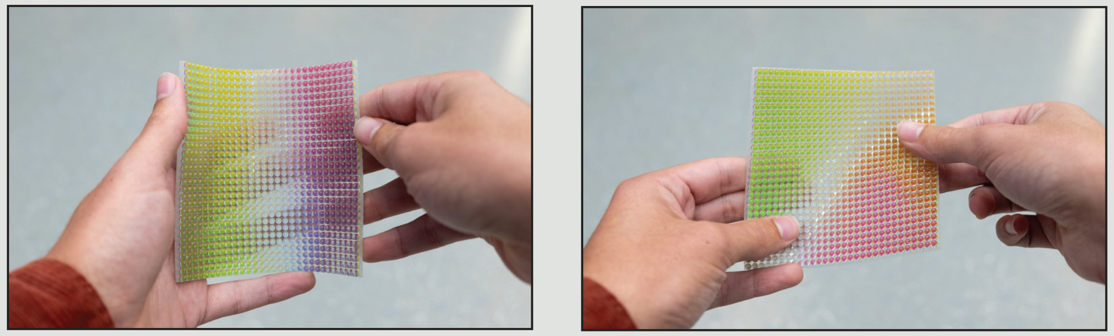


Fig 77 Motion tracking.

Pressure sensitive controls:

For instance, by evaluating the deformation of a fiducial marker inputs can be allocated to certain deformation characteristics. Evaluating the flatness of a marker, colorful bits can be used as an actuator that activates once a certain deformation threshold is reached (Figure 78)

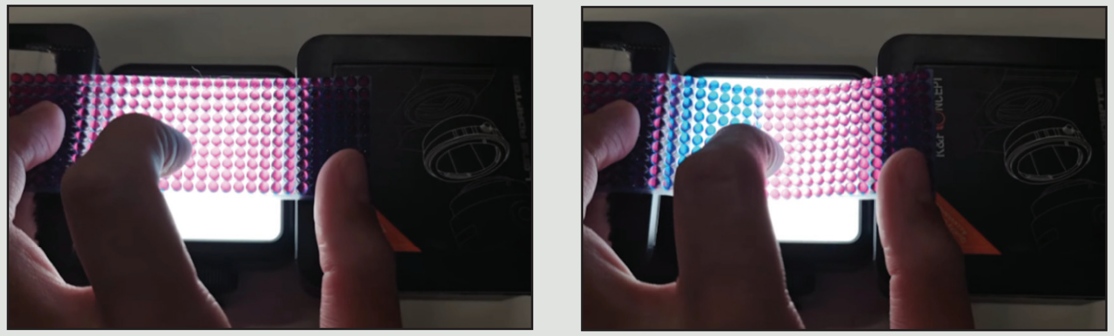


Fig 78 Actuation of a button through deformation.

Moreover, analog and linear responses can be established by mapping measurements of hue and saturation to inputs directly. For example, by utilizing part of the marker for reference, a potentiometer can be constructed that scales intensity to the average difference in hue relative to the reference point (Figure 79).

Fig 79 Kinetic Deformation as a pressure sensitive potentiometer.

Movement and motion:

Combining the aspects of movement and motion, Colorful Bits presents a rich interactive medium for multi-modal interactions. By combining spatial movement with kinetic motion, Tangible Interfaces can be created that consider both direction and actuation (Figure 80).

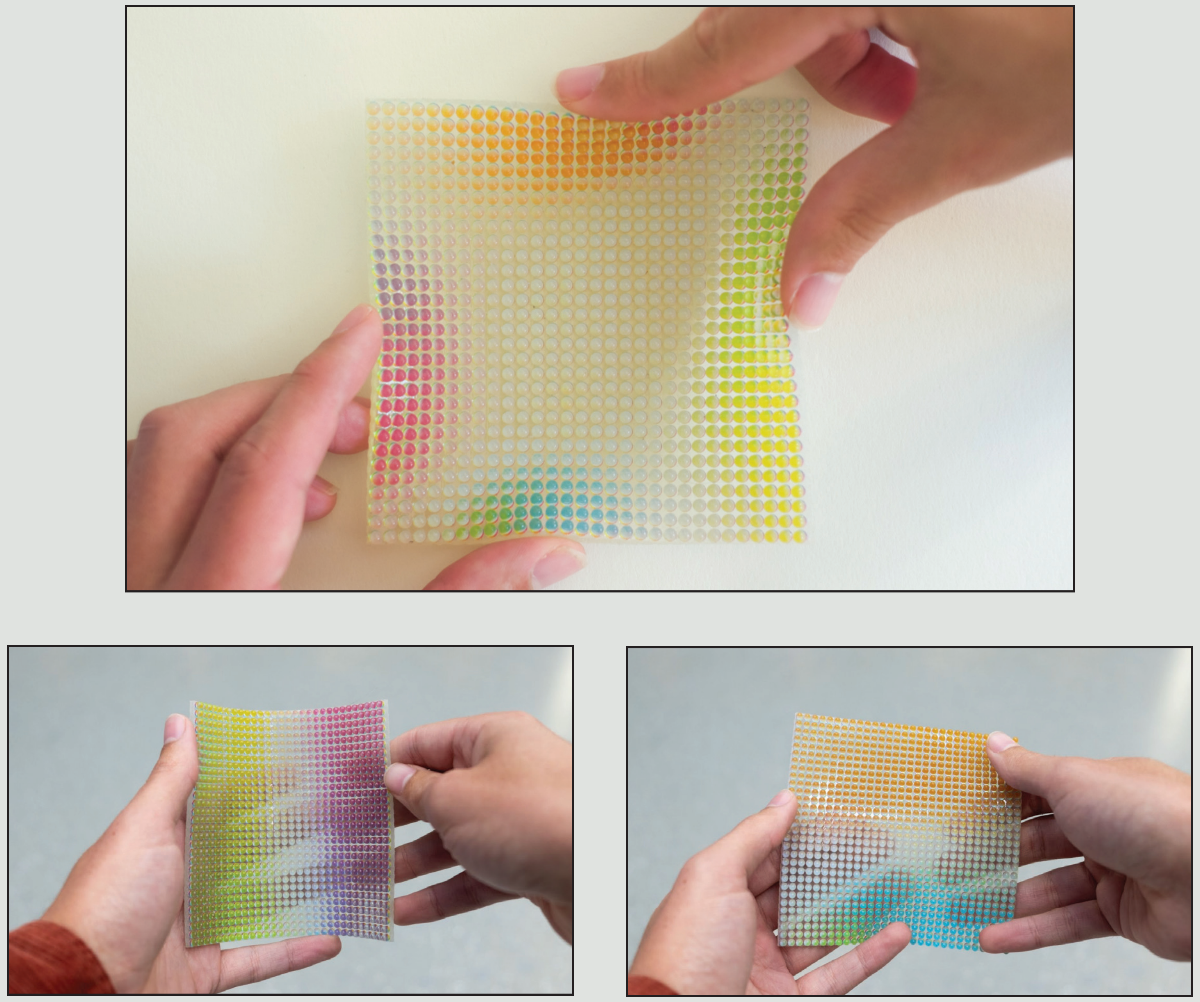


Fig 80 Interaction that is sensitive to both orientation and deformation.

The ability to embed information and allow for users to manipulate and interact with the content provides interaction designers with a ubiquitous medium for tangible interaction. Similar to work of MoireWidgets (Zamora et al., 2024) and DynaTags (Scheirer & Harrison, 2022), where dynamic fiducials are used control the environment involving physical, graphical and auditory experiences, it is envisioned applications can be modularly allocated to Colorful Bits (Figure 81). Moreover, as Colorful Bits represent a material that can be allocated to any surface, it is envisioned that kinetic interfaces for XR can be interwoven in any object without electronics, allowing for ubiquitous employment (Figure 82).

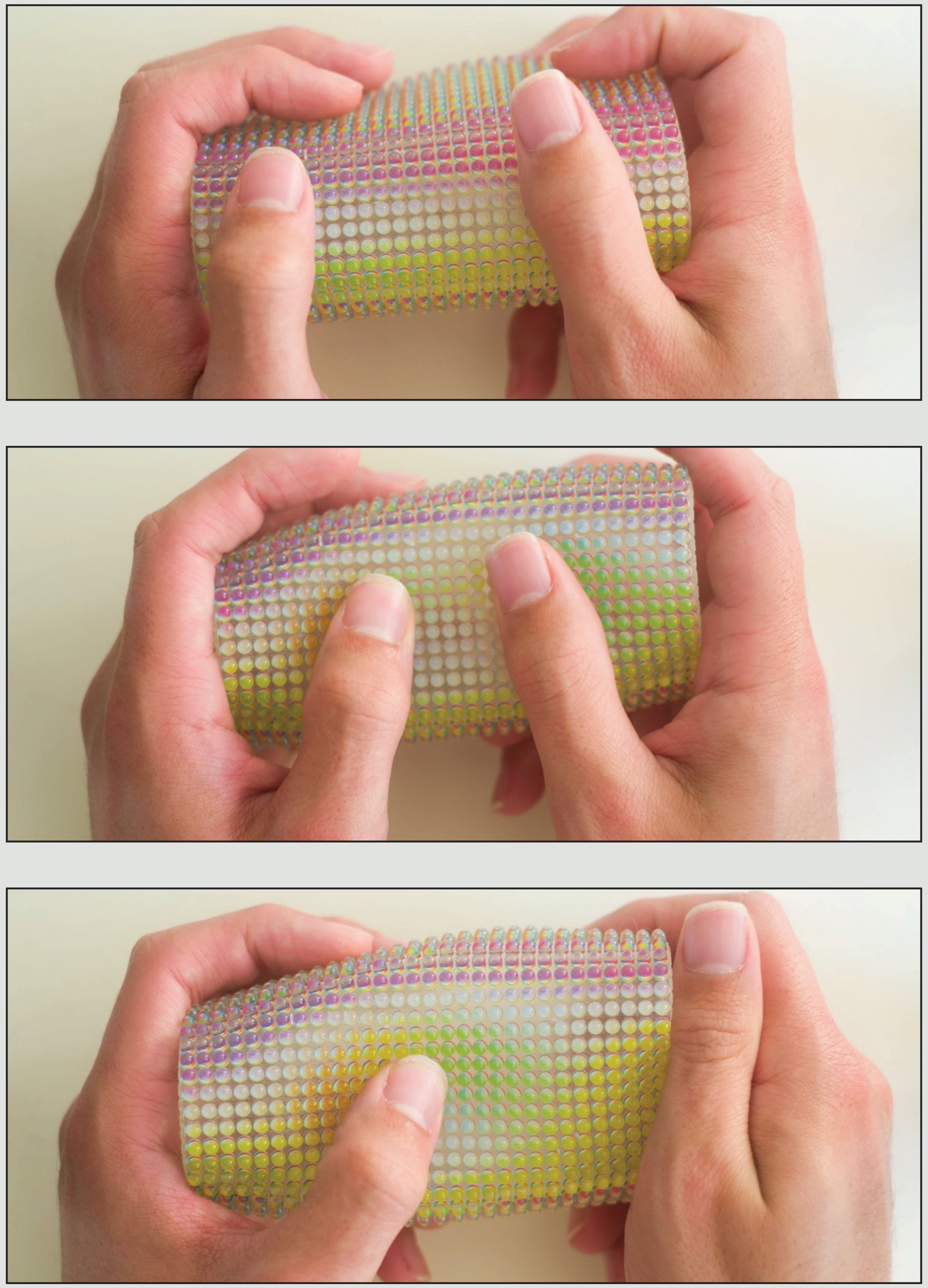


Fig 81 Colorful Bits as a ubiquitous controller.

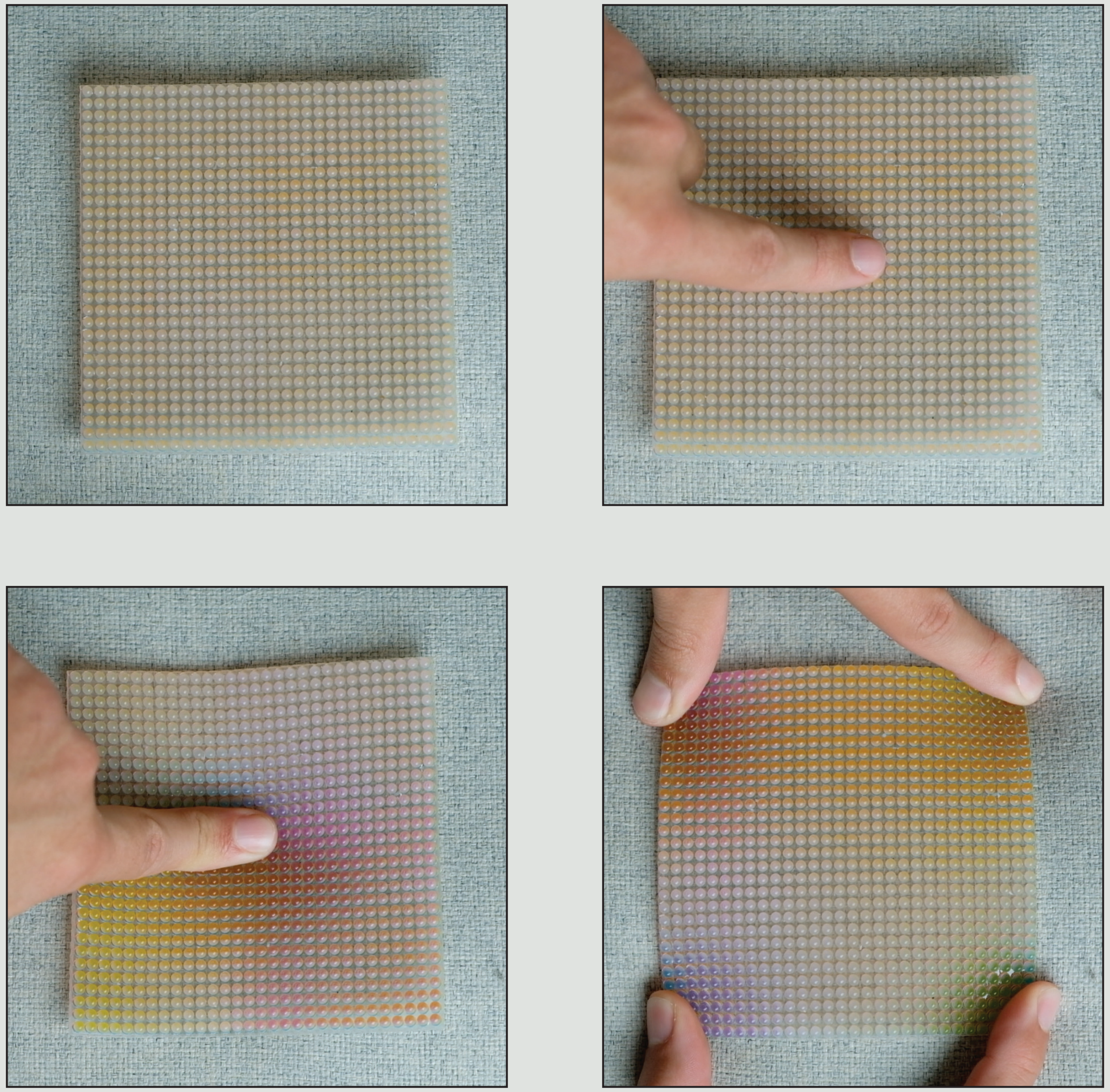


Fig 82 Kinetic interfaces for Extended Reality embedded in ubiquitous physical environments.

PHYSICAL AND DIGITAL FEEDBACK

Physical feedback: Stimulus-Responsive behavior:

As described in chapter 2.3.1, the mechanical properties of materials can be manipulated through microstructural arrangements of materials. This allows for the mechanical matrix material that can be configured for the desired physical behavior. Through manipulation of the mechanical properties and stimulus-responsive behavior, the interactive character and experience of Colorful Bits can be modified (Figure 83).

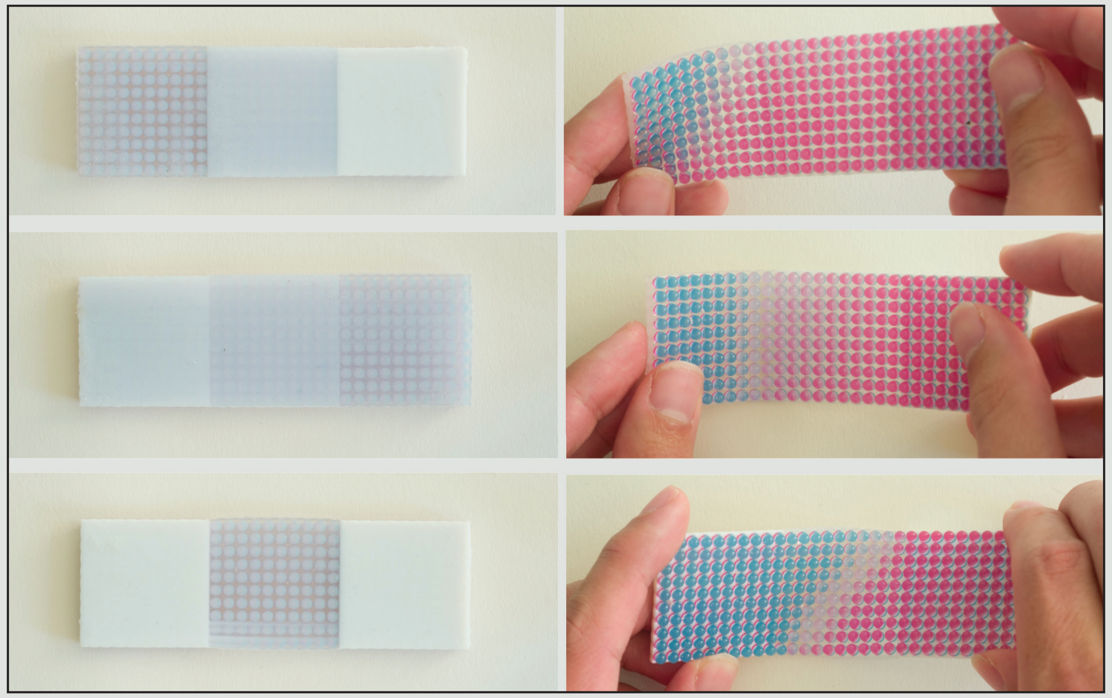


Fig 83 Mechanical properties can be allocated to configure the Stimulus-Responsive behavior and interactive experience.

Digital Feedback: adaptive virtual feedback:

Moreover, bits outline the potential for dynamic and interactive virtual feedback. For instance, the physical manipulations that are tracked and captured through deformation can be mapped to scala of virtual feedback including sounds and graphics. One particularly relevant feature of high fidelity tracking of deformation is that it is required for the alignment and registration of virtual graphics (Salhi et al., 2019) (Figure 84). This potentially allows for graphical feedback to be directly mapped on deformed surfaces, further interconnecting physical interactions with virtual experiences (Figure 85).

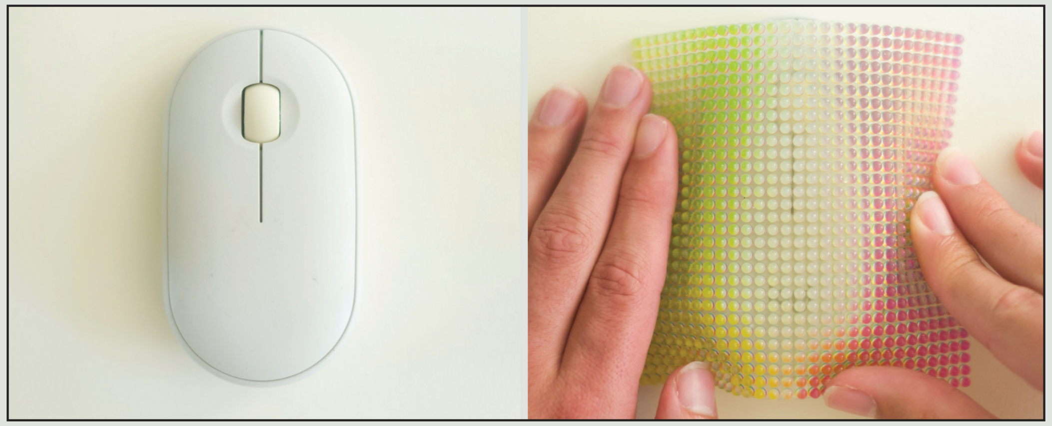


Fig 84 Surface tracking for alignment and registration of virtual feedback.

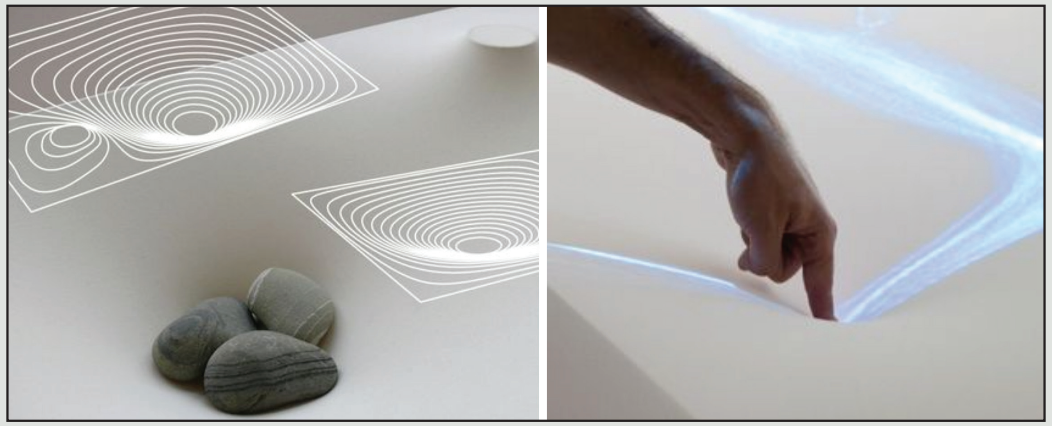


Fig 85 Responsive virtual and graphical feedback intertwined with kinetic interactions (Martinazua, n.d.).

3.6 EVALUATION

In this section, the feasibility and viability of Colorful Bits are explored through a series of prototypes. First, Digital renderings and simulations were used to test the theoretical working principles of Colorful Bits. Next, Physical prototypes were fabricated to test and validate the degree to which theoretical concepts could be translated into physical practice. Finally, the collected data was used to identify limitations of multi material jetting and the envisioned solutionspace of stimulus responsive materials to provide a connection between physical interaction and digital information. The identified limitations are examined and future improvements are proposed.

3.6.1 DIGITAL PROTOTYPING

COLOR BASED POSE ESTIMATION

Research question:

“Can lenticular surfacing create HSI Vectors suitable for pose estimation?”

Prototype: A Digital model and renderings of Colorful Bits.

Method: Render positions and measure fiducial color response by averaging the color of a bit. Next, the measured colors are represented within the HSI color space. To evaluate the fiducial performance for pose estimation, the measured colors are compared to the predicted color to evaluate the accuracy.

Results: From digital renderings (see figure 86), it is found that measured hue and corresponding Phi response of colorful bits behave as expected, smoothly transitioning between specific viewpoints and projected colors. It was observed that the accuracy of hue remains accurate within 1 degree form a viewpoint angle Theta) from 40 to 20 degrees. At smaller angles, the margin of error increases to 18 degrees. This is likely caused at the lower saturation colorfulness the effects of optical artifacts become proportionally larger. The results demonstrate a strong connection between displayed hue and viewing angle, thus making it suitable for pose estimation.

Regarding saturation and Theta, the results show a significant deviation from the predicted values. Observing the renderings and associated measured values, it is hypothesized the shift in saturation is caused by optical reflections and artifacts. Despite the desaturated measurements, the predicted linear relationship between viewing angle Theta and saturation appears present. Though absolute viewing angle operates at an approximate 25% deviation from the predicted values, the deviation appears largely consistent across all measurements.

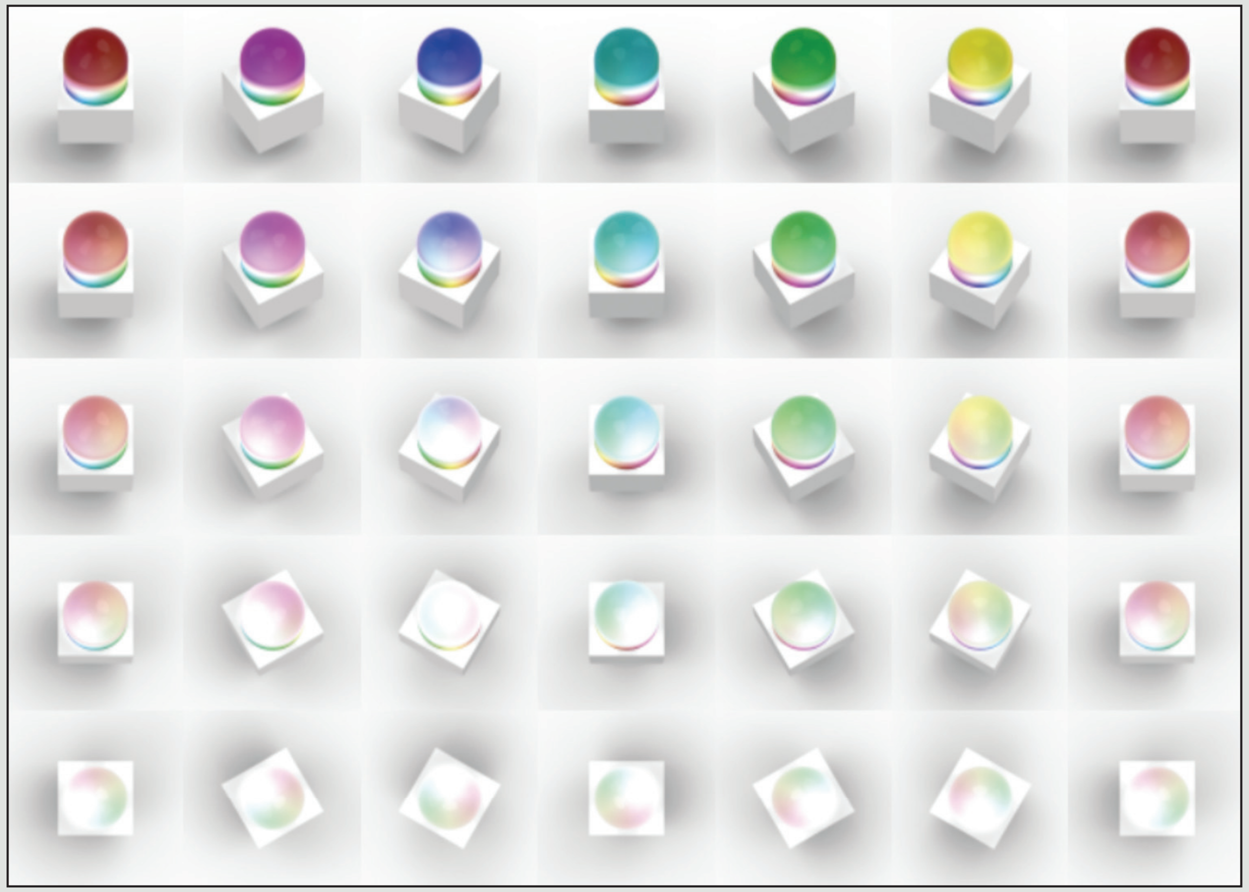
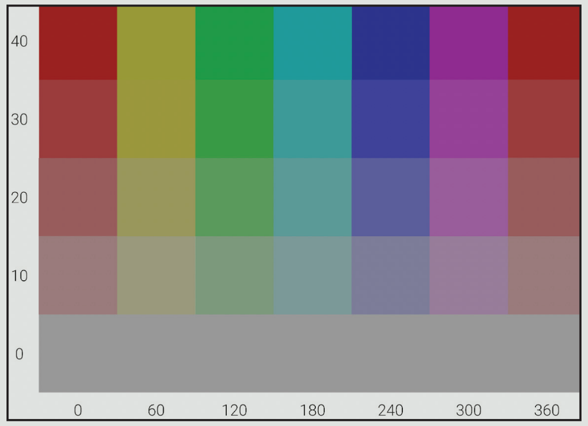
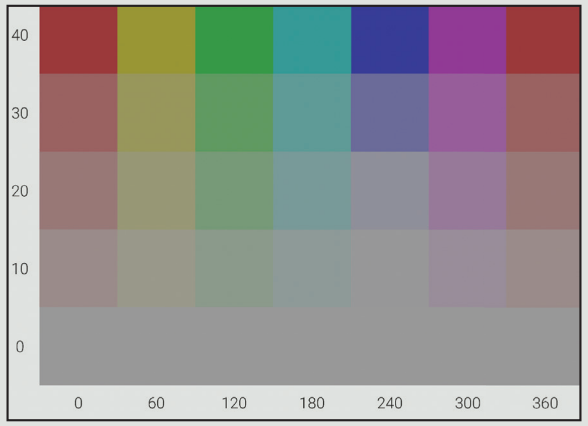


Fig 86 Digital renderings of various polar viewpoints.



40	H0 S80	H60 S80	H0 S80	H180 S80	H240 S80	H300 S80
30	H0 S60	H60 S60	H0 S60	H180 S60	H240 S60	H300 S60
20	H0 S40	H60 S40	H0 S40	H180 S40	H240 S40	H300 S40
10	H0 S20	H60 S20	H0 S20	H180 S20	H240 S20	H300 S20
Theta/Phi	0	60	120	180	240	300



40	H0 S62	H60 S67	H120 S62	H181 S65	H240 S64	H300 S65
30	H0 S37	H60 S40	H120 S37	H180 S39	H240 S31	H300 S40
20	H0 S22	H60 S23	H120 S22	H176 S21	H240 S7	H306 S21
10	H3 S10	H60 S10	H117 S10	H162 S8	H240 S1	H318 S8
Theta/Phi	0	60	120	180	240	300

Fig 87 Theoretical results versus measured results, top: theoretical, bottom: measured.

Conclusion: The digital rendering behaves similar to the predicted behavior. Hue in particular translated well and is both accurate and precise reference point for phi at larger viewing angles of Theta. Considering the relationship between Theta and saturation, results were less consistent and accurate among different measurements. The expected cause observed are optical reflections of light which are blended with the average causing saturation to be affected.

Though absolute saturation measurements were shifted, the relative change in saturation proportional to Theta was found to be linear to a degree. While the results cannot be directly converted into Theta for accurate pose estimation, it is potentially possible to normalize the range of saturation values. Normalizing the saturation values could allow for the interpretation of saturation measurements in respect to the effective saturation range, allowing for an adjusted interpretation of Theta.

CAPTURING DEFORMATION AND RECONSTRUCTING OF PHYSICAL FORM

Research question:

“Can Polar pose estimation of Colorful Bits be used to capture kinetic deformation and reconstruct the original shape from a color image?”

Prototype: Digital Simulation and demonstration of hue-saturation vectorization protocol.

Modeling conditions: The camera lens distortion was neglected assuming bit size to distance ratio between marker and camera is at least 100:1. It therefore is expected that the shape and size of bits within an image is predominantly caused by relative angle to the observer and relative distance to viewpoint can be neglected. The implication of this assumption allows for linear reconstruction where the all bits color-orientation vectors can be multiplied by the average distance between the markers and viewpoint without significant effect on accuracy. This allows for pose estimation without additional depth sensing and requires less computation.

Results: A 10x10 point Grid was modeled that represents colorful bits. The color of each point is calculated based on the polar orientation relative to the camera. Theta is represented by saturation and Phi is represented by hue. The Phi and Theta Vectors are represented in their respective color (Figure 88, right). Through a camera obscura, the points are projected on a flat plane (Figure 88, left). It can be seen how from the steep angle the image is significantly distorted from the viewpoint. Next, the Phi and Theta of each point are converted into relative orientation vectors that reconstruct the position in relationship to each other point from the observer (green vectors). The green vectors showcase how the points of the image are reconstructed on an averaged plane, represented by blue points. The blue presents a reconstruction of the original shape.

Summarizing the process: the distortion of the projected image is relative to the angle between each point and the observer. By calculating the Phi and Theta angles represented by color, the relative distortion can be reversed for each point.

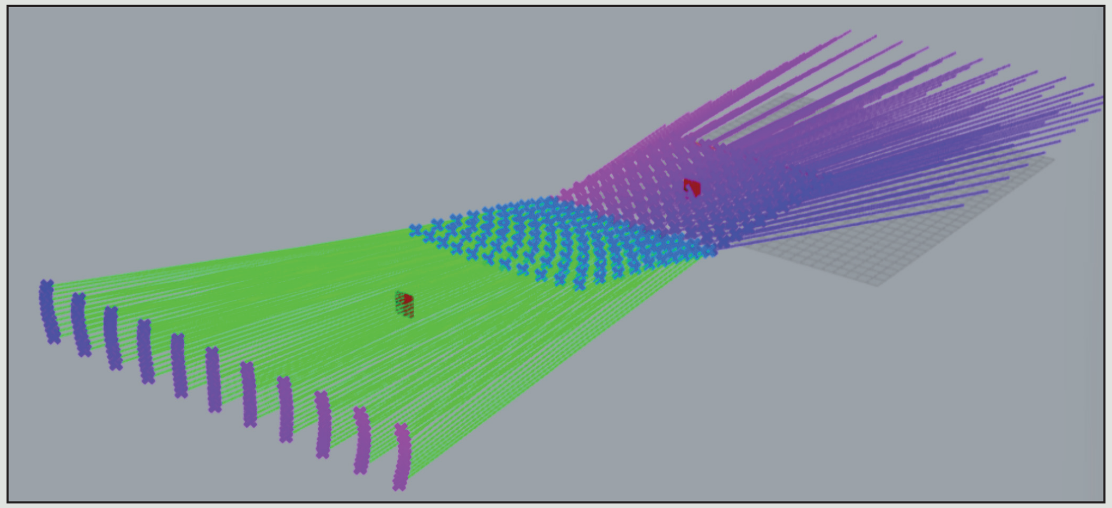


Fig 88 Colors can be used for pose estimation of each bit, allowing for the reconstruction of original shape from viewpoint distorted image.

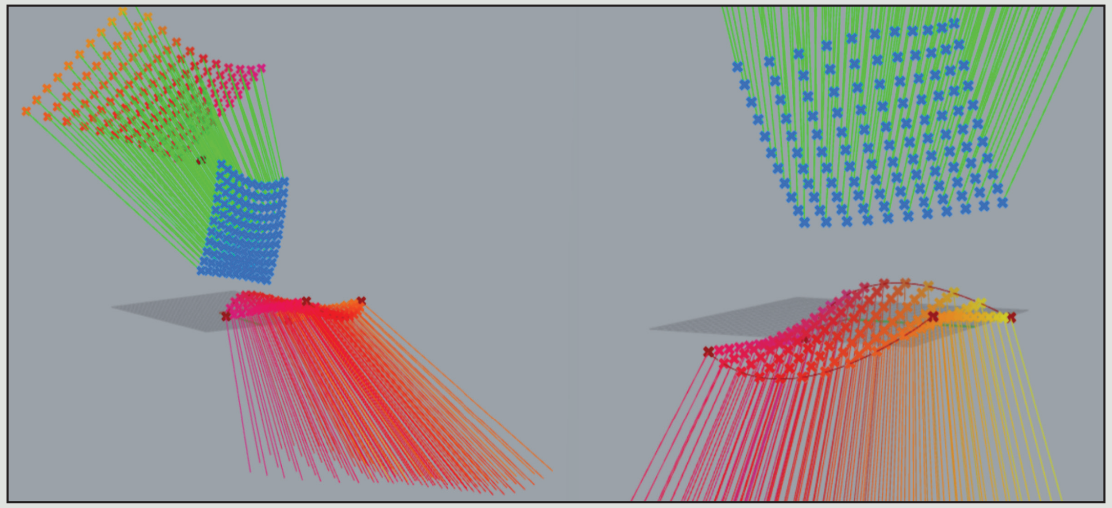


Fig 89 Color pose estimation can be used to reconstruct original shape from double-curved deformed surface.

Next, to evaluate the form reconstruction capabilities, a 10x10 square surface was deformed. In Figure 89, the rebuilding capabilities of colorful bits are demonstrated, where a double curved surface is reconstructed to the original flat square surface. On the right side it can be seen that there remain slight inconsistencies and warping in the reconstructed surface. However, these are the result of the camera being relatively close to the image for the visual showcase. In practical applications, the relative camera distance to marker is significantly larger to the point where these inconsistencies become negligible.

Conclusion: In contrast to conventional fiducial approaches that require static feature points to read and interpret encoded information, colorful bits showcase an approach that allows for information to be obtained from any deformed superposition of physical form.

Provided Phi and Theta can be obtained from hue and saturation respectively, the potential ability for colorful bits to estimate the pose of each bit and reconstruct a 3D deformed surface to a normalized plane is demonstrated. This process allows for color imaging to both capture and reconstruct the information from a dynamic deformed representation of data.

Moreover, it allows for both original information as well as the deformation information to be obtained separately as well as jointly, allowing for kinetic deformation to be captured and interpreted by evaluating deformation in respect to the original shape.

3.6.2 PHYSICAL PROTOTYPING

COLOR BASED POSE ESTIMATION

Research question:

"Can the simulated Stimulus-Responsive behavior from the digital renderings be replicated through multi-material 3D printing?"

Method: Fabricate the design through Multi-Material Jetting (MMJ). Next, reproduce positions from digital renderings and measure fiducial response by averaging the color of a bit, and then representing the measurement within the HSI color space. Finally, the measured hue and saturation were compared to the predicted hue and saturation to evaluate 3D printed performance.

Prototype: A series of full color lenticulars was produced utilizing CMYW and various texture mapping techniques. All prototyping variants share the same geometric and optical design. However, Various approaches for color reproduction were explored (Figure 90).

Initial prototyping included the texture mapping of the target HSI color space on the image plane. Relative Colorimetric rendering intent was used to optimize saturation for out of gamut colors. However, texture mapping approaches yielded poor color saturation (Appendix A - Prototype A), which is further discussed in chapter 3.7.3.

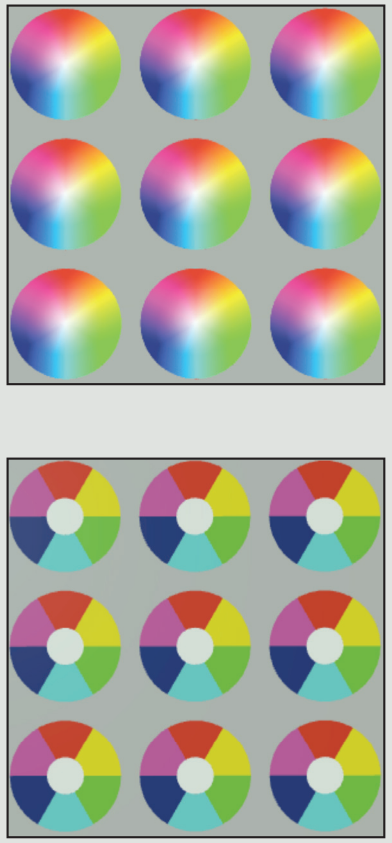


Fig 90 Above: texture mapping, below: manual color allocation.

Instead, manual allocation of color was explored through both the “color picker” feature (Appendix B - Prototype B) and manual override of materials through “CMYK input” Ultimately, Prototype C which used the CMYK manual override yielded the most consistent results and saturated colors, which was therefore chosen for further evaluation.

Test setup:

Lighting setup:
For lighting, a dual-softbox setup was used at a 45 degree angle. The lighting setup was designed to approximate the lighting conditions of the digital rendering, which utilized a dual-softbox lighting. The flashes were operated at the same power, aiming to recreate homogenous lighting conditions (Figure 91).

Fig 91 Lighting setup.

Alignment:
Crucial for the evaluation of the relationship between relative position and color, both material and camera have to be precisely aligned for proper measurements. A backdrop for alignment was designed and printed to ensure consistent alignment between different measurements (Figure 92). It is important to note the material plates were rotated rather than the observing camera to ensure consistent lighting and alignment between measurements.

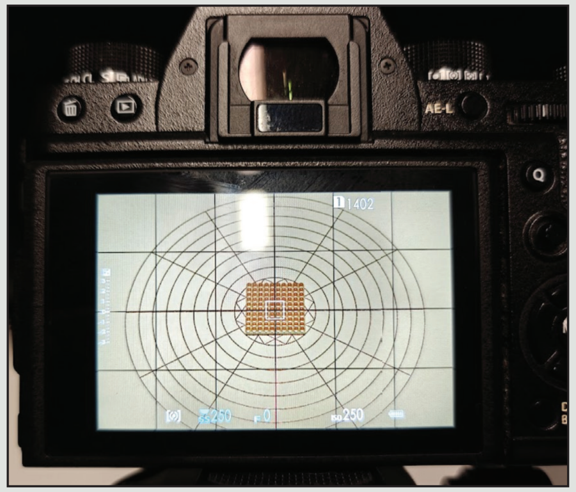


Fig 92 Optical alignment of prototype and camera.

Color calibration:
Equally crucial to alignment is the color accuracy of the captured image. All cameras- and editing software operate ICC-profiles which may interpret colors differently. To ensure accurate color representation an industry standard colorchecker was used to calibrate colors for consistent and objective measurements between devices (Figure 93).

Fig 93 X-rite colorchecker passport and calibrite software were used for color calibration.

Color measurement:
Next, the calibrated image was imported in Adobe Photoshop. For color measurements all pixels within a bit were averaged with the “average” filter. A camera was used instead of dedicated spectrometers to replicate intended operating conditions (Figure 94).

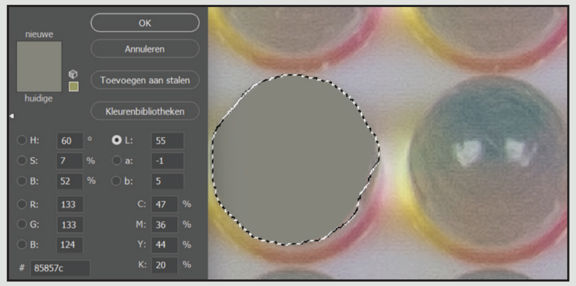
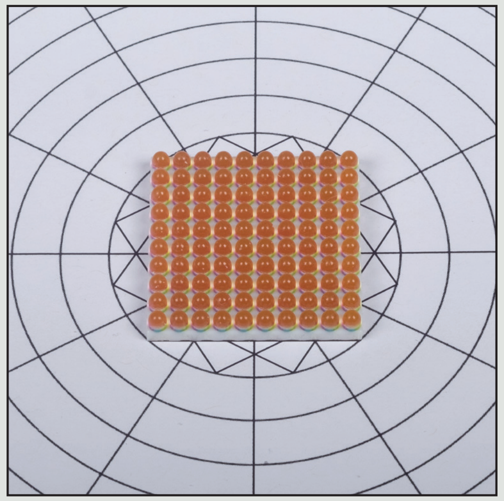


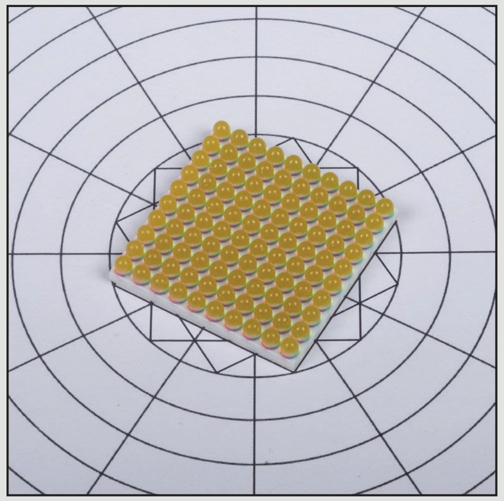
Fig 94 Color measurement procedure.

Results: See following pages (figures 95 and 96).

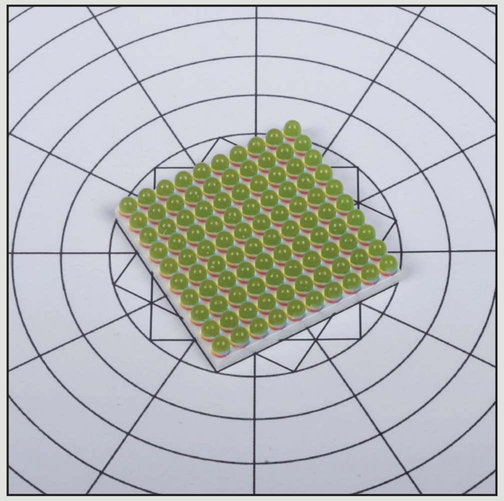
Fig 95 Fiducial color response according to viewing angle Theta (=40) and Phi.



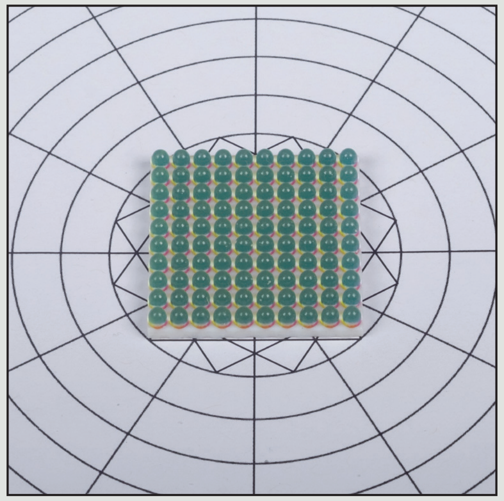
Phi 0 - "Red"



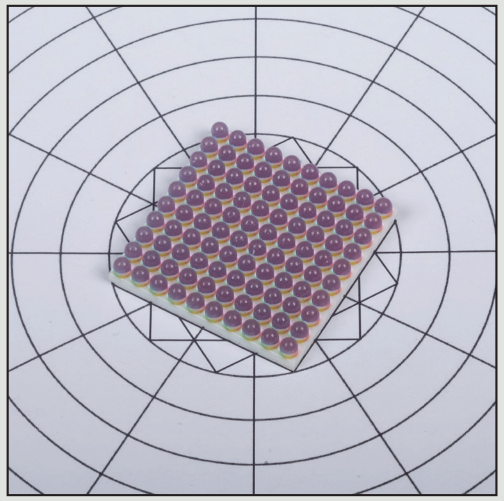
Phi 60 "Yellow"



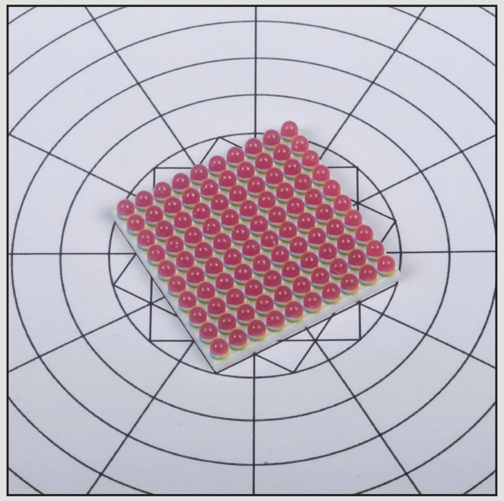
Phi 120 "Green"



Phi 180 "Cyan"

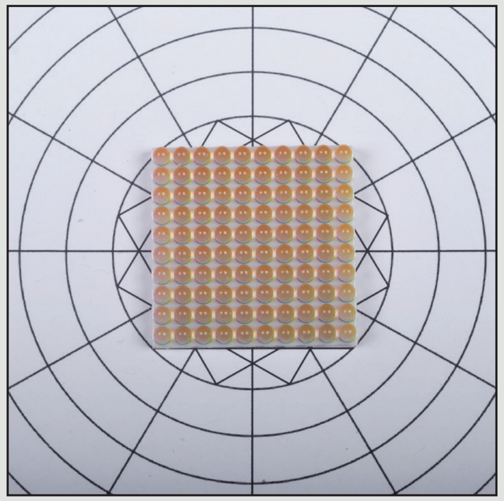


Phi 240 "Blue"

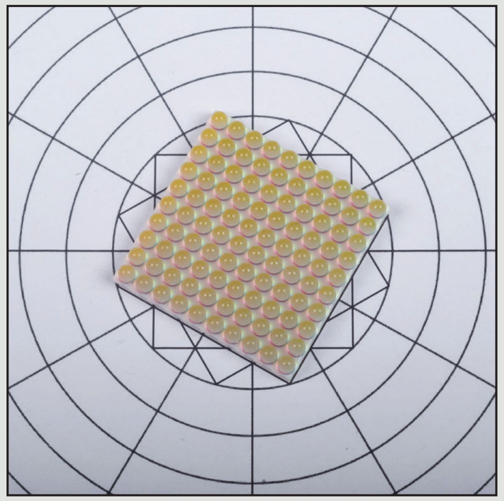


Phi 300 "Magenta"

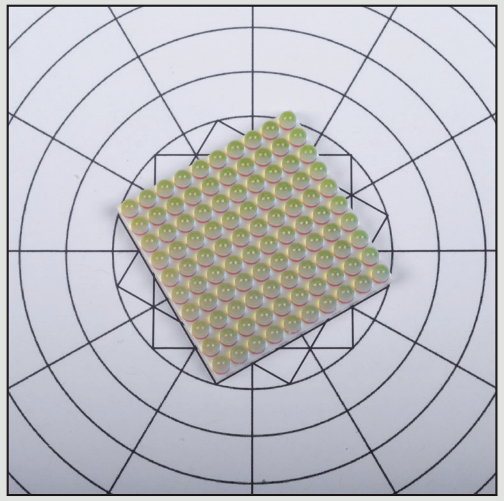
Fig 96 Fiducial color response according to viewing angle Theta (=20) and Phi.



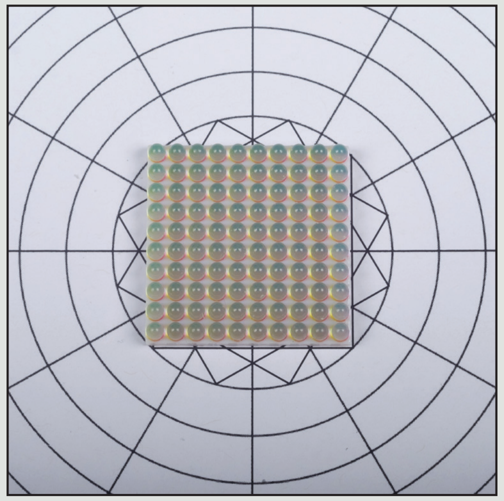
Phi 0 - "Red"



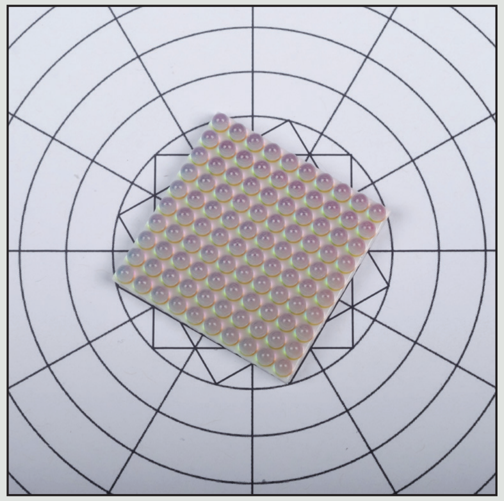
Phi 60 "Yellow"



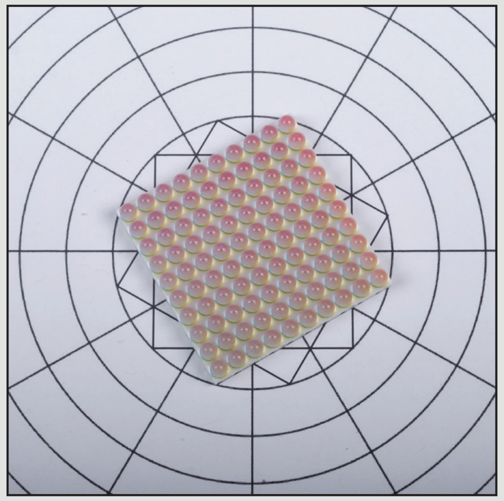
Phi 120 "Green"



Phi 180 "Cyan"



Phi 240 "Blue"



Phi 300 "Magenta"

Prototype C - Manual CMY override				
Polar Orientation Viewpoint		Color		
Phi	Theta	Theoretical Color	Digital Rendering	Physical measurement
0 (Red)	40	H0 S80	H0 , S62	H20 S67
	20	H0 S40	H0, S22	H23 S39
60 (Yellow)	40	H60 S80	H60, S67	H44 S74
	20	H60 S40	H60, S23	H41 S40
120 (Green)	40	H120 S80	H120, S62	H73 S57
	20	H120 S40	H120, S22	H60 S23
180 (Cyan)	40	H180, S80	H181, S65	H170 S34
	20	H180 S40	H176, S21	H190 S13
240 (Blue)	40	H240, S80	H240, S64	H291,S24
	20	H240, S40	H240, S7	H321 S11
300 (Magenta)	40	H300, S80	H300, S65	H345 S55
	20	H300, S40	H306, S21	H348 S19

Table 2

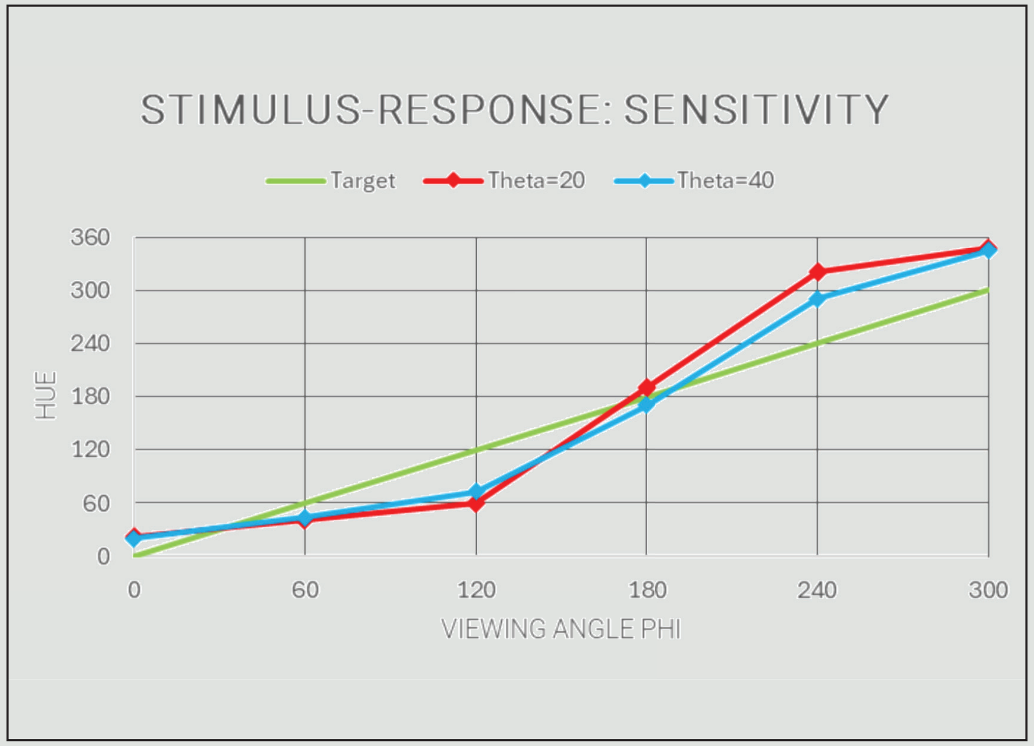


Fig 97 Stimulus-Response: sensitivity. Despite the shifted hues, no overlap of hues are observed that break the circular color space characteristics.

Fiducial relationship between hue and Phi:

Evaluating the Hue and respective Phi, the physical prototype displays a considerable shift in measured hues compared to the theoretical predicted value and digital rendering (Table 2). At a 40 degree viewing angle (Theta), the margin of error is between 16 to 51 degrees. At a 20 degree viewing angle (Theta), the margin of error increases to a range from 19 to 81 degrees.

Despite the shifted hues, no overlap of hues are observed that break the circular color space characteristics (see Figure 97). Consequently, measured hues can be utilized for estimation of viewing angle Phi, albeit significantly less accurate than theoretical models have suggested.

Unlike the homogenous performance of the digital renderings, it is observed that the accuracy of particular hues perform differently, indicating a heterogeneous performance of color reproduction. In particular green, blue, and magenta are significantly more shifted and inconsistent across viewing angles Theta than red, yellow, and cyan. These shifts could be caused by a variety of causes including poorly optimized manual color allocation as well as technical limitations of the MMJ-CMY printing process, which will be further discussed in chapter 3.6.3.

Fiducial relationship between saturation and Theta:

Considering the absolute measurements of saturation and Phi, a similar heterogeneous performance is observed. Red and yellow behave similarly to the theoretical prediction at a margin of error between 0 to 13 (0 to 6 degrees) which increases for magenta and green and ultimately a large difference is observed for cyan and blue ranging from 27 to 56 (13.5 to 23 degrees).

Similar to the digital rendering measurements, the saturation behavior relative to observing Theta angle behaves similar to the predicted behavior. A clear relationship between viewing angle Theta and saturation is observed (Figure 98). Provided the measured saturation can be normalized for evaluation, saturation could potentially be used for estimation of Theta. It should however be noted that compared to the digital renderings, optical artifacting is significantly more pronounced affecting saturation/Phi accuracy and behavior, moreover in chapter 3.6.3.

Effects of lighting:

Evaluating the shifted hues in conjunction with the saturation measurements, it is expected that the results have been affected by the lighting conditions. The lighting used in the measurements were not evaluated for color balance, thus the intensity of particular hues/wavelengths could be over- or under-represented. At high saturation values that approximate the chromaticity plane, hue and saturation should be less affected by inconsistent illumination.

Provided the shifted hues increase significantly at lower saturation and shift toward the 30 degree Phi angle, it is likely the heterogeneous performance is in part caused by the lighting conditions being biased. This is further substantiated by the relatively consistent and high saturation values of red and yellow contrasting the low saturation of cyan and blue at the opposite end of the color spectrum.

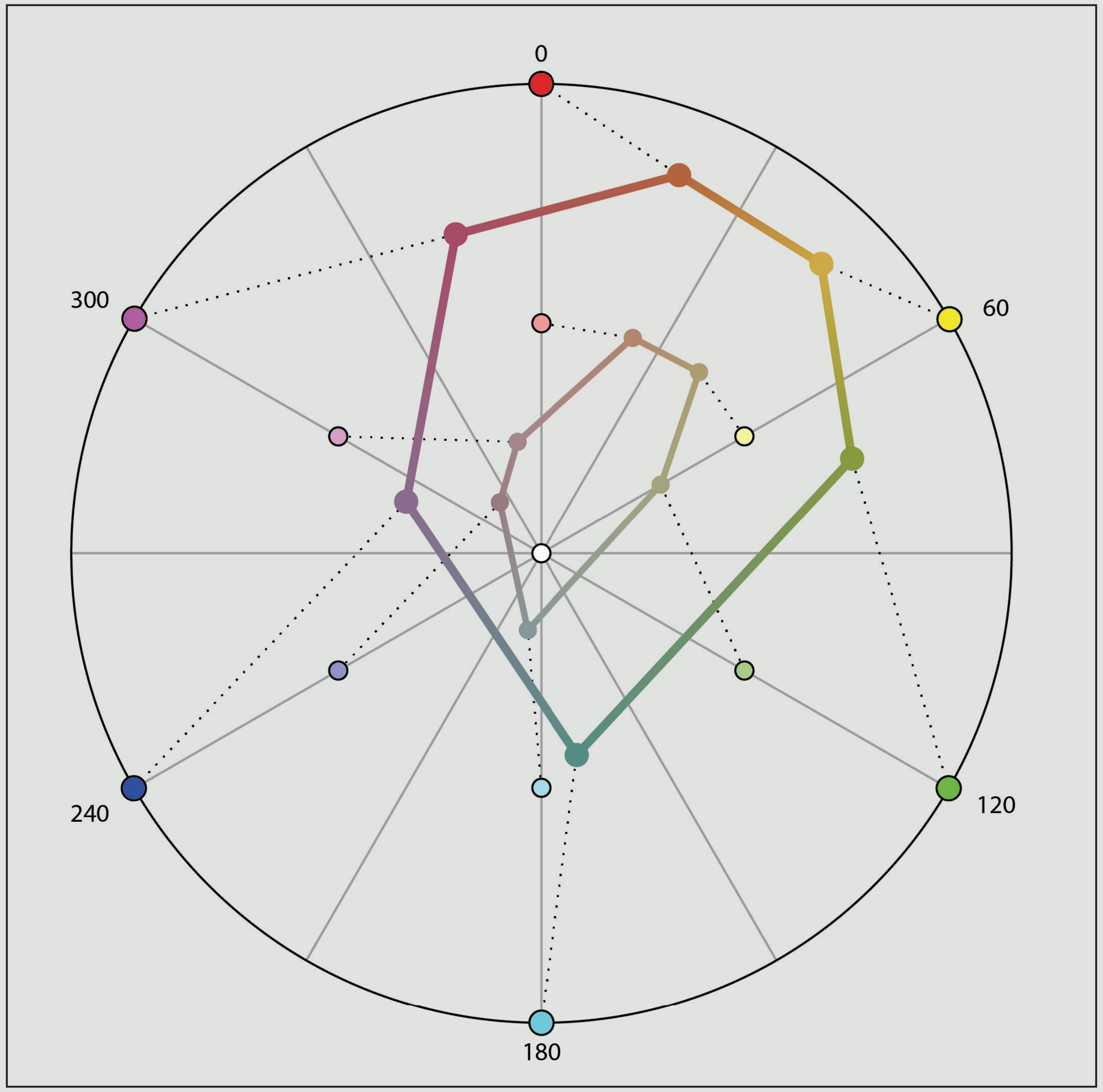


Fig 98 Predicted colors (Black outline) and measured colors connected by dotted lines.

Conclusion:

The fiducial relationship between viewing angle and measured color behaves similar to the predicted behavior. A strong relationship is established between hue and Phi, as well as between saturation and Theta. Compared to the theoretical color prediction and digital rendering measurements, the accuracy and precision of colors for pose estimation yields significant differences.

In contrast to the predictions, the absolute measurements of hue and saturation are heterogeneous in accuracy across the color space. Moreover, regardless of the viewing angle, the margin of errors is significantly larger. Considering the current color output, absolute pose estimation measurements are not directly suitable for tracking and alignment of virtual graphic feedback.

However, considering the fiducial relationships between viewing angle and color shifts are maintained, further improvements in accuracy remain a promising prospect. Further improvements are suggested in chapter 3.6.3.

Though the pose estimation is not accurate, the consistent relationship between hues and viewing angle can be used to establish interactions that consider approximate directions. This is further explored in the next chapter.

INTERLINKING MECHANICAL PROPERTIES AND FIDUCIAL RESPONSE

Research question:

> *"Can mechanical and optical properties be interlinked in a manner that establishes a relationship between physical input and fiducial color response?"*

Method: To validate the relationship between kinetic deformation and fiducial color response, a series of lenticular plates was printed with mechanical matrices with different stiffness (Figure 99). To evaluate the relationship between stiffness, applied load and optical response, each plate was loaded under a series of loads.

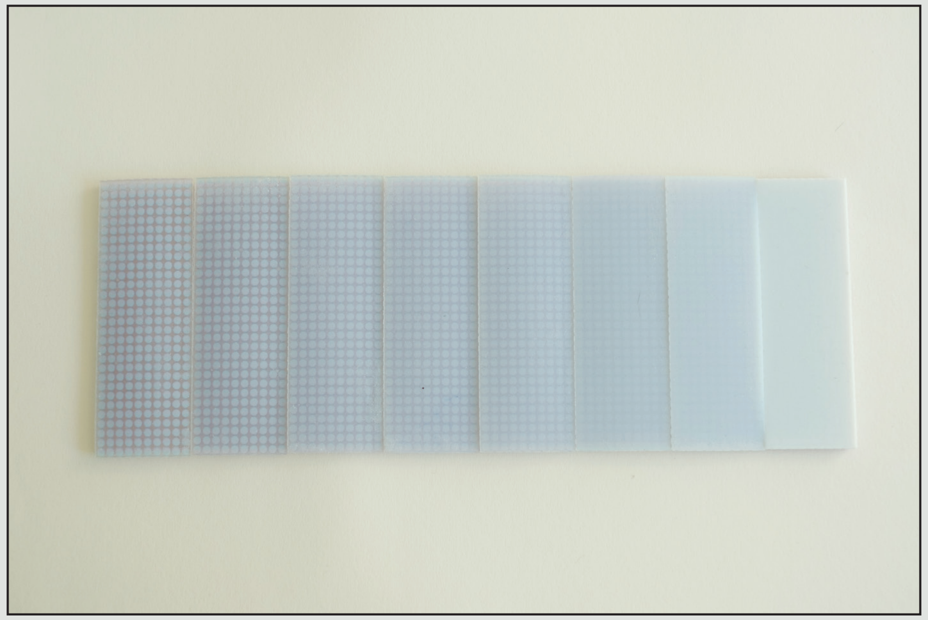


Fig 99 Mechanical matrixes with increasing stiffnesses (left to right).

To evaluate the color response, absolute color measurements were converted into "absolute color distance" and "relative actuation". Absolute color distance describes the measured contrast in colors as a result from an applied load. To obtain the absolute color distance, the following trigonometric formula was used:

$$\text{Absolute color distance} = \sqrt{S_{LEFT}^2 + S_{RIGHT}^2 - 2 * S_{LEFT} * S_{RIGHT} * \cos(\Delta hue)}$$

Absolute color distance provides a proportional measurement of color shift which is not affected by the accuracy of pose estimation, but is dictated by the relationship between viewing angle and color response. Provided the previously established limitations, this allows for the consideration of color as a proportional output regardless of its directional accuracy.

Next, relative actuation describes the absolute color distance measurement as a percentage of the maximum achievable color distance. Considering magenta and cyan colors were used in this experiment and the maximum saturation is 80%, the following Max Color distance was calculated as follows:

$$\text{Max color distance} = \sqrt{80^2 + 80t^2 - 2 * 80 * 80 * \cos(\Delta 120)} = \sim 139$$

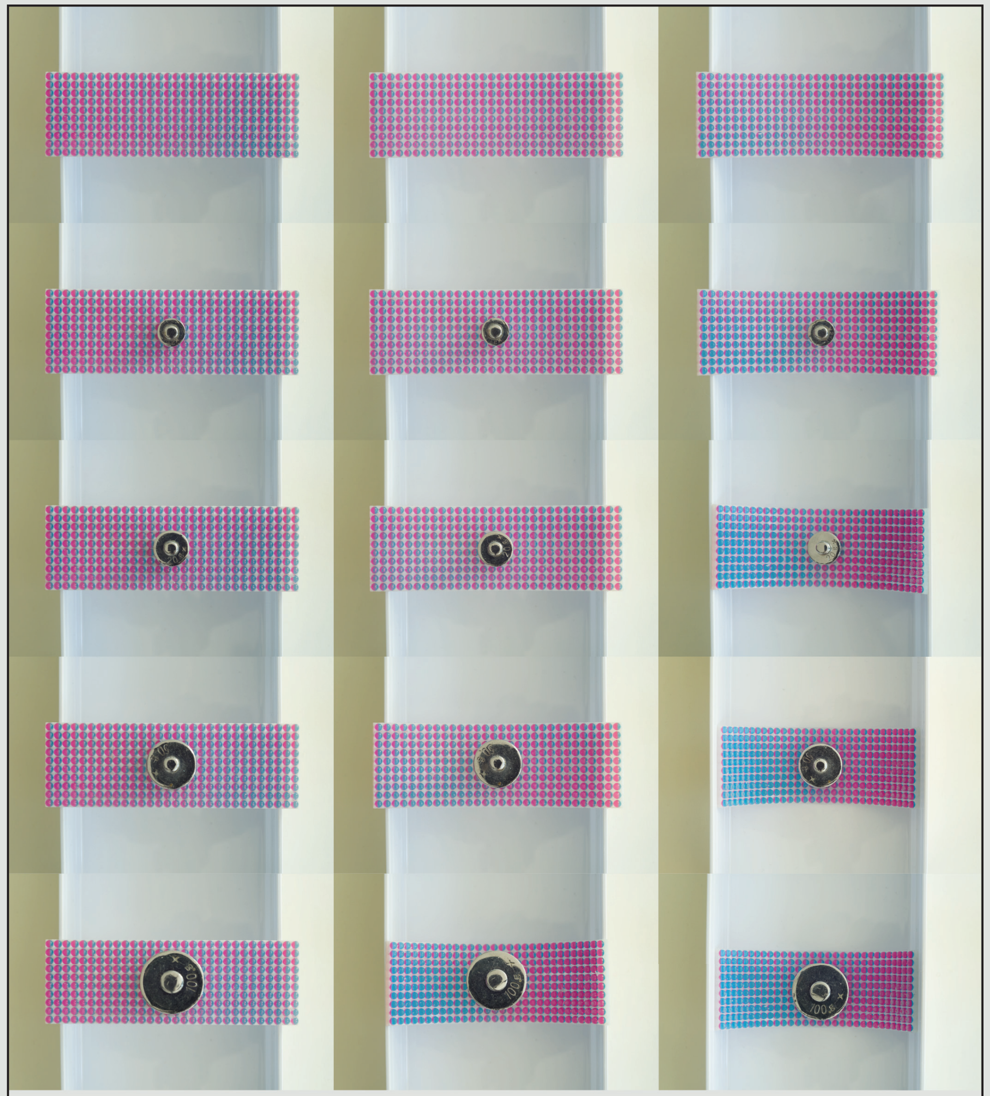
Results: See following pages (table 3, Figure 100).

Vero PureWhite (E = 363000 psi)				
Weight	Left side	Right side	Absolute Color Distance	Relative Actuation
0	H314 S45	H264 S24	35	25%
10	H314 S45	H263 S27	35	25%
20	H315 S45	H265 S27	35	25%
50	H317 S45	H265 S26	36	26%
100	H317 S43	H268 S25	32	23%

Shore A95 (E = ~4700 psi*)				
Weight (g)	Left side	Right side	Absolute Color Distance	Relative Actuation
0	H310 S33	H312 S30	3	2%
10	H299 S28	H318 S36	12	9%
20	H275 S25	H322 S41	30	23%
50	H226 S27	H325 S47	57	41%
100	H198 S65	H327 S60	113	81%

Shore A85 (E = ~1800 psi*)				
Weight (g)	Left side measurement	Right side Measurement	Absolute Color Distance	Relative Actuation
0	H219 S37	H321 S48	66	47%
10	H211 S46	H319 S53	80	57%
20	H198 S68	H325 S62	116	83%
50	H195 S72	H327 S64	124	89%
100	H195 S83	H324 S63	132	94%

Table 3 Measured fiducial color responses under load. * Retrieved from (Hertz et al., 1998).



PureWhite Shore A95 Shore A85

Fig 100 Visual results of Stimulus-Responsive behavior.

Stimulus-Response Relationship: Applied force and color response

To determine the Stimulus-Response Relationship, the relationship between the applied load and color response was evaluated. For the “Vero PureWhite” and “Shore A85” prototypes, the applied loads were inappropriate for evaluation. ‘Vero PureWhite” stiffness far exceeded the threshold for the selected weights to become statistically significant, while the stiffness of “Shore A85” was too low causing maximum color distance and actuation at only 20g (Table 3 (previous page).

However, “Shore A95” showed promising results. Plotting the absolute color distance over the applied weight, a strong linear relationship was found (Figure 101). Moreover, plotting the relative actuation over applied weight, a linear relationship between applied load and actuation is demonstrated (Figure 102). These results indicate a strong relationship between applied loads and fiducial color response, allowing applied stimuli to be used as a physical input for digital information.

Mechanical properties and Stimulus-Response Sensitivity:

Comparing the absolute color distance measurements and relative actuation values of the prototypes under the same load (Table 3), a clear connection between matrix stiffness and fiducial color response is observed.

Comparing the “Shore A 85” and “Shore A 95” with less extreme differences in estimated stiffness, it is observed that the color response of “Shore A 85” is approximately twice as sensitive to applied loads than Shore A95 (Figure 103). Provided deflection inversionally proportional to the Young’s Modulus, This proportional sensitivity conforms with the associated estimated Young’s Modulus, which is approximately twice as high for Shore A 95 (Figure 104).

From these results, it can be plausibly concluded that the fiducial color response is directly related to the allocated stiffness of the mechanical matrix material. Therefore, allocation of mechanical properties can be used to control the relationship between physical inputs and optical response.

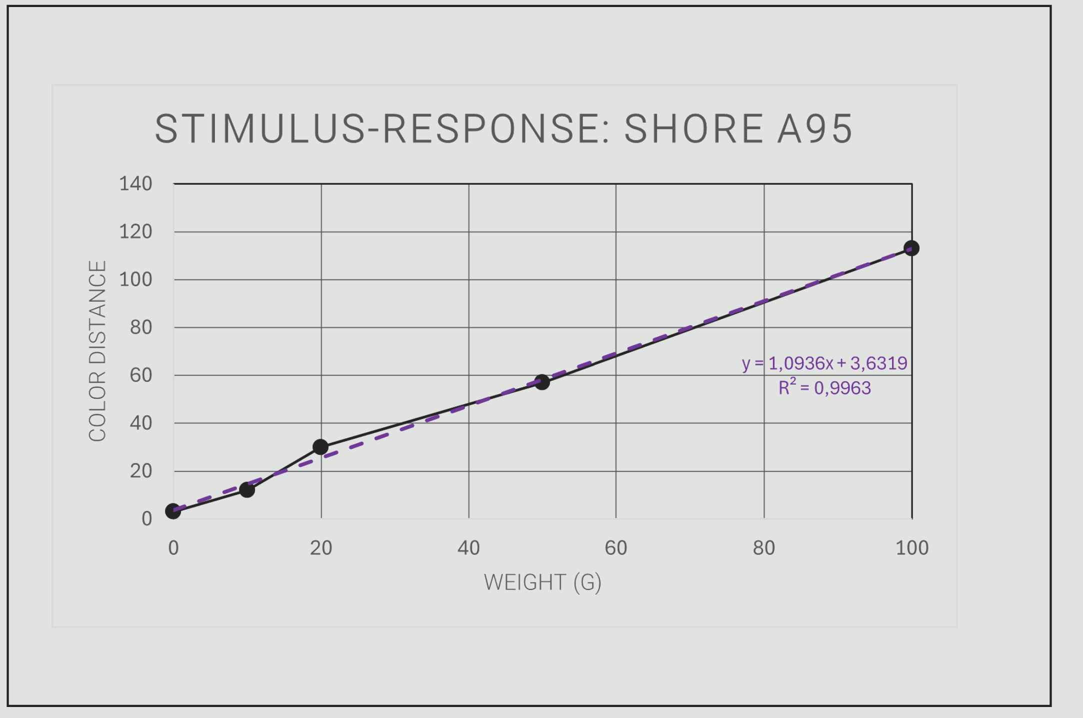


Fig 101 Stimulus-Response Relationship between weight (stimulus) and Color Distance (response).

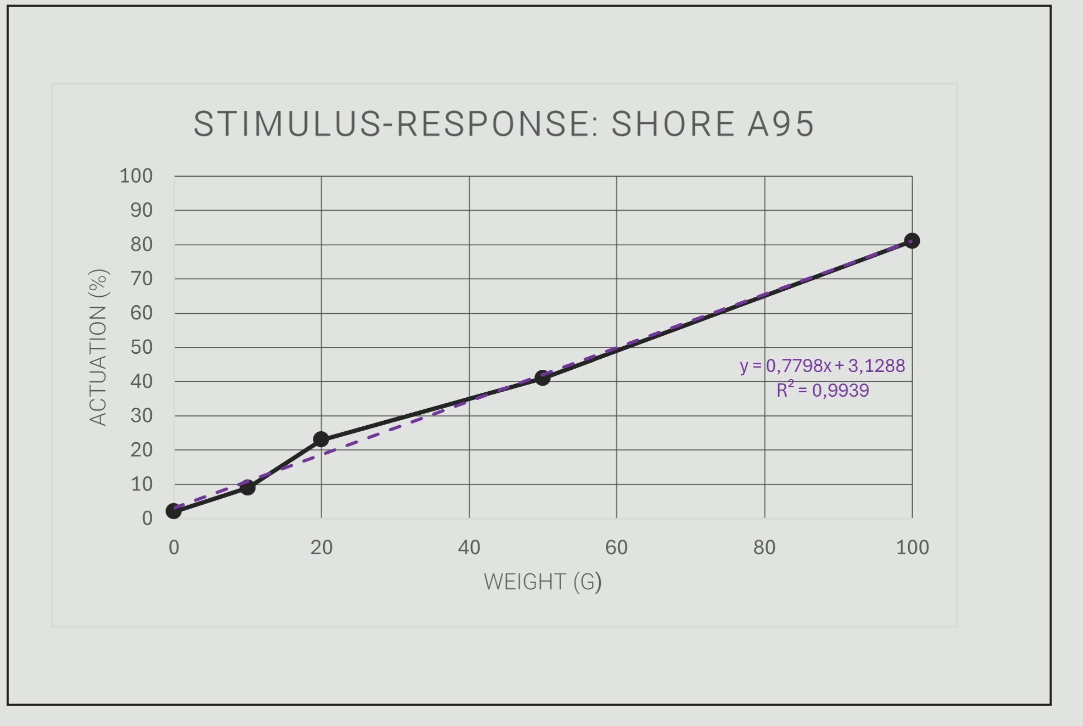


Fig 102 Stimulus-Response Relationship between weight (stimulus) and Actuation (interpreted response).

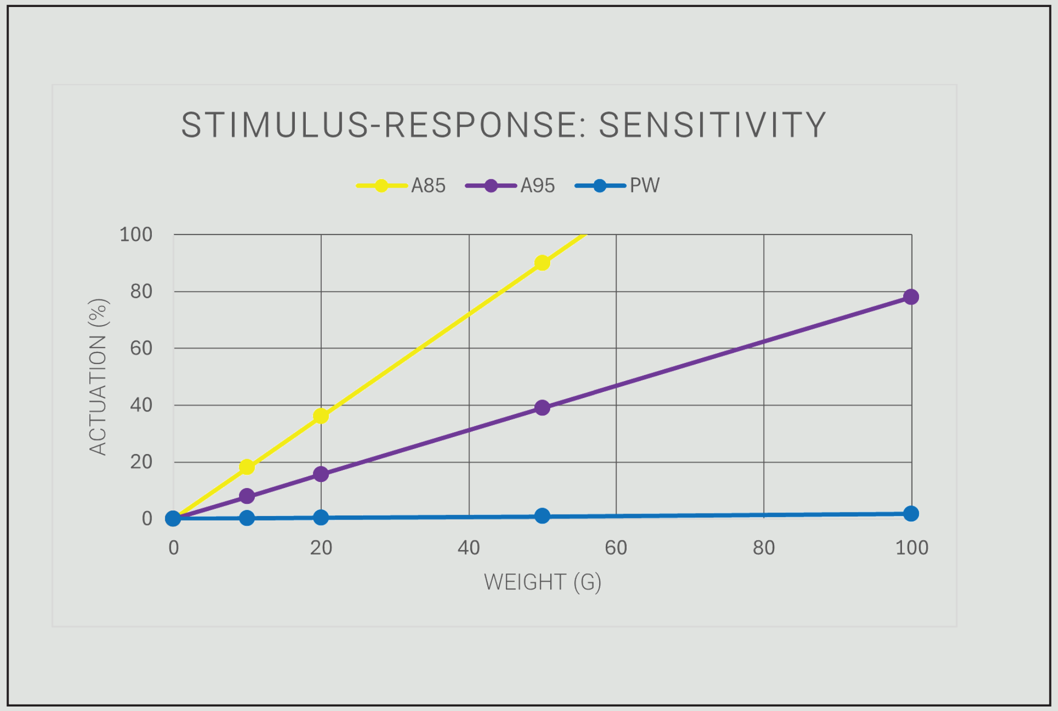


Fig 103 Angular coefficients of mechanical matrix materials. Remark; A85 was extrapolated from first 0g,10g, 20g measurements at which maximum actuation limit was reached.

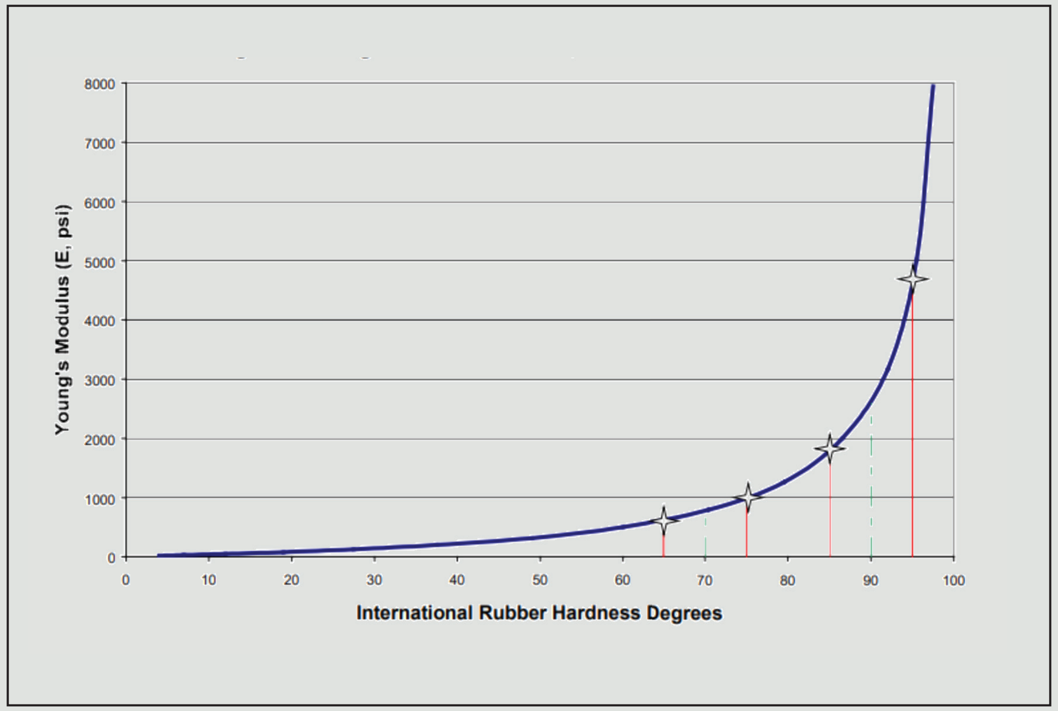


Fig 104 Shoar hardness to Young's Modulus (Hertz & Farinella, 1998).

Conclusion:

The results indicate a strong relationship between applied loads and absolute color distance, allowing a proportional change in color that reflects a change in applied load. Given any mechanical stiffness, this allows for the interpretation of absolute color distance caused by an external load as a percentage of actuation, allowing deformation to be used as a physical input

Moreover, a strong relationship was found between the allocated Young's Modulus and Stimulus-Response Sensitivity. Provided the Young's Modulus and mechanical properties can be allocated within the manufacturing process, relative actuation and absolute color distance can be interpreted to obtain the applied load.

Combining these insights, a fiducial relationship between allocated mechanical properties and color response is established. This allows color measurements to be used as a fiducial reference for kinetic deformation and applied forces, allowing kinetic deformation to be used as physical user input for Extended Reality.

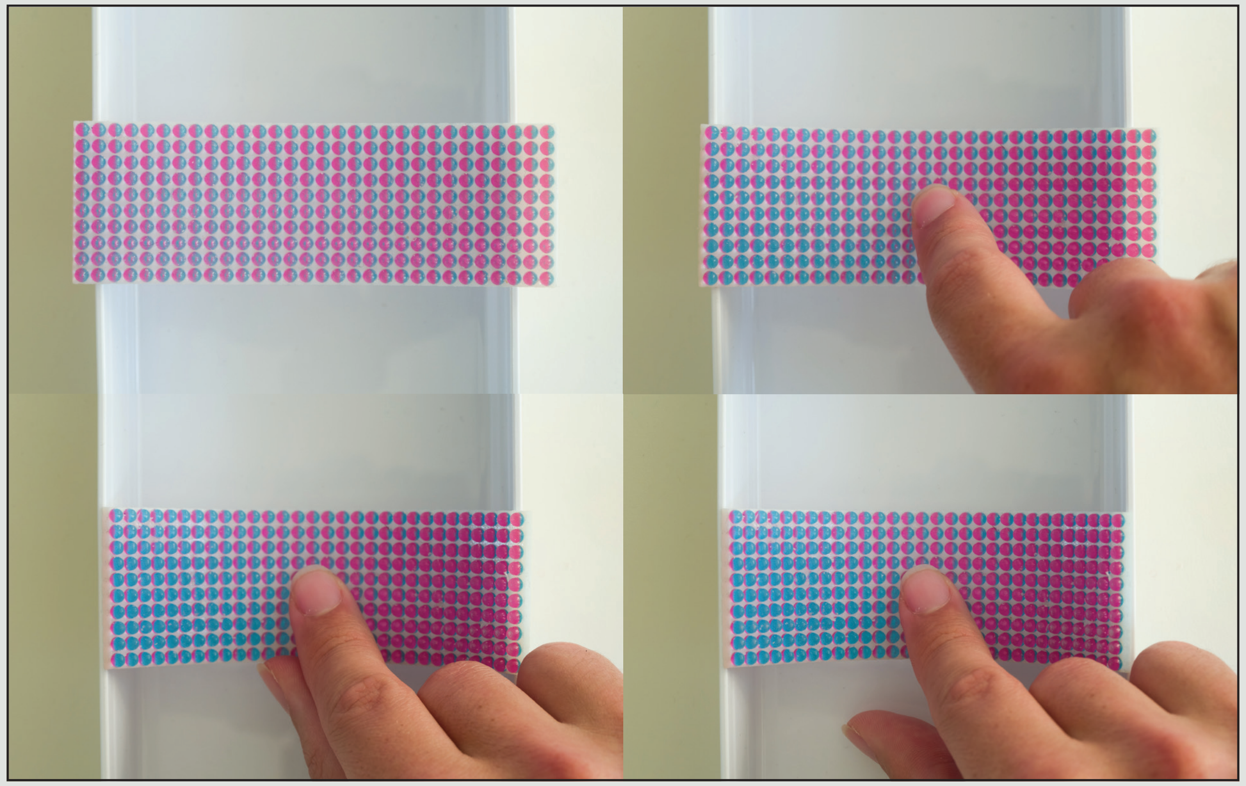


Fig 105 Relative actuation and respective applied load can be obtained from the allocated relationship between mechanical properties and optical response.

3.6.3 LIMITATIONS & FUTURE WORK

LIMITATION: COLOR REPRODUCTION

There is a clear connection between hue and viewing angle Phi. However, compared to the digital predictions the hue measurements are shifted. Contributing factors have been identified including the accuracy of color reproduction within the fabrication process.

Within the current color reproduction pipeline the HSI color space is translated from RGB to CMYK. The CMYK color gamut does not fully cover the RGB color gamut (Figure 106), which results the source image colors had to be transformed to match the target color gamut. The mismatch in color gamut may cause a myriad of issues.

Fundamentally, the limited color gamut of CMYK poses limitations on the achievable saturation of colors. The printing process struggles to reproduce saturated reds, greens and blues which cause a loss in color reproduction accuracy. This limitation likely contributes to the heterogeneous pose estimation performance observed in the physical prototypes, where the out of gamut colors were significantly less saturated and hue-shifted.

Moreover, the mismatch in color gamuts posed significant challenges in the fabrication of the digital model. Initially, texture mapped models were imported into the native Grabcad software to reproduce the HSI colors in CMYK. In order to maximize saturation, relative colorimetric color intent was used to map out of gamut colors to the edge of the CMYK color gamut. For unknown reasons, Grabcads native color printing yielded inconsistent saturation for different hues (Appendix A + B).

Within the scope of this project, current design required a manual override to allocate colors to the image plane (Figure 107). However, to reproduce colors accurately, color mixing should consider and optimize for the printing process and respective inks used.

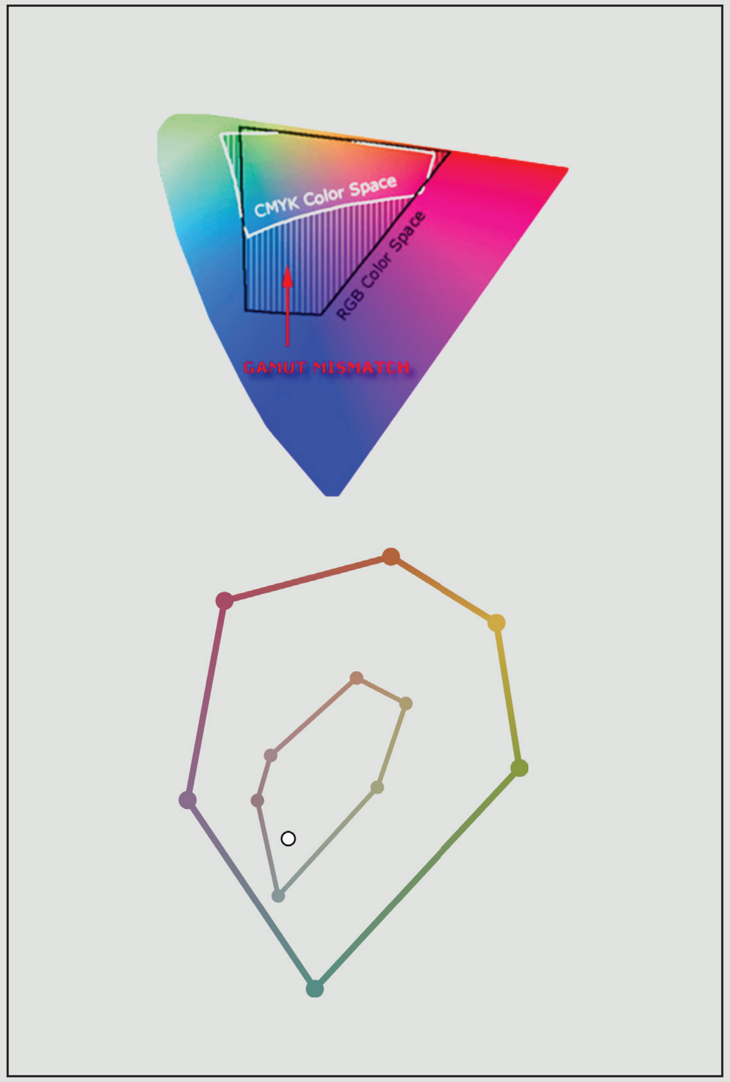


Fig 106 CMYK color gamut struggles to reproduce blues, magentas and greens, which is observed in the physical measurements (Color Management: Color Space Conversion, n.d.).

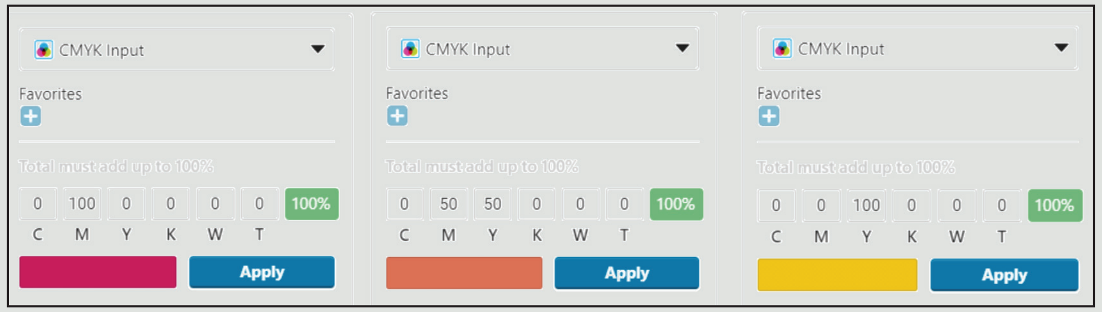


Fig 107 Manual allocation of CMY: Red is hue shifted from 0 to 12 in preview.

FUTURE WORK: COLOR REPRODUCTION OPTIMIZATION

First and foremost, future design pipelines should introduce a computational approach to color reproduction that considers both design specifications as well as printing parameters to optimize for colorimetric accuracy. Within literature, various approaches have yielded significantly better color reproduction through implementation of printing techniques like dithering, halftoning. A particularly interesting prospect is 3D halftoning (Abedini, 2023), which introduces a voxel based approach to halftoning for further improvement of color reproduction.

Considering the current design of Colorful Bits, colorimetric optimization should yield improvement in reproduction of hues, significantly improving in the pose estimation accuracy of phi respectively.

Saturation and respective Theta estimation are however bound to the limitations of the CMYK color gamut. Addressing the more fundamental limitations of the CMYK colorspace, future work could explore the use of the extended CMYLOGB colorspace to improve the homogeneity of saturation/ colorfulness across the Hue-chromaticity plane. The extended color gamut would improve both absolute reproduction of saturation, as well as the homogeneity of accuracy across the hue spectrum. The Stratasys J750 printer and material ecosystem does not (currently) offer OGB colors and is limited to printing up to 6 materials at once. Alternative means of production would have to be considered.

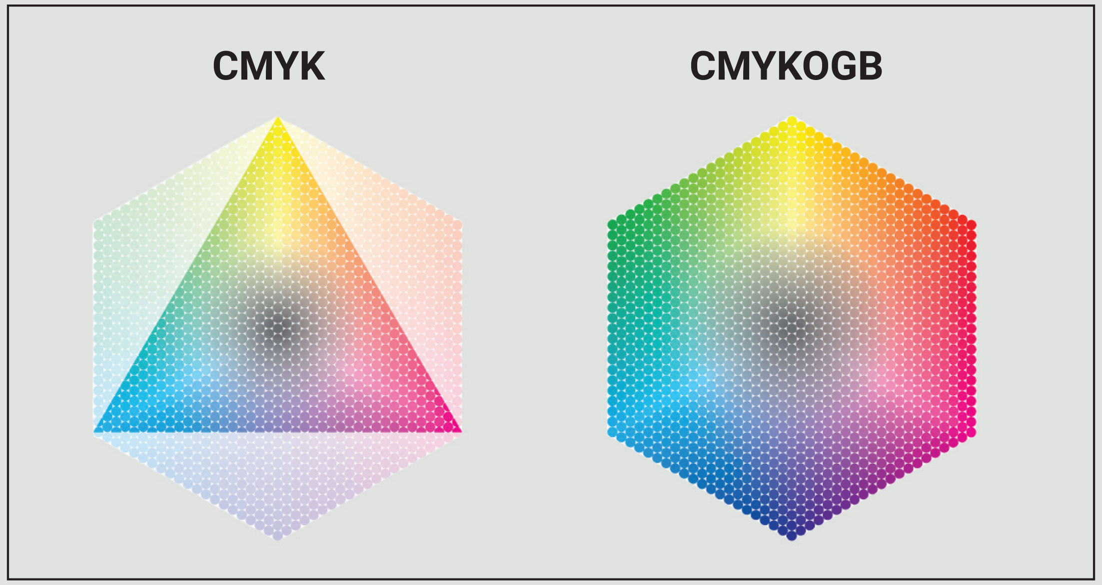


Fig 108 Extended CMYKOGB color space improved color gamut (Extended Color Gamut Printing. The Future of Perfectly Printed Colors, n.d.)

LIMITATION: SURFACE QUALITY AND OPTICAL PERFORMANCE

Besides color reproduction, various limitations in the reproduction of the optical design were discovered within the current manufacturing process. Within the grabcad software, the "glossy" surface finish setting was used to print Vero clear as a transparent optical material. To achieve a transparent surface finish, the printer uses no support material or structures to construct printing layers. It was found that the lack of support material negatively affected the geometrical reproduction of the optical design (Figure 109). Uneven surface quality and geometric distortions of the optical design cause several challenges for Hue and saturation based pose estimation.

Geometric distortions of the optical design cause inaccurate projections upon the image plane, causing shifted measurements of hue and saturation. Moreover, the surface quality of the lenses causes light to scatter and diffuse the projected image circle, negatively affecting the saturation. These factors may both cause shifted hues and inconsistent saturation measurements, contributing to the heterogeneous pose estimation performance (Figure 110).

Another limitation observed is the sensitivity to lighting conditions (Figure 111). Lens reflections introduce highlights, which causes desaturation and possible hue shifts depending on the color balance of the light source. Another optical artifact observed that relates to the lighting direction are internal light reflections. Though the exact nature is not clear, colored reflection on the matrix material can be seen. This indicates potential color bleeding of colors outside the target image projected, affecting the saturation and hue.

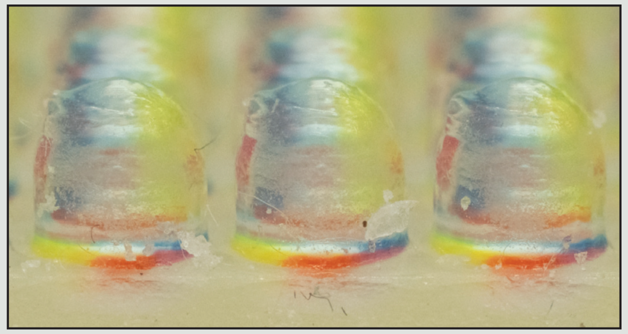


Fig 109 The top left of optical designs showcase distorted surface artifacts: uneven surface transparency.

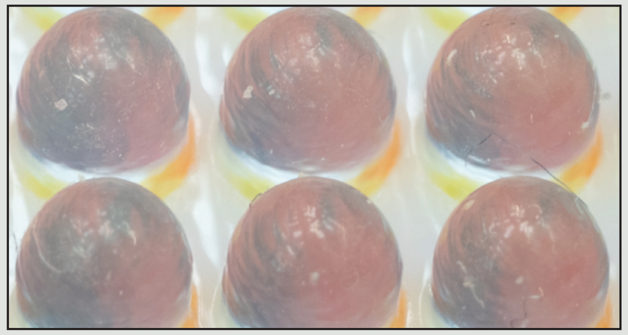


Fig 110 Geometric artifacts and surface quality causing distorted and uneven color projection affecting hue and saturation.

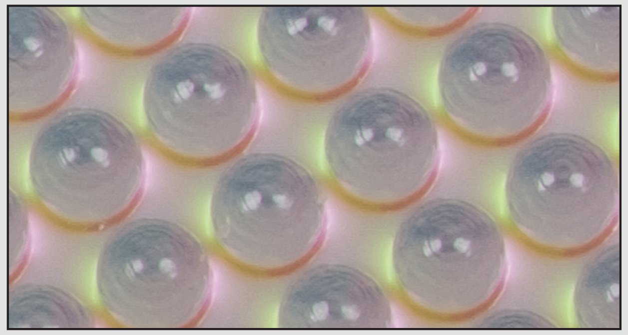


Fig 111 Various optical artifacts affecting saturation: uneven lens surfaces, light scattering, color bleeding and reflected highlights.

FUTURE WORK: OPTICAL DESIGN AND POST-PROCESSING

Within the scope of this project, the optics of the lenticular design have not been optimized for optical distortions. In the demonstrators it is observed that poor surface quality and reflections may be an important cause for inconsistent perception and measurement of color. Future work could explore further optimization of the optical design through consideration of the printing speed and quality settings, as well as adjusting geometric design and scale of colorful bits.

Another avenue to improve the optical performance could involve further post-processing of the printed design. Zeng et al. (2021) demonstrated the application of coatings may improve spherical roundness and reduce reflections and light scattering. These improvements in optical performance could yield more accurate and consistent saturation response, mainly improving absolute and relative performance for Theta.

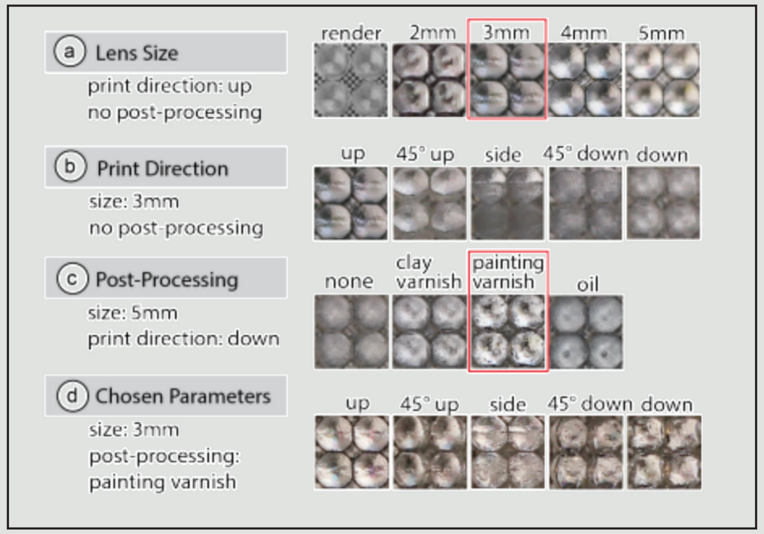


Fig 112 Post-processing of surfaces provides better optical performance (Zeng et al, 2021).

LIMITATION: DIGITAL MODELING CALIBRATION & ERROR CORRECTION

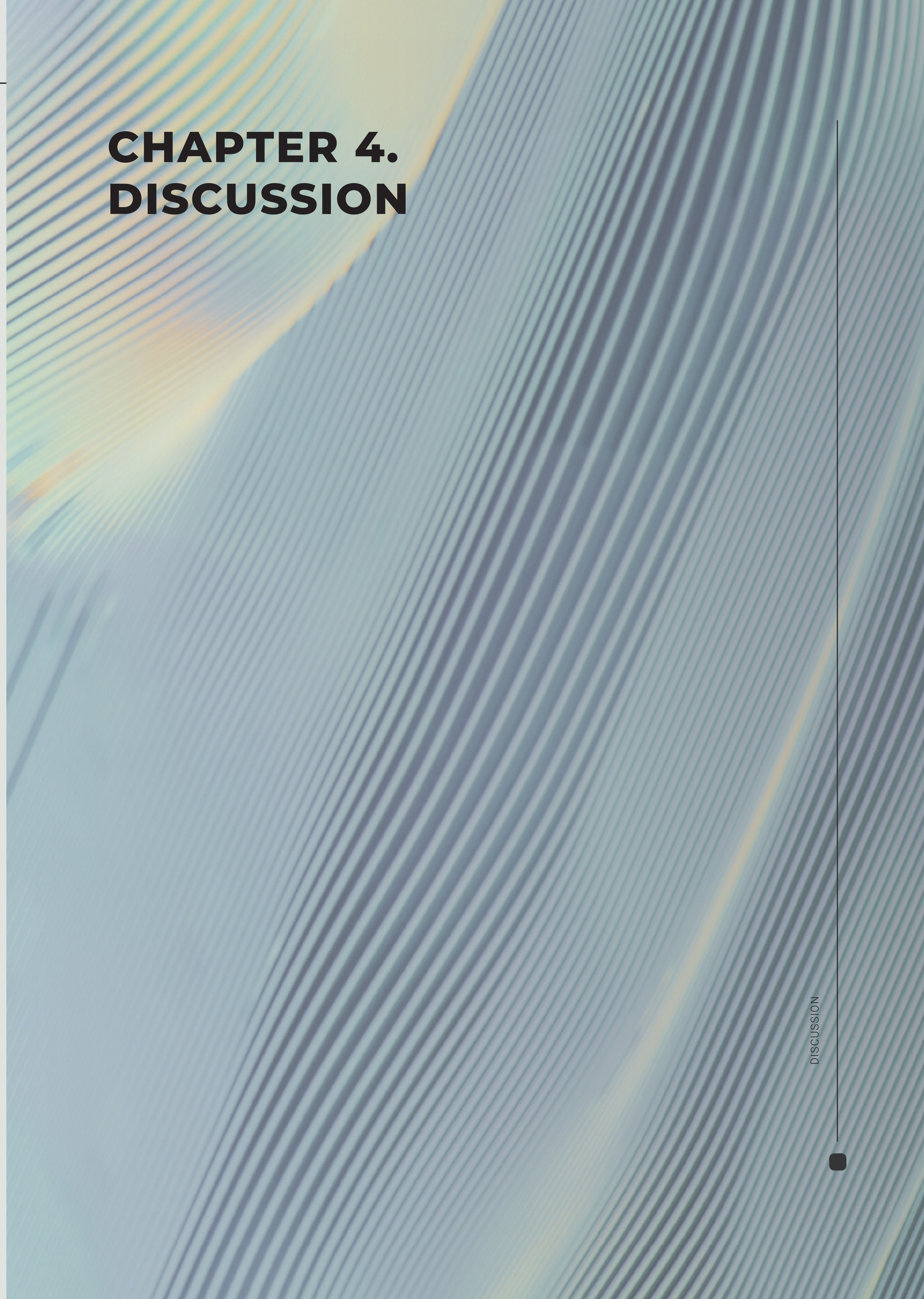
Finally, the usability of results is currently limited by the development of the pose estimation approach itself. The current approach to obtain and compute color information for the estimations of Phi and Theta has not considered any image processing besides color calibration. Moreover, no error-correction or optimization of feature extraction has been applied. Consequently, the quality of information could be further improved by pre-and post processing of the color data.

FUTURE WORK: DIGITAL MODELING CALIBRATION & ERROR CORRECTION

For error correction, highlight recognition could be used to data exclude highlights that exceed a certain intensity threshold relative to the average of the bit. This could increase the absolute and relative measurements of saturation and Theta.

Another prospect for improvements for pose estimation could include adjusted color interpretation. As described in the previous limitations, the CMY printing process may not fully reproduce the target HSI colors. Through integrating these limitations in the processing of color data, the measured colors data can be reinterpreted based on the reproducible color space rather than the target color space.

The normalization of the color space could improve the absolute measurements by correcting hue and saturation shifting relative to the reference color space. However, this only addresses the mapping of absolute color measurements to a respective Phi and Theta. The relative contrast between measurements remains unaffected, meaning the heterogeneous performance across the hues remains.



CHAPTER 4. DISCUSSION

The design exploration has examined fiducial Stimulus-Responsive materials as a potential solution space, Tangible User Interfaces and Extended Reality (XR). Colorful Bits was developed to showcase how mechanical and optical properties may be interlinked through material and structure to establish a connection between physical interaction and digital information.

Colorful Bits present a fiducial Stimulus-Responsive material for kinetic interaction that encodes polar-orientation relative to the observing viewpoint in color, which allows for pose estimation, deformation mapping and reconstruction physical form. Through allocation of mechanical properties at voxel-states, an approach is outlined to obtain applied forces from deformation data through the physics principle of superposition.

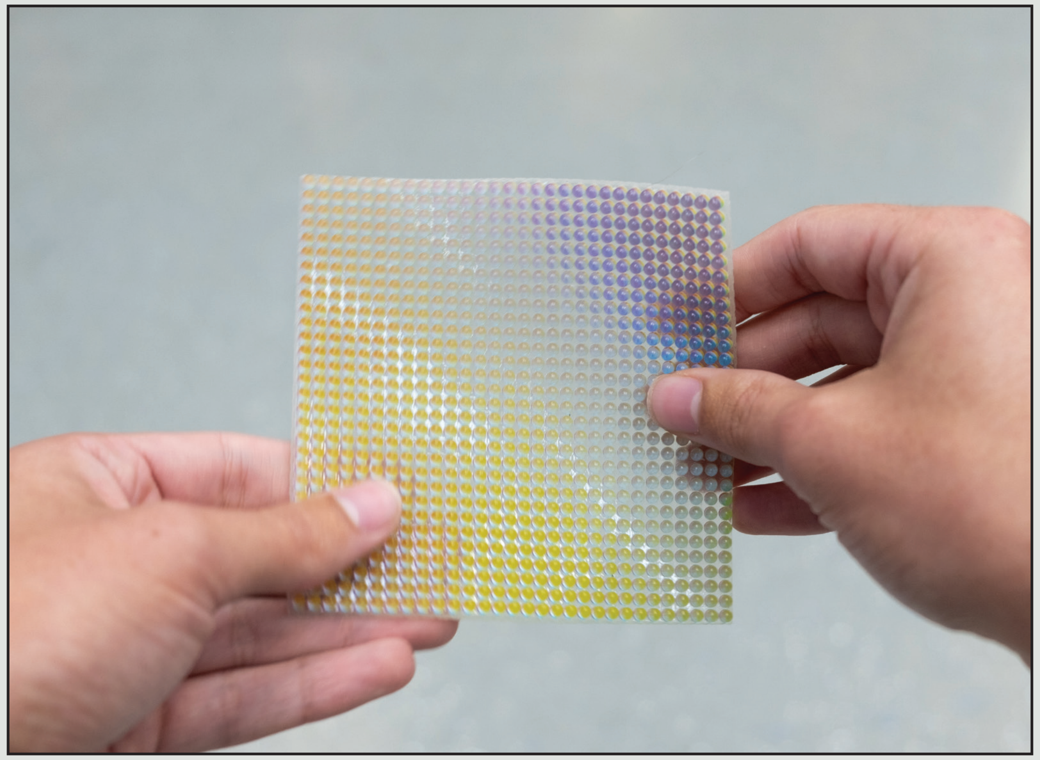
The Research through Design approach has both demonstrated the possibilities of Multi-Material Jetting (MMJ) to interconnect physical interactions with digital information, as well as the challenges and limitations that emerge within the process of materialization.

Through digital prototyping the theoretical working principle of Colorful Bits was evaluated. Digital renderings have demonstrated a strong relationship between color and polar orientation, where Phi and Theta vectors can be estimated from hue and saturation respectively. Furthermore, digital simulations of the color-vectorization protocol have demonstrated potential to reconstruct deformed surfaces. These insights support the feasibility of the working principle of the fiducial mechanism.

However, physical prototyping has revealed numerous challenges that emerge in the translation from digital models to physical material. Limitations imposed by the MMJ printing process involving color reproduction, geometric and optical distortions and poor surface quality have introduced inconsistencies with the predicted results. Absolute measurements of hue and saturation were significantly less accurate for the estimation of Phi and Theta. Consequently, the use of color for pose estimation is less effective than predicted, resulting in certain envisioned applications being unfeasible. For instance, current results are not suitable for tracking and alignment of virtual graphic overlays.

Although absolute measurements were skewed, other fiducial properties were maintained. A strong linear relationship was found between the viewing angles Phi and Theta and the relative change in hue and saturation. An alternative approach demonstrated how this feature could interconnect assigned mechanical properties with color responses. This enabled color measurements to serve as a fiducial reference for applied forces, allowing kinetic deformation to function as a physical user input for XR applications.

Ultimately, these results provide insight into the feasibility and viability of fiducial Stimulus-Response materials for Tangible User Interfaces. Colorful Bits showcases a novel approach for MMJ to facilitate a medium between tangible interaction and digital information. On the other hand, this thesis highlights how discrepancies between digital models and physical behavior limit the degree to which these concepts can be deployed for real world applications.



CHAPTER 5. CONCLUSION

This research has explored potential avenues for multi-material 3D printing to connect physical interaction and digital information within the scope of tangible interaction and Extended Reality (XR).

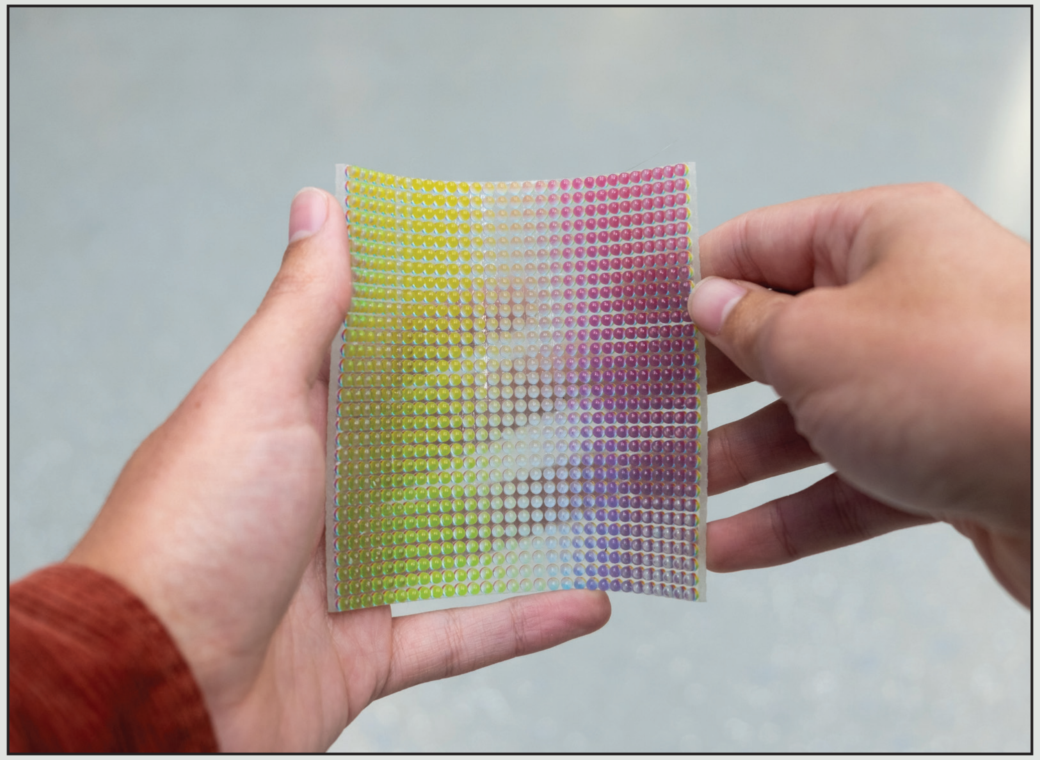
Based on opportunities discovered in the literature study, this thesis contributes to a potential solution space for Multi-Material Jetting (MMJ), where fiducial Stimulus-Responsive Materials are introduced as a focal point. Here, it was proposed that physical interactions and digital information can be interconnected through material and structure, outlining an embodied approach to Tangible User Interfaces (TUIs) for Human-Computer Interaction (HCI).

The potential opportunities and limitations of fiducial stimulus-responsive materials have been explored through a Research through Design (RtD) approach, which makes use of insights collected through the practice of design to better understand complex, future-focused design challenges.

Through this RtD approach, a demonstrator for fiducial stimulus-response materials to capture novel forms of interaction was designed: Colorful Bits. More specifically, the design showcases how MMJ's control over physical and optical properties can be linked in a novel way that allows for new forms of interaction to be captured through a fiducial approach.

Unique features of Colorful Bits include the ability to reconstruct deformed objects from color which allow for the interpretation of applied forces. The described relationship between physical form and digital information ultimately represents the envisioned bisynchronous nature of Radical Atoms (Ishii et al., 2012), where manipulations in physical form constitute dynamic transformation in digital models.

While Colorful Bits have focused on kinetic interactions, it is envisioned the concept of fiducial Stimulus-Responsive materials can be expanded to a broader field of physical and environmental stimuli. In literature, specific configurations of material and structure have been described that respond in a predictable manner to changes in temperature, light and moisture. Future work could explore the potential of MMJ to interconnect these properties to a fiducial response, highlighting MMJ as a potential platform for Extended Reality (XR) applications.



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APPENDIX

The Appendix to this work has been delivered separately and can be found in the TU Delft Education Repository.

COLORFUL BITS

EXPLORING STIMULUS-RESPONSIVE MATERIALS FOR TANGIBLE USER INTERFACES THROUGH MULTI-MATERIAL 3D PRINTING

INGO VERLSUIJS