From conventional to programmable matter systems: A review of design, materials, and technologies

Ahmed Amine Chafik, Jaafar Gaber, Souad Tayane, Mohamed Ennaji, Julien Bourgeois, Tarek El-Ghazawi

From conventional to programmable matter systems: A review of design, materials, and technologies

AHMED AMINE CHAFIK, FEMTO-ST/DISC/OMNI, UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UTBM, France
JAAFAR GABER, FEMTO-ST/DISC/OMNI, UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UTBM, France
SOUAD TAYANE, Laboratory of complex cyber physical systems LCCPS, Hassan II University of Casablanca, ENSAM, Morocco
MOHAMED ENNAJI, Laboratory of complex cyber physical systems LCCPS, Hassan II University of Casablanca, ENSAM, Morocco
JULIEN BOURGEOIS, FEMTO-ST/DISC/OMNI, UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UFC, France
TAREK EL-GHAZAWI, Department of Electrical and Computer Engineering, The George Washington University, USA

Programmable matter represents a system of elements whose interactions can be programmed for a certain behavior to emerge (e.g. color, shape) upon suitable commands (e.g., instruction, stimuli) by altering its physical characteristics. Even though its appellation may refer to a morphable physical material, programmable matter has been represented through several approaches from different perspectives (e.g., robots, smart materials) that seek the same objective: controllable behavior such as smart shape alteration. Researchers, engineers, and artists have expressed interest in the development of smart modeling clay as a novel alternative to conventional matter and classical means of prototyping. Henceforth, users will be able to do/undo/redo forms based on computed data (CAD) or interactions (sensors), which will help them unlock more features and increase the usefulness of their products. However, with such a promising technology, many challenges need to be addressed, as programmable matter relies on energy consumption, data transmission, stimuli control, and shape formation mechanisms. Furthermore, numerous devices and technologies are created under the name of programmable matter, which may pose ambiguity to the control strategies. In this study, we determine the basic operations required to form a shape, then review different realizations using the shape shifting ability of programmable matter, their fitting classifications, and finally discuss potential challenges.

Additional Keywords and Phrases: Programmable matter, Smart materials, Reconfigurable robots, Kinetic interface, Shape-Changing, Prototyping, Haptics

NOMENCLATURE

Authors' addresses: Ahmed Amine Chafik, FEMTO-ST/DISC/OMNI, UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UTBM, Belfort, 90000, France, ahmed.chafik@femto-st.fr; Jaafar Gaber, FEMTO-ST/DISC/OMNI, UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UTBM, Belfort, 90000, France, jaafar.gaber@utbm.fr; Souad Tayane, Laboratory of complex cyber physical systems LCCPS, Hassan II University of Casablanca, ENSAM, Casablanca, Morocco, souadtayane2013@gmail.com; Mohamed Ennaji, Laboratory of complex cyber physical systems LCCPS, Hassan II University of Casablanca, ENSAM, Casablanca, Morocco, ennaji.moh@gmail.com; Julien Bourgeois, FEMTO-ST/DISC/OMNI, UMR CNRS 6174, Univ. Bourgogne Franche-Comté, UFC, Montbéliard, France, julien.bourgeois@univ-fcomte.fr; Tarek El-Ghazawi, Department of Electrical and Computer Engineering, The George Washington University, Washington, DC 20052, USA, tarek@gwu.edu.

0360-0300/2024/2-ART $15.00
https://doi.org/XXXXXXX.XXXXXXX

PM : Programmable Matter
MRB : Modular Reconfigurable Block
MSRR : Modular Self-Reconfigurable Robot
MSRMR : Modular Self-Reconfigurable Morphing Robot
SMP : Shape Memory Polymer
SMA : Shape Memory Alloy
PMS : Propitient Matter System

ACM Reference Format:
Ahmed Amine Chafik, Jaafar Gaber, Souad Tayane, Mohamed Ennaji, Julien Bourgeois, and Tarek El-Ghazawi. 2024. **From conventional to programmable matter systems: A review of design, materials, and technologies**. *ACM Comput. Surv.* 1, 1 (February 2024), 30 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Shape creation has been a subject that has captured the interest of civilization since ancient times. During the Stone Age, primary materials such as stone were used as a design tool to shape other materials through basic intuitive operations: smashing and scraping. This was followed by the advent of metals and the advancement of metallurgical practices. Molding was introduced in Bronze and Iron Age as a reliable process to model, form, or deform materials. With the rise of automation and smart industries, research on this subject has resulted in more versatile materials and advanced means of rapid prototyping, offering complex, precise design operations.

Although the development of the prototyping process has come a long way, its technologies lack speed, reversibility, complexity, and interactivity [29] . Products are released after numerous iterations using conventional matter which is not easily reusable. Therefore, attention has been increasingly devoted to morphable matter [39] , that undergoes shape transformations in response to user input (e.g., instruction and stimuli). From an engineering perspective, this transition may simplify and ease the design process with the ability to embed programming directly into matter. This morphable matter is referred to as programmable matter.

With programmable matter, engineers can unlock more features to a point where products can increase their versatility and usefulness. These features depend on the approaches used to create the programmable matter. The earliest theoretical models aimed to design molecules embedded with the required instructions to spontaneously assemble into complex structures, under the name of “informed matter” [27]. Robots then replaced atoms and molecules to form complex shapes at the macro level using distributed algorithms [72] [3] [74]. Smart materials have also been used to represent programmable matter with their ability to sense and react to stimuli in a fast, automatic, reversible, controllable, and predictable manner [2]. The term "smart" refers also to their inclusion of sensors and actuators that functions in response to various environmental conditions or input signals. The use of smart materials can lead to more efficient and innovative technologies in fields like aerospace, medicine, and construction, as they enable materials and structures to adapt and optimize their performance in real-time, making them appear "smart" in their responses to changing conditions.

In this study, we will explore, review, and classify the technologies behind different hardware-based approaches that can be set to represent programmable matter, excluding theoretical and molecular approaches, even though the classification could potentially be applied to them. More precisely, we aim to offer a comprehensive resource for researchers, designers, and engineers who are seeking an introduction to the shape shifting ability of programmable matter and its different approaches. The established classification can serve to improve or design novel morphable device. Section 2 determines and evaluates the basic mechanics behind shape creation, and discusses

the possibility of dynamic shape alteration. Section 3 describes the historical evolution of programmable matter and determines a classification for several analyzed devices. Section 4 examines the challenges that limit the dynamic shape-shifting capabilities of different programmable matter approaches.

2 SHAPE CREATION

2.1 Shape creation parameters

The form of an object determines its main function as well as other features that may improve the usefulness of the product and user experience. Features such as shape and color for appearance, texture and heat for sensing, and mechanical structure for handling are obtained through manipulation of the parameters. These parameters concern the form to design (targeted shape), how to establish this form (operations and mechanisms), and what to model (type of matter).

To set up a shape, we must determine the complexity and feasibility of the geometrical aspect of the object. **Complexity** defines the combination or sequence of shape-creation mechanisms to perform the necessary operations. The complexity of a shape increases with the number or the variety of the mechanisms to be performed, such a parameter will serve to determine the best sequence and thus ease the shape creation process. **Feasibility,** on the other hand, evaluates whether a shape can be obtained through a certain sequence of operations or approximated using another sequence.

The execution of a sequence requires the selection of an appropriate technology that combines precision with speed. **Technology** varies the methods to proceed with a certain mechanism; that is, the same mechanism can be achieved through multiple technologies. For instance, cutting can be performed using a plasma torch, water jet, or laser. **Precision** is expressed as the accuracy of the motion mechanism. The use of smaller steps allows the rendering of smooth forms and realistic textures. **Speed** ensures the delivery of the right model when features (e.g., shape and functionality) are validated within a relatively small number of revisions.

Morphability and **recyclability** are two parameters that need to be considered when choosing the appropriate matter to shape. The former determines whether matter can be shaped easily using a sequence of mechanisms. With the latter, rendered matter can either be processed to create a new shape using an adequate recycling process, or rebuilt using reusable matter or structures such as modeling clay or interlocking blocks.

2.2 Shape alteration

Current manufactured objects are mostly made out of conventional matter, whose characteristics do not help overcome today's design or engineering limitations. Conventional matter, while essential for many applications, lacks embedded controlled behavioral features, limiting the adaptability and functionality of the objects created from it. An object cannot regenerate its original shape if needed and must be recycled through means that do not guarantee the rebuilding of matter with the same properties. Moreover, the emergence of nanotechnology has demonstrated that conventional matter systems are failure-prone [40] , inviting new ways to rethink actuation, energy consumption, and mechanical links. Faced with these challenges, researchers think that matter can do more by looking at how to enable or implement advanced features such as interactivity, to alter physical properties, and reversibility, to recover or heal from deformation.

Natural phenomena provide compelling evidence for the viability of shape modification, with certain systems possessing inherent properties that enable them to respond to specific energy sources. The pine cone exemplifies this capability, as it opens in dry conditions and closes in response to increased moisture levels, as depicted in Figure 1. Open and close are forms of Transform; see Table

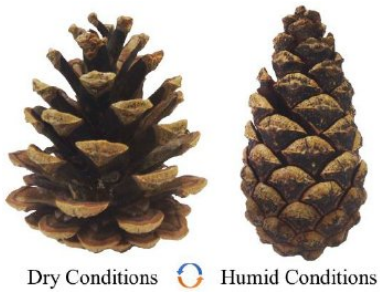

Fig. 1. Pine cone opens in dry conditions and closes when subjected to moisture. Opening and closing here are examples of "Transform" [2] .

1. Similarly, the heliotropic movements of the sunflower, which orients itself to track the solar trajectory, further illustrate this concept. These instances showcase the capacity of biological entities to oscillate between predefined configurational states to execute particular functions, a process biologically termed as nastic movements. Conversely, they may also demonstrate adaptability in reaction to the spatial orientation and intensity of environmental stimuli, a response known as tropism. The pine cone serves as one of myriad natural exemplars evidencing the potential for morphological transformation.

The objective within the domain of programmable matter is to engineer a novel form of integrated material that integrates sensors and responsive capabilities. This material is intended to either demonstrate pre-set behaviors or to adjust autonomously to the characteristics of environmental stimuli, including their position and intensity. Figure 2 provides a schematic representation of the functional logic inherent to this emergent class of material.

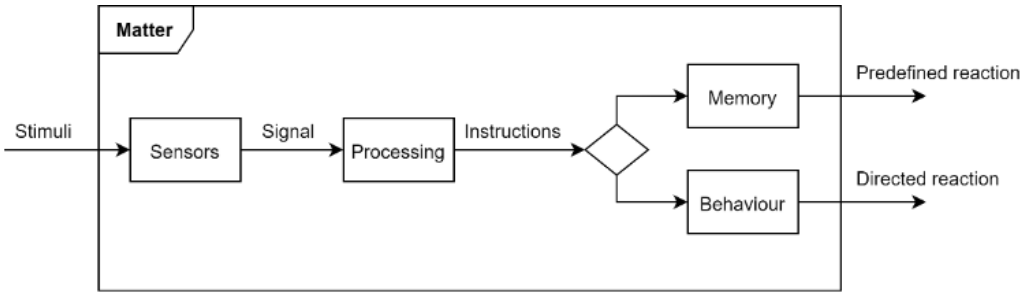

Fig. 2. Shape alteration mechanisms.

2.3 Basic Operations

An object or artifact is defined by the parameters that describe its physical composition and geometrical appearance. These parameters contribute to defining and improving the object utility. As they vary, features change and new quirks emerge. Taking as an example a tire, while changing its dimensions, material, and tread pattern, companies can create models to target a certain vehicle, seasons, and speed. The customization of these parameters implies that the matter undergoes basic shape-making operations, such as transformation, removal, and deformation.

Shape-making operations can be classified into two main categories: conservative and non conservative. These categories contain different types of operations that rely on the execution of certain mechanisms partially or totally on the matter. A mechanism is a means of performing shape-making operations on a given matter. For example, deform operations can be performed on Shape Memory Alloys (SMAs)—metals that can be deformed and then return to their pre-deformed shape upon heating—through kinetic maneuvers or through stimuli control, such as the application of heat (see Table 1).

The conservative category aims to alter the appearance of the base model to target a shape while respecting the initial volume and quantity of matter. Hence, shapes are made of either singular or a combination of fold, expand, or deform operations. On the contrary, the non conservative category tends to make shapes following operations that change the volume and/or type of matter. In this case, shapes are generated from the add, remove, and transform operations.

Add uses an assembling and merging mechanism to create shapes by gathering a group of elements with certain physical and geometrical characteristics. Assemble serves as a mechanism to attach separate elements using the reaction of chemical substances (e.g., glue), mechanical fasteners (e.g., rivets, bolts), or interlocking shapes (e.g., Lego). On the other hand, Merge aims to combine single elements into one entity, either by mixing matter (e.g., modeling clay) or by changing its physical nature.

Remove takes off a fraction of the matter from a well-defined position to form complex shapes, add texture, or cavities. This operation is achieved using scrape or reaction mechanisms. With the Scrape mechanism, matter is removed by applying friction to the surface using a shaped tool. However, Reaction removes matter through its interaction with an external substance (e.g., water or fire), which changes the current state of the matter to another (e.g., from solid to gas). Several parameters must be considered when an object is submitted to Remove operations concerning the tool and applied substance. The sharpness, form, and feed rate of the tool are the key parameters for creating precise and complex shapes.

Transform evolves matter from one state to another to make a change in form, nature, or appearance. This evolution is achieved via Solidification and Fusion mechanisms. The hardening process is performed by changing the physical parameters of matter (e.g., temperature) or by reacting to an external element (e.g., resin hardening with UV). Shapes are determined by the form of their container or by the pattern of the hardening element (e.g., SLA 3D printers). On the other hand, the fusion mechanism causes an object to semi-melt or fully melt through intense heat or reaction to an external element. Hence, matter can be easily shaped with the help of a container or through free modeling. The desired form can be permanently maintained through active passive cooling.

Deform renders shapes using mechanisms that imply modeling, squeezing, and twisting matter manually or using proper tools. For example, forms such as curves, cavities, straight edges, and sharp angles can be obtained by modeling. Squeeze is another mechanism that helps to eliminate internal cavities and renders sub 3D shapes from matter via the application of firm pressure using external surfaces (e.g., hands). Twist serves to change the orientation of the matter, which creates motifs and shapes by rotating a sub-shape around a stationary point. Shapes can also be made out of actuation, specifically on a soft thin sheet, using an array of actuators, or by enabling a certain stimulus if a stimuli-sensitive matter is used.

Expand is achieved by enlarging and stretching the matter through traction or inflation. These mechanisms require a particular geometrical and physical aspect of matter. Semi-closed soft objects or flat soft sheets can be inflated into basic shapes (e.g., spheres) or complex shapes by adapting them to an external surface (e.g., mold). The evolution of the stretched form relies on Poisson's ratio effect. With a positive ratio, the matter expands in one direction and thins in the other; however,

Table 1. Summary of shape creation operations.

	Operation	Mechanism		Involved matter
Non conservative	Add	Assemble		Solid matter
		Merge		Solid matter Liquid matter
	Remove	Scrape		Solid matter
		Reaction		Solid matter
	Transform	Solidification		Liquid matter
		Fusion		Solid matter
Conservative	Deform	Kinetic	Twist, Squeeze Model Actuate	Solid matter
		Stimuli	Heat	SMA MSMA SMP
			Current	SMA MSMA
			Electric field	Piezoelectric Electrostrictive
			Magnetic field	MSMA Ferrofluid
	Expand	Kinetic	Inflate	Solid matter
			Traction	Solid matter
		Stimuli	Heat	SMP
			Electric field	EAP Electrostrictive
	Fold	Kinetic	Origami	Surface
			3D Fold	Surface
			Random	Surface
		Stimuli	Heat	SMP SMA MSMA
			Electric field	Electrostrictive EAP

the structure expands and thickens in the case of a negative Poisson ratio. Auxetics [37] is a good example, as they expand when stretched and thins when compressed.

Fold operation requires making local bending of the matter manually or by using a hinge, according to the folding pattern. The complexity of the rendered model relies mostly on the difficulty of the folding pattern. With this technique, one can create lightweight prismatic shapes, origami, and even filled objects (e.g., ball paper).

3 PROGRAMMABLE MATTER

Programmable matter is conceptualized as a system comprising numerous discrete elements, capable of collectively altering their physical properties in a controllable fashion. Upon receiving a user

command or through autonomous sensing, these elements can be programmed to modify attributes such as shape, density, color, and conductivity, thereby adapting their functionality to a variety of scenarios and applications.

Lehn [63] developed the earliest model based on supra molecular behavior, which allowed the design of molecules that spontaneously assemble into complex shapes through principles of self-organization. These molecules can store information, recognize other molecules, and form what Lehn labeled as “informed matter” [27].

The term ‘programmable matter’ was originally introduced by Toffoli and Margolus [63] in 1991 to refer to a fine-grained computing node distributed throughout the space. These nodes communicate through nearest neighbor interactions to shift between multiple formations as the authors state:

> *"The same cubic meter of machinery can become a wind tunnel at one moment, a polymer soup at the next; it can model a sea of fermions, a genetic pool, or an epidemiology experiment at the flick of a console key"*

Fig. 3. Different prototypes of planar catoms (V2 to V6) [retrieved from: http://www.cs.cmu.edu/~claytronics/hardware/planar-stuff/catomelectromagneticmodules.pdf]

With the development of nano-and self-assembly technologies, several creations have been established based on the approach addressed by Toffoli and Margolus using robots. The claytronics project [25], one of its major contributions, defines catoms (Figure 3) as individual agents (robots) that move in three dimensions in relation to their neighbors using adherence mechanisms to replicate a physical artifact. However, the formation of catoms only replicates synthetic reality, without any sensory augmentation.

Computation is always performed using physical processes (matter) as a support for transmitting or processing information. However, we can also revert this logic to use computation to perform physical processes, as long as the involved phenomena are reversible. In this way, we can approach programmable matter from another perspective, using computation to trigger the behavioral capabilities of physical materials [5, 12].

Ranging from conventional to smart, materials can be physically programmed to sense fluctuations in the environment and behave according to their embedded features. For instance, wood structures can either swell or shrink and deform, depending on their geometrical structure, when exposed to humidity changes. Smart materials such as shape memory alloys [38] combined with magnets have been used to develop programmable origami that folds to form shapes (Figure 4) [20]. Programming materials enable the design of complex robotic mechanisms that would otherwise be difficult to build, bulky, energy-inefficient, and prone to failure.

Investigations into programmable matter have diverged into three principal research trajectories, each with its distinct disciplinary focus and methodological approaches. The first trajectory

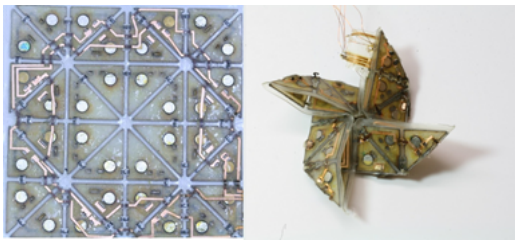

Fig. 4. Programmable flat sheet folds into windmill shape [20]

emerges from the field of robotics, where programmable matter is envisaged as an ensemble of discrete robotic entities or modular constructs capable of collective behavior. The second trajectory is rooted in mechanical engineering, emphasizing the exploration of actuation mechanisms and the resultant material deformations. The third trajectory transcends disciplinary boundaries, amalgamating expertise from computer science, mechatronics, and materials science to foster a holistic understanding of programmable matter systems.

In the subsequent sections, we present an introduction to each research direction by outlining a selection of its methodologies. This is succeeded by an analytical evaluation and classification of these approaches, based on their respective advantages and limitations.

3.1 Collection of modular components

3.1.1 Modular Component types. Programmable matter is represented by the geometrical formation of modular components that have the ability to move or assemble themselves on command. Shape is mainly rendered by Add and Form/Deform operations out of components capable of scaling to complex and larger formations. The component can move locally to change its global shape according to a received instruction. This self-reconfigurable behavior can be modeled either through a multi-agent system using robots or through individual control using blocks. In this approach, features such as self-configuration and self-healing are achieved [28].

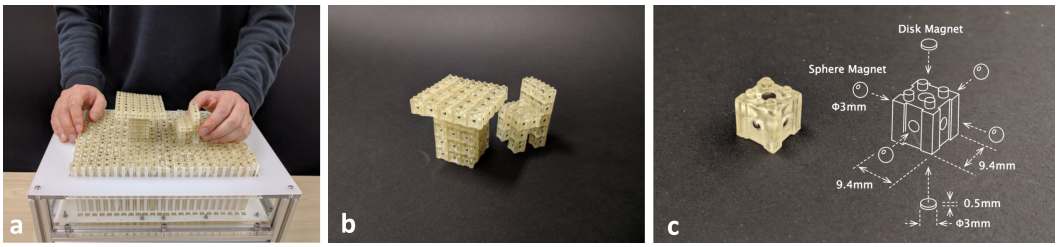

Fig. 5. a) Construction of chair and table model using parallel leverage system. b) the constructed model. c) Dynablock's structure [58]

Modular reconfigurable blocks (MRB) are objects equipped with an interlocking mechanism and have no processing ability. They can latch into each other to form a shape, but their behavior is driven by an external constraint. Hence, they are power efficient and yet delicate to control precisely. Devices, such as Dynablocks [58] follow the same pattern, making constructible shapes out of the magnetic block lattice (Figure 5). Formations are made using a system of parallel assemblers (array of 24×16 linear actuators) that moves to connect or disconnect blocks out of the lattice. Dynablocks can simultaneously construct multiple models using a parallel leverage system. Constructed objects

are graspable and can be disassembled to reconstruct a new formation. Kinetic Blocks [55] used a pin-based shape display to freely move, roll, assemble, and disassemble the magnetic cubes. Unlike Dynablock, the user determines and places the required cubes and then proceeds to assembly using a pin-based shape display.

Modular self-reconfigurable robots (MSRR) can build physical objects through collaborative construction. They are embedded in sensing, processing, and actuating abilities that favor shape formation. Their collaborative construction is governed by distributed computations, which are performed in a communication network. Goldstein et al. [17] developed modular robots (catoms) that can move in three dimensions relative to other catoms. Each catom is equipped with a processing unit, energy store, network, sensors, and actuators. However, as catom shapes present constraints to build formations, Piranda and Bourgeois designed a quasi-spherical structure [51] that allows smooth rollability and advanced organization (more latching facet).

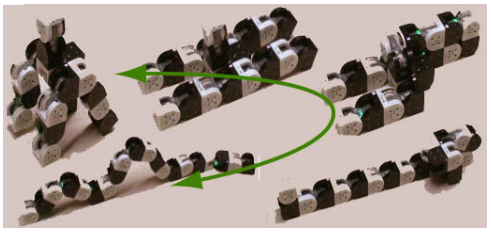

Fig. 6. M-Tran metamorphosis from a 4-legged walker to snake shape [42]

Modular self-reconfigurable morphable robots (MSRMR) are collaborative units that exhibit both self-reconfiguration and shape-shifting abilities. Self-reconfiguration refers to the robots' capability to autonomously change their physical configurations, enabling them to adapt to various tasks or environments dynamically. Shape-shifting ability, on the other hand, allows these robots to alter their shapes, facilitating advanced motion, expanding latching possibilities, and achieving complex shapes. Robotic modules such as CKbot [49] and M-Tran [42] are composed of two semi-cylindrical boxes linked by a base. They used a magnet as the latching mechanism to create a chain-like structure. This structure can move using embedded servomotors to form complex dynamic shapes or to stimulate a robotic configuration such as the movement of the leg (Figure 6). M-Tran modules can move locally using shape memory alloy springs to unlatch, servomotors to rotate, and finally magnets to latch. Piranda and Bourgeois proposed datom [52] as a morphing catom that contracts and deploys facets using a shape memory alloy. This shape-shifting ability allows not only performing advanced motion, but also ensuring that the robot has reached its final position (optimized rolling).

3.1.2 Reconfiguration architecture and methods. Parameters such as robot uniformity, architecture, and assembly method affect the precision and efficiency of constructing formations. Heterogeneous components such as M-TRAN III [32] could either represent a passive form of the robot using the same shape with no processing abilities, which simplifies computation, saves energy, and costs less. Alternatively, different shapes can be used to create complex formations. Homogeneous components are used for the uniform coherent models.

Depending on their shapes and features, the modular components (MSRR and MSRMR) are assembled into different architectures (Figure 7). Lattice is the most common architecture; it represents a series of robots arranged in distinct patterns inspired by atomic structures, such as cubic-centered lattices. Although the lattice structure provides a simple platform, the elements in

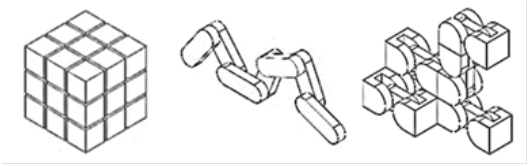

Fig. 7. Main reconfiguration architectures a) Lattice-style b) Chain-style c) Hybrid.

this structure cannot perform random reconfiguration, which refers to the ability to autonomously rearrange their positions to reach a desired configuration without following a predetermined sequence. Additionally, position feedback control is not required in this configuration, since their movement is defined in a coordinate system, meaning that their positions are determined directly by coordinate inputs rather than needing continuous feedback adjustments. Catom [51] ATRON [24] and M-blocks [54] fit in this architecture. The chain architecture represents serially connected elements that are capable of making snake-like shapes. Relying on actuators, robots can move to change formations or perform robotic functions. In this case, position feedback is necessary to control the positions of the modules. Reconfiguration of robots such as Polybot [43], YaMoR [41], LineFORM [43] and CONRO [4] is based on a chain architecture. SMORES [10] and M-TRAN III use a hybrid architecture that combines the properties of lattice and chain-style architectures to establish geometric configurations.

The formations established through self-reconfiguration are based on stochastic or deterministic methods. The stochastic method employs random disturbances in the environment to bring the modules into contact [70]. For each random contact, the modules decide whether to accept or reject the bond. The reliance on probabilistic disturbance favors the use of passive modules [71, 75]. Therefore, the complexity and size of the module were reduced, and the formation time was probabilistic. The deterministic method relies on computational capabilities to transfer modules from one position to another [62]. The position of the module was known at every stage of the reconfiguration process. Hence, modules require feedback control and an advanced actuation system that allows them to coordinate with their neighbors to attain the desired formations [51].

3.2 Kinetic interface

In this approach, programmable matter is represented as a morphable interface whose shape is determined from the actuation pattern. Deformation is generated by a set of actuators arranged in a defined configuration to replicate the shapes, deformation, or inflation of matter. Shapes are made out of Expand, Fold and Transform/Deform operations, which can be performed through different types of actuations. The interface architecture allows the integration of numerous features to display 2.5D shapes, which refer to representations characterized by complete two-dimensional coordinates and only positive z-coordinates. This is achieved through soft-to-device interaction. Additionally, it enables manual adjustment of actuators to correct shapes and incorporates haptic feedback such as vibrations through device-to-soft interaction.

3.2.1 Actuated interface. Matter can be shaped and represented through a system of patterned actuators that perform oriented deformations. Hence, we defined four subcategories for the actuated interface: axial, lateral, radial actuation, and articulation.

Normal actuation : Parallel leverage system. devices using a parallel leverage system are capable of making shapes out of the movement of individual elements. The local position of these moving

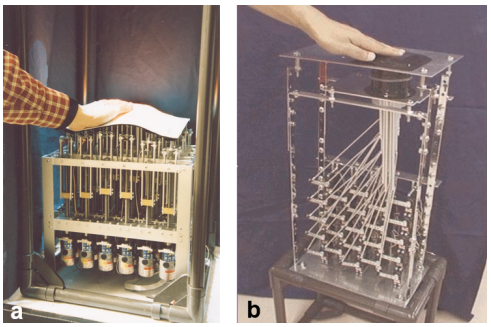

Fig. 8. Device overview: a) FEELEX rely on lead screw mechanism to deform flexible covering sheet b) FEELEX 2 uses crank rod instead, to reduce the distance between the actuating rods, thus increasing the precision [22].

elements determines the global shape, which is affected by several factors, namely the array configuration, size, number, travel, presence, and type of covering material.

Deformation is performed using actuators such as linear motors (e.g., potentiometers), which provide position feedback in addition to linear movement. This technology is used in devices such as Inform [14], Emerge [59], Materiable [44] and Relief [35], in which the potentiometer acts not only as an actuator to make deformations but also as a sensor so that the user can establish changes on the 3D model directly from the platform.

Motors coupled with motion conversion mechanisms are designed to deliver deformation under different stroke, torque, and speed settings. FEELEX [22] and Shapeshift [56], use a lead screw to deliver movements with high precision and low speed. The successor FEELEX 2 was designed to trade off bulkiness over resolution using a crank shift mechanism (Figure 8). Pulley cables can also be used as conversion mechanisms in scalable interactive platforms [66].

Fluid actuators rely on the fluid flow in chambered tubes or cylinders for actuation. They can lift heavy weight at slow speeds and apply high torque without the need for a gearing system, and they are suitable for linear actuation. Models built with cylinders target shape-changing interfaces on a larger scale, which can be integrated in architectural design. The Gemotion screen [26] combines a potentiometer with pneumatic cylinders to create a 2.5D precise shape over an interactive flexible screen, Aegis Hyposurface [18]; however, it uses only pistons to raise a connected metallic meshed surface. Nakashige et al. [46] proposed two prototypes that use vacuum/compression to move pins, which are later fixed in position by using a low-melting metal point. Therefore, constant heating is required to dynamically move the pins of the interface.

Smart materials (e.g., shape memory alloy SMA) have the ability to retain a certain behavior over a programming process, and the behavior is then exhibited when the matter is submitted to a stimulus. Smart materials are usually used as actuators due to their morphability and flexibility, which contribute to simplifying the complexity of the actuating mechanism and, thereby, the size of the device. Lumen [53] relied on the contraction of the SMA string to actuate the LED array block, 3D Form Display with SMA v0, v1 [48] and Pop Up! [47] used SMA springs as they provide high travel, and other interfaces [61] used SMA wires or SMA leaf strings [45] to actuate a soft rubbery surface.

Lateral actuation : in-surface deformation. Devices in this category use actuators attached to the surface to create a NURBS-like shape while they expand or contract (Figure 9). This requires soft and lightweight actuators that do not restrict deformation to reach the target form. The majority of the developed solutions use smart materials, as they have plenty of room for customization.

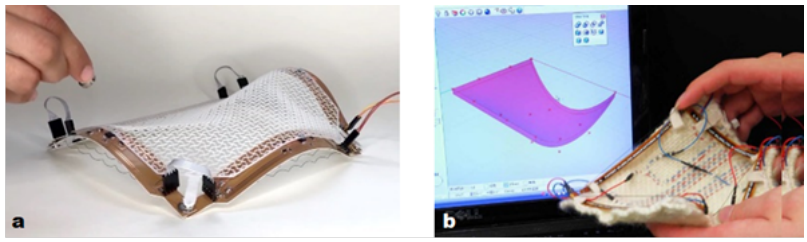

Fig. 9. Device overview: a) NURBSforms's modules react to change in magnetic field to curve, they are linked to an auxetic shape which does not limit the movement [60] b) SMAAD is embedded with SMA wires and flex sensors to bridge virtual and physical models [69]

Shape memory materials (alloys and polymers) are widely used because of their affordability and versatility.

Bosu [50] used soft materials knitted with shape memory alloy wires to create transformable structures that can record and play back motion along with prototyping. The bending sensors are embedded in these structures to monitor the deformation rates in each module. These modules can be heterogeneous and move independently to form a global shape. The knitting pattern determines the form of the generated shape.

NURBS forms [60] are modular shape-changing interfaces that rely on the bending of a self-contained lightweight flexible module to render NURBS shapes. These modules are interchangeable and represent the edge of a variable curvature when joined together. The variable curvature is then covered with an auxetic mesh. The modules are composed of an elastic PCB, where the micro controller, MOSFET, and hall-effect sensor are soldered to control the shape memory alloy wires attached under. This composition allows the curvature shape to be performed when heated and flat when cooled down through a Hall effect sensor.

Surflex [7] is another model that creates curvatures using a grid of four SMA springs implemented on both sides of a foam surface. It can produce up to 2^8 shapes by contracting a combination of SMA springs in the grid system through the Joule effect, with the ability of the foam to passively return flat. On the other hand, SMAAD [69] uses the same approach but with SMA wires coupled with bending sensors to ensure a reversible prototyping process (from object to 3D file).

Radial actuation. Radial actuation devices rely on mechanisms that allow the deformation and expansion of the external surface of an object. This category suits empty soft objects and delivers an inflatable shape. Devices such as AMPHORM [33] use radial motorized actuation to shape a cylinder. The shape is defined by five vertically stacked elements using a Hoberman sphere-inspired mechanism that can dynamically change its radius. This mechanism is composed of 16 aluminum scissor joints motorized by a servomotor that actuates super-elastic platinum-catalyzed silicone.

Articulated actuation: built-in hinge. Similar to the second category, actuators are embedded directly into the surface as hinges to perform local articulation. This mechanism allows for the replication of surfaces that cannot be achieved through other types of actuations. This is possible by combing the local deformation induced by a pattern of articulations bent at various angles. The precise aspect of the surface can be obtained by increasing the number of articulations (Figure 10).

This architecture is adopted in deployable shapes such as origami, which requires the use of mechanisms based on fold operations to render a shape. Programmable matter by folding [20] uses a similar architecture to create origami-like shapes, such as paper airplanes and boats. It is a self-folding sheet that integrates SMA actuators and magnets such that it can be folded and

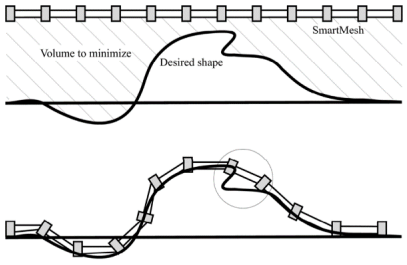

Fig. 10. Approximation of a surface using an articulated structure (low resolution error is marked with a circle) [73]

maintained into a certain shape. Programmable matter by folding can have different SMA actuator patterns, allowing to render various outputs. Other devices [21] use a pattern of triangular rigid tiles linked by foldable joints. The foldable joints were made of an SMA hinge, heater, and strain gauge, which allowed the SMA to be deformed at a precise angle.

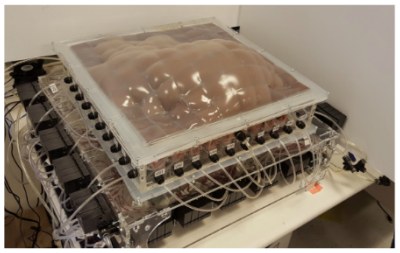

Fig. 11. Haptic Jamming's silicon cells are individually inflated to represent a down-scaled rabbit shape [57]

3.2.2 Inflatable interface. In this classification, programmable matter is represented by the expansion of inflatable cells made of soft materials. The disposition of these cells allows multiple shapes and complex movements. Inflation is achieved through the pressure applied by the flow of fluids in a patterned cell, which can be mixed with other particles to add texture or to stimulate haptic feedback. The majority of the developed solutions rely on pneumatic force because they use air that is compressible, lightweight, easy to collect, and controllable.

PneUI [73] is a pneumatically actuated soft material generated through a predefined structure with a computationally controllable shape. It is made of a fabric-elastomer composite that allows the fabrication of patterns through rapid digital fabrication methods (e.g., laser cutting) rather than making customized molds. The PneUI is embedded with sensing capabilities that monitor global structural changes (height, side, and diagonal bending) using copper electrodes. Local surface deformation is also sensed through the resistance of the liquid metal, which changes in response to deformation.

Haptic jamming [57] is a silicon membrane consisting of an array of hallow-deformable thin cells filled with coffee grounds. This architecture allows the display of 2.5 D shapes via air pressure, and adds variable stiffness using particle jamming. Cells are selectively solidified when air is vacuumed jamming coffee grounds together, which selectively solidify in the chosen cells. Various combinations and sequences of air pressure and vacuum created shapes with different sizes and levels of stiffness (Figure 11).

Volflex [23] is composed of a group of air balloons arranged in a lattice architecture to create 3D shapes embedded with haptic feedback. These balloons were controlled using an air cylinder equipped with a pressure sensor to detect the deformation force. Based on the computational data, the device delivers 3D shapes with the ability to undo previous operations using sensors and balloon controllers.

3.3 Programmable materials

Matter is generally utilized as a means of transmitting and processing information that is governed by physical laws. Rearranging matter in architectures led to computation being approached differently to achieve power, speed, and efficiency. Rolf Landauer coined the slogan "information is physical" [34] to represent information as a physical substrate.

By reversing the past definition, we can use computation to control the physical process that governs the behavior of matter. Consequently, triggering a change in the physical law can cause matter to alter its characteristics (e.g., shape and color) or to interact with its neighbors to render geometric configurations. This supposes matter to be embedded with at least one of the following means: sensors, actuators, memory, and behavior (i.e., program).

Viewing computation as a physical process suggests another approach to programmable matter, which we define as Propitient matter. The word propitient comes from the Latin terms "propitius," which refers to favorable, with the suffix "-ent" derived from the term emergent behavior. Propitient matter refers to the ability of materials to cope with environmental conditions, relying on internal behaviors that can be memorized and controlled depending on the nature and intensity of the triggering stimuli.

These materials are classified into three categories: conventional, smart, and propitient. The main difference between them is their limitations in terms of programmable forms and shapes. Programmable matter based on conventional materials target well-defined forms, such as from flat to curved forms. PMs based on smart materials can manifest limited shapeshifting abilities in response to a certain simuli. PMs based on Propitient matters can target a non limited number of forms or shapes, and thus exhibit an emergence feature.

3.3.1 Conventional materials. Conventional materials are widely used due to their affordance, availability, and static properties. They are not embedded with information-processing abilities; instead, they can change their properties based on user inputs.

Wood is a good example, as it swells and shrinks due to moisture intake and loss. but it is still hard to control precisely. Correa et al. [8] introduced a method for programming wood structures to customize their behavior, sensing, and actuation capabilities by using multimaterial printing (Figure 12). This process relies on printing custom wood fibers using a synthetic mixture of wood and polymers.

Fig. 12. Printed wood composite that self-transforms from flat to curved [8].

This process shows that it is possible to program conventional materials if they are structured in a particular architecture and then activated with energy. Skylar Tibbits thinks that

"Every material has some property that allows it to respond to an energy source, which points to how you can activate the transformation"

3.3.2 Smart materials. Smart materials are different from conventional materials as they are capable of changing not only their physical properties on command but also embedded with information processing and storage abilities. The word "smart" refers to the fact that they can replicate the same functionalities of a complex conventional system, using compact and simplified models. They can convert absorbed energy to perform programmed changes in their physical properties, such as color, shape, conductivity, and transparency. This phenomenon can be reversible for some materials, as it can be triggered by their behavior to generate stimuli (e.g., piezoelectric, thermoelectric). Smart materials can be identified and classified from different perspectives depending on their nature, structure, response, or triggering stimuli. Esther et al. [13] proposed a classification system that gathered most of the previous characteristics (Figure 13).

Addington et al. [1] defined 5 characteristics to describe the exhibited behaviors by systems and element that are classified under "Smart Materials" category:

- **Immediacy**, as their behavior is exhibited as soon as the stimuli are triggered.
- **Transiency**, as they respond to more than one environmental state
- **Selectivity**, as their behavior can be described and tracked trough mathematical models.
- **Self-actuation**, as their reaction is generated from embedded intelligence and programming.
- **Directness,** as the material reacts not only to the intensity of the induced stimuli, but also to its position or direction, which provokes local changes in properties.

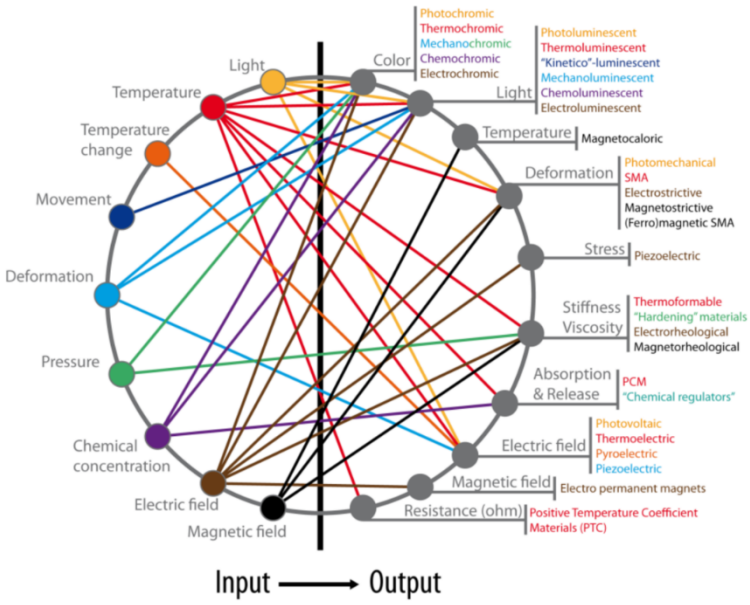

Fig. 13. Smart Materials classification based on behavior [13]

In the following, we define a classification of smart materials based mainly on their deformation mobility for static or dynamic shaping. This classification refers to the dimension numbers of the coordinate systems, which are 2D, 2.5D, and 3D shapes.

2D Shapes: Liquids and gels. Liquids and gels are widely used to render 2D shapes to their negligible thickness and mobility. Moreover, they can be mixed with other particles or substances to embed features that customize their control experience. In the literature, we distinguish between two types of smart liquid materials: **electrorheological** and **magnetorheological** [2]. Both can change their characteristics (form, rigidity, and viscosity) in response to a physical stimulus (electrical or magnetic). The former becomes viscous when an electric current or field is applied, whereas the latter reacts in the same way when subjected to a magnetic field.

The objective is to drive liquids using the proper stimulus over an actuated board to create static or dynamic shapes. The board contains cells arranged in a given distribution, and each cell acts as a trigger (anode/cathode for electrorheological, and electromagnet for magnetorheological) that can either attract or repel matter. This architecture allows the delivery of shapes, mainly through unify, divide, translate and deform operations (Figure 14). Blobs can move and transform based on the nature and pattern of stimuli (Figure 14). Blobs, which are cells without locomotive limbs, use their veins to move forward. By contracting, they push the liquid that flows inside against the edge of their membrane, and then contract to get that liquid back to move forward. They move forward in two steps and back in one step (Figure 14). Blobs have been a source of inspiration for the implementation of smart materials.

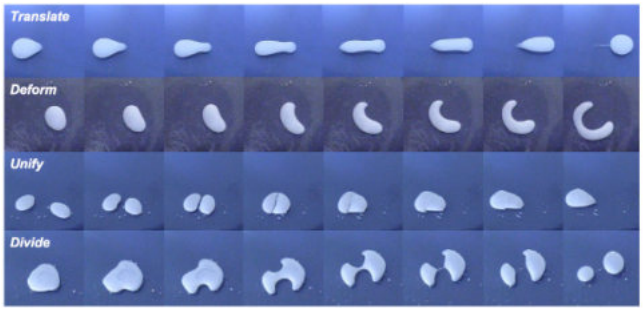

Fig. 14. Blobs can move and transform, based on stimuli nature and pattern [68]

Magnetorheological:

Snoil [15] relies on a grid of small electromagnets to precisely control the movement of ferrofluids by activating a certain sequence. The actuation performed is binary (On/Off) and is achieved by a built-in tilt sensor or trough software instructions. The display is able to render animated pixel art and text and can simulate a snake game.

Gels such as pBlob [68] (Programmable Blob) used the same principle, adding poppy oil to reduce the friction caused by the attraction-repulsion of honeycomb electromagnets. These gels are viscous and malleable, which allows them to act like a metaball with a slow latency as they float and move smoothly in an oil container. In contrast to Snoil, pBlob is controlled through PWM actuation, which allows for smooth transitions and better transformation.

Wakita et Nakano [67] introduced a Blob Manipulation with a new interaction technique, in which a stirring rod is used as an input tool to perform transformations. The blob is actuated according to rod movements, which are detected by a depth camera and then converted to magnetic units to perform and maintain the transformation. Blob Manipulation uses a magnetic unit instead of electromagnets, which is composed of neodymium magnet contained in a pom rod, driven by a DC Motor.

Electrorheological:

2D shapes can also be created using electrorheological fluids such as programmable liquid matter [64]. It consists of a highly conductive liquid metal immersed in an electrolyte solution that flows and grips electrodes with a certain charge. The architecture of the controlling platform resembles that of magnetorheological fluids that use electrodes instead of electromagnets. It is composed of a 7×7 electrode array with an integrated image-tracking system to easily control the liquid. Shapes can be drawn manually or through camera control by setting the platform to anodes and then the corresponding sequence of electrodes to cathodes, which results in liquid moving to the desired form.

2.5D Shapes: Polymers, Composites and Ferrofluids. In addition to thin films, the shape-shifting capabilities of ferrofluids can also be categorized and expressed in a 2.5 Dimensions system. The term 2.5D refers to shapes in which a pair of (x, y) coordinates has only one z-value, which can be obtained through unidirectional deformation. This deformation is induced through stimuli control (e.g., ferrofluids) or memory effects (e.g., polymers).

Ferrofluids:

Ferrofluid's earliest use in design was established by Kodama [30] to create organic ephemeral aesthetic shapes. The surfaces of these shapes formed a pattern of spikes that were directed by the lines of the magnetic field. Visual output changes dynamically according to the position and power of the electromagnets. The first application was **Protrude, flow** [19] which uses six electromagnets (five as base and one above) along with sensing capabilities (sound lever meter and microphone) to interact and produce shapes.

Linetic [31] inherited the common architecture of most ferrofluid displays, which are a set of electromagnets arranged in a 4×5 grid and a pool of ferromagnetic fluid. Moreover, it integrates sensing and haptic capabilities using an array of Hall effect sensors, which offers the ability to measure the magnetic field and thus interact with matter using a magnetic ring. Linetic can form transitional button-like shapes, along with sound and haptic feedback (ring vibration).

Polymers and Composites:

Polymers are well known for their unique properties, which can be adjusted to create soft and rubbery models or hard and tough models. Some of these polymers integrate intelligence, as they are embedded with sensors, actuators, behavior, and memory.

Shape memory polymers (SMP) [36] can change their shape to two forms when subjected to an external stimulus (e.g., light or heat). They are easier to program and can perform complex geometrical changes as they apply larger strains (400%). SMPs can be modified to either improve their properties or embed additional features (stimuli) by mixing materials (e.g., elastomer and SMP) to form a composite (SMPC). Tolley et al. [65] designed a self-folding origami using SMPC, which consisted of a layer of SMP placed between two patterned layers of paper. Contraction of the heated SMP layer causes the system to transform according to the folding patterns.

3D Shapes. Smart malleable materials, such as SMP and magnetic putty, introduce a new approach to model 3D objects out of a modeling clay, as they can be trained, programmed, or directed to form a certain shape in different directions. Objects can be made or printed in a certain form factor (shape and layout size) and then programmed to perform a certain behavior each time. Grassi et al. [19] introduced multi material liquid printing to develop shape-shifting thin-film composites using a combination of materials, and Ge et al. [16] developed a new multi material printing method that creates complex structures with shape-memory behavior that can be programmed after the curing process to develop programmable grippers (Figure 15).

3.3.3 Propitient Matter systems (PMS). Although conventional and smart materials exhibit controllable behaviors and features that fit in programmable matter, their shape-shifting capabilities are

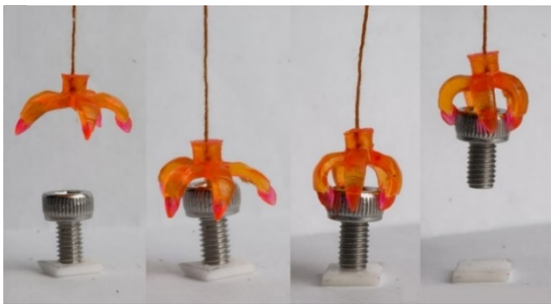

Fig. 15. 3D SM Printed grippers holds weight (bolt) [16]

limited. Current materials offer the ability to store limited behaviors that must be programmed using time-and energy-consuming training routines. Moreover, materials such as ferrofluids are stimuli-directed and require stimuli to be always applied to preserve the current shape. Therefore, we introduce propitient matter as a novel approach for addressing programmable matter. The word propitient comes from the Latin terms "propitius" with the suffix "-ence" from the term emergence. Thus, the term Propitient designates the ability of a system of elements to cope with environmental conditions by relying on internal behaviors that can be memorized and controlled depending on the nature and intensity of the triggering stimuli. Furthermore, propitience expresses emergence behavior; therefore, the system can deliver numerous shapes according to user inputs.

The approach to implementing a PMS can be tackled from two different perspectives. The first consists of creating a system of elements that can be controlled independently, so that the combination of their local deformation will render a global shape; in this case, the system can be represented by a composite or an assembly of smart and conventional materials. Ennaji et al. [11] developed a composite membrane that used woven SMA fibers covered in a thin polymer film, where the shapes are made out of SMA deformation using the Joule effect or local heating. The polymer film preserves the SMA temperature and smoothens the rendered shape. This device can also be used as a dynamic Braille screen by creating bumps in their specific positions (Figure 16). The latter consists of creating a meta material that can exhibit multiple transformations in response to input commands.

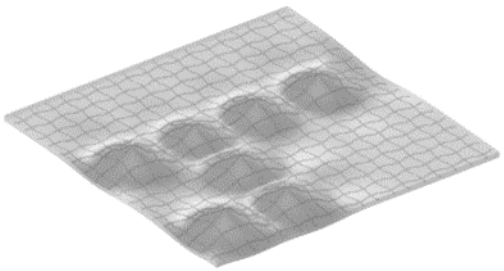

Fig. 16. Membrane can be used as a braille screen. [6]

3.4 Approaches analysis

When working with programmable matter, it is important to consider several features, including the capacity to produce a shape that is both programmable and controllable by external stimuli,

the ability to perform smooth transitions during shape alterations, the possibility of bridging the cyber and physical models, so deformations can be applied and updated in both directions, and the ability to perform autonomous reconfigurability of a self-contained element in a constrained space.

As programmable matter can be interpreted using different approaches, the analysis first concerns each approach individually and then consolidates all the discussed aspects.

3.4.1 Collection of modular components. As described in Section 3.1, a PM can be viewed as a collection of individual modules or components such as blocks (MRBs), modular robots (MSRRs), or morphable robots (MSRMR) that can be assembled or disassembled to form shapes (Figure 17). In what follows, we examine the advantages and limitations of this approach.

Advantages:

Although MRB, MSRR, and MSRMR have different architectures and mechanisms, they share the same advantages, which call attention to self-reconfigurability. These advantages can be summarized as follows:

Modularity: the construction of the overall shape is based on uniform modules, which optimizes production costs through mass production. This uniformity also supports the self-repair and recovery of the system from partial damage.

Versatility: modules are embedded with quirks that allow to target variant applications, according to their configurations. They act as transformable robots using the morphing and actuating abilities of MSRMR, such as M-TRAN III, a moving platform (conveyor, wheels [9]) to transport objects, and prototyping.

Flexibility: modules can attain high levels of transformation by relying on their mobility combined with various latching/unlatching mechanisms. Furthermore, MSRMR can use their morphing ability to shift back and forth between formations.

Configurability: the shape of the overall structure can be configured by changing how the modules are interconnected. Configurability can be offline or online. It is also possible to have configurable modules, where in this case configurations can happen intermodule and/or intramodule.

Mobility: modules can operate over a wide range of movements (slide, jump, or roll) depending on their configuration. In addition, improving their shape (number of contact surfaces) offers a greater degree of freedom, which results in an enhanced shape.

Control: the behavior of modules is governed by a decentralized control architecture that promotes intermodular interactions and scales better as the number of modules increases. Nonetheless, this is applicable to MSRR and MSRMR configurations, as Modular Robotic Blocks (MRB) do not possess processing, sensing, and actuation capabilities.

Limits:

The performance of the modular components is highly dependent on their technological level. Still, with advanced features, robots lack efficiency in terms of energy and costs and are limited in terms of resolution; a generic form factor that optimizes interaction and grouping is still an open research question. The limitations of the modular components can be described as follows:

Scalability: rendering precise and realistic 3D models would require the use of a large number of micro-sized modular robots that are embedded with advanced down-scaled technology. Therefore, the manufacturing cost of the complexity, quantity, and time to assemble increases compared to other methods.

Power management: in relation to their capabilities, some modules are not power efficient, as they permanently latch/dock using active methods that rely on electrical/magnetic energy. Power transmission between modules is still uncommon in current designs, as it affects the size and complexity of the decentralized control.

Structure: rendering complex shapes is not only limited by the rigidity of the structure but also by the reliability of the docking mechanism and the force/torque to weight ratio. Current models of modular components do not consider the stability of the shape and how long it will last.

Analysis:

Fig. 17. a) MRB reconfiguration using magnets. b) MSRR self-reconfiguration using CPU and I/O. c) MSRMR Morphing self-reconfiguration using actuators.

The followingTable 2 describes the difference between the 3 types of collaborative components.

Table 2. Comparison of MRB, MSRR, and MSRMR properties

	MRB	MSRR	MSRMR
Versatility	Low	Medium	High
Flexibility	Low	Medium	High
Control	Centralized	Decentralized	Decentralized
Mobility	Limited	Free	Precise and Free
Hardware	Latching mechanism	CPU + Sensors + Actuators	CPU + Sensors + Advanced actuation
Scalability	High	Scalable	Low (Hard to scale down)
Operations	Add(Assemble)	Add(Assemble)	Add(Assemble) Deform

MRBs are the easiest components to manufacture because of their small and simple form factors. Therefore, they are only embedded with a passive latching mechanism, which implies the use of an additional platform to serve as control. Adapting centralized control in MRB allows easy power management in exchange for self-configuration and self-healing abilities.

In contrast, MSRRs are the most used components due to their embedded processing abilities and advanced latching mechanisms that allow them to move freely based on collaborative decisions. The composition and shape of the MSRR favor self-healing and self-configuration.

On the other hand, MSRMRs are versatile and flexible but lacks scalability and are complex to manufacture.

3.4.2 Kinetic interface. Kinetic interface is another approach used to represent programmable matter, as presented in Section 3.2. It serves more to bridge the cyber physical models offering interactivity and haptic feedback, along with other advantages highlighted below.

Advantages:

Interactivity: The architecture of a kinetic interface favors interactivity because it can be embedded with tactile sensors or depth cameras to provide signals that can change the computed models or send back haptic feedback (vibration).

Modularity: Devices can be easily stacked horizontally to form larger shapes or to show more details in a shape.

Versatility: Devices in this category are not only used to make interactive shapes from computed models, but they also serve to make dynamic molds for the thermoforming process, to represent data in tangible user interfaces by providing physical object digital information through augmenting means such as projection.

Configurability: Components such as rods, actuators, and sensors are easily interchangeable and can even be upgraded without changing the form factor of the device. This allows for the ease of maintainability and adaptation of the interface to form advanced shapes.

Cost: Most of the components used are generic and easily accessible, which reduces the cost compared to the first approach.

The performance of Kinetic interfaces is limited by factors, that we state as follows:

Limits:

Portability: The majority of available devices are designed in the form of a table as the control, and the power management unit is centralized, which limits its portability and compactness. Furthermore, the shapes are rendered by extending the actuators to the specified coordinates, which makes them ungraspable and unusable.

Scalability is a major concern to take into consideration when working with programmable matter. Rendering realistic 2.5D shapes requires the use of small rods and pins that are not limited by the minimum size of existing actuators/sensors. Therefore, complexity and cost increase.

Form Factor: The kinetic interface lacks the form factor because its architecture requires a centralized energy source in addition to control and power management circuits. Moreover, larger shapes require more travel, resulting in the use of longer rods/pins.

Analysis:

The following Table 3 describes the differences between actuated and inflatables interfaces.

Table 3. Comparison of Actuated Interfaces and Inflatable Interface Properties

	Actuated interfaces				Inflatable interface
	Normal	**Lateral**	**Radial**	**Articulation**	
Scalability	High	Medium	Medium	High	Low
Modularity	High	High	Low	High	Low
Graspable	No	Yes	Yes	Yes	Yes
Hardware	Actuators + Sensors+ Control and Power circuit				Fluid compressor + Sensors + Control circuit
Operations	Deform(Actuate) Deform(Model)			Fold	Deform(Model) Expand(Inflate)

Actuated interfaces are suited for representing 2.5D forms by providing a pixelated geometrical representation of the cyber model. These shapes are produced through deformation and actuation; therefore, they need to be consistently maintained, which makes them not fully utilizable. In addition, energy is permanently delivered to the device, as it needs to rectify its shape while using smart materials as actuators.

Similarly, inflatable interfaces exhibit the same limitations as actuated interfaces do. Moreover, their cell architecture prevents them from being modular, as it is difficult to embed docking mechanisms. In addition, inflation requires active control of the pressure, as the object needs to be connected to the fluid compressor, which limits the portability of the shape.

3.4.3 Programmable materials. As described in Section 3.3, programmable material approaches aim to integrate means such as sensors and actuators into materials to control and modify their characteristics (e.g., shape and color). The PMS-based approach is different and consists of looking for programming means that already exist in the material itself. More precisely, instead of integrating computation and communication means in the material by adding embedded electronics, we seek to exploit the already existing programming means in the material itself, using, for example, shape memory alloys (SMA), piezoelectric materials, or their combination to develop programmable matter. In what follows, we examine the advantages and limitations of these approaches.

Advantages:

Unlike previous approaches, programmable materials introduce devices that are originally embedded with sensing and actuating capabilities, allowing for the following features:

Performance: Programmable materials deliver high performance compared with their form factor. For example, SMA has a high power-to-weight ratio, and SMP have a high recoverable strain (up to 400%).

Bidirectional: A class of programmable materials can perform reversible behaviors that bridge embedded sensing and actuating capabilities. In particular, piezoelectric energy is delivered when deformed, and vice versa.

Compact: Programmable materials are compact and lightweight, making them suitable for nano-robots and complex actuation.

Self-healing: Programmable materials are capable of self-repairing/healing when subjected to inconvenient damage by resetting to their original shape under an external stimulus.

Simple to integrate: With their ability to perform controlled behavior and their small form factor, programmable materials are simple to integrate in mechatronic solutions as actuators or sensors. They simplified the mechanical junctions and reduced bulkiness.

Limits:

Still, with their advanced features, Programmable materials are limited in:

Control: Some programmable materials exhibit nonlinear behavior, making it difficult to precisely control finer movements.

Memory: Shape memory materials can cycle between two maximum states, which limits their flexibility. Moreover, they were trained each time to memorize a different shape, following a time-consuming process. In most cases, a counter actuator is used to reset the material, producing pseudo-memory.

Input stimulus: Some stimuli are hard to apply and focus on when the programmable material is integrated into a system of elements, due to their nature. In addition, they are not power efficient (e.g. heat by Joule effect), and they are easily influenced by environmental changes.

Reactivity: The reactivity of programmable materials depends on the ability of transmitted energy to trigger a fast transition. The greater the power, the better the reactivity.

Fatigue: The performance of programmable materials diminishes over time. For example, when SMA are subjected to considerable stress, they begin to lose their memory over time.

Analysis:

Conventional materials are traditionally used to form artifacts, mechanical joints, and transport energy. They are referred to as conventional materials because they are the most commonly used class of materials. However, they are limited in terms of performance and reactivity, and their architecture needs to be refactored to target shape/movement. Therefore, conventional materials are rarely used in shape-shifting or programmable interfaces.

Smart materials, on the other hand, fit more in programmable matter as they can store programming means (shapes/behaviors) that emerge when they are subjected to different types of stimuli. In addition, they replicate controllable, reversible operations. still with good compatibility,

smart materials are difficult to control, as the majority have a nonlinear behavior in addition to hysteresis. In addition, they are not energy efficient because the stimulus is triggered through energy transformation (e.g., heat is generated by the Joule effect).

Propitient matter combines the properties of multiple smart materials by creating a system of individual materials (e.g., composites). Therefore, the number of possible shapes depends on the characteristics of the elements of the system {materials, maximum memory, stimulus, behavior}. Therefore, it is possible to create multiple shapes using various types of stimuli. Nevertheless, control and energy remain the main concerns, as control becomes complicated with the combination of different types of materials (linear and nonlinear) along with their stimuli interference.

Table 4 presents a comparison between the features of the conventional, smart, and propitient matter-based approaches.

Table 4. Comparison of the properties of Conventional, Smart and Propitient materials

	Conventional materials	**Smart materials**	**Propitient matter**
Memory	No memory	Low (Up to 2 memories)	High
Control	Hard	Hard	Very hard
Energy	Low	Medium	High
Stimuli	Mono (Material's structure needs to be modified)	Multi (Heat, Ph, Magnetic, ...)	
Operations	Deform(Stimuli) Expand(Stimuli)	Add(Merge) Deform(Stimuli) Expand(Stimuli) Fold(Stimuli)	

The following Table 5 presents the difference between smart materials that lies in their integration properties.

Table 5. Comparison of theproperties of different smart materials

	SMA	**SMP**	**Piezoelectric**	**Dielectric EAP**	**Ionic EAP**	**Fluids (MR, ER)**
Energy	Bad	Bad	Good	Bad	Bad	Bad
Cost	Medium	Medium	High	Medium	Medium	High
Speed	Medium	Low	High	Medium	Low	High
Control	Hard	Hard	Easy	Hard	Hard	Easy
Strain	8%	400%	0.1%	300%	2%	-
Stimuli	Heat Magnetic	Heat Light Magnetic Moisture Ph	Electric Mechanical	Electric	Electric	Magnetic Electric

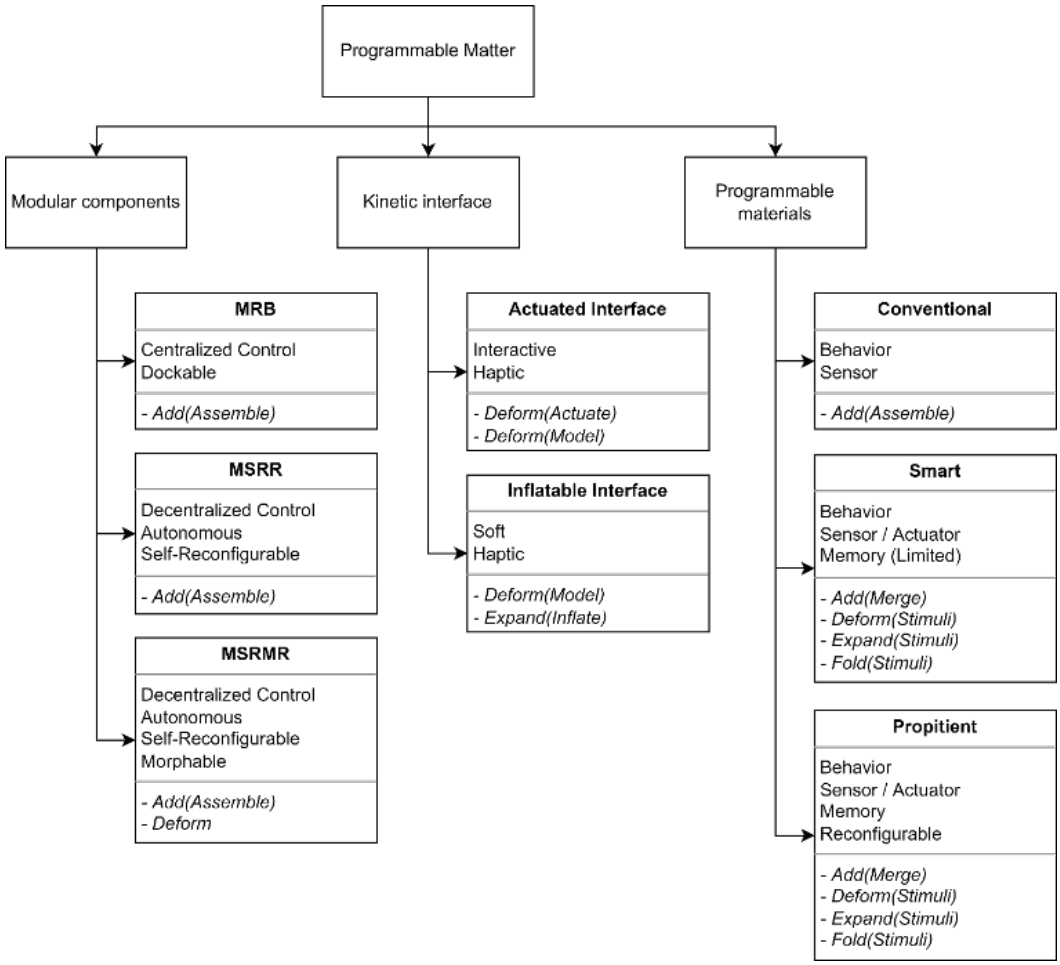

Fig. 18. Programmable matter classification with characteristics and operations

3.4.4 Discussion. The approaches to implementing programmable matter can be categorized in the following figure (Figure 18).

Programmable matter is represented by three approaches that aim to render the physical form of a cyber model dynamically. Each approach has its own mechanisms for forming, handling, and representing matter. The choice of the appropriate approach depends on criteria that suit the user's needs, such as

Interactivity: The kinetic interface favors interactivity because it can be easily embedded using touch sensors (pressure, capacitive) to reshape a model, a depth camera that updates the computed model and scans user gestures, and a projector to feed the shape with augmented rendering (live data, colors). Modular components trade-off interactivity for scalability, as their form factor limits the number of embedded features.

Modularity: Modular components are suited to modular tasks as interchangeable, mobile collaborative agents. This configuration favors self-healing and maintainability, and prevents reprogramming, as robots adapt themselves to deliver the shape. Programmable materials and kinetic

interfaces are limited in terms of modularity because they lack mobility, and their architecture prevents them from being docked tridirectionally.

Control: Kinetic interfaces are easily controllable, as they involve driving actuators to the targeted coordinates, in addition to handling the feedback loop. On the other hand, modular components are controllable through collaborative decentralized methods, which have a long execution time compared to other approaches. Programmable materials are difficult to control because they exhibit nonlinear behavior, in addition to hysteresis. However, they can be precisely controlled by modeling their behavior through experimentation and simulations.

Shape: Programmable materials deliver scalable smooth shapes because they can deform locally according to the applied stimuli. In addition, they are able to render 2D, 2.5D, and 3D shapes more than the other approaches, and they are faster than modular components. Kinetic interfaces and modular components lack scalability because their shape is made by discrete agents/actuators, and the smaller the value, the better the scalability. However, the kinetic interface forms quick shapes compared to programmable materials.

Portability: The architecture of the modular component favors portability, as every component has its own actuators, sensors, and energy source. On the other hand, programmable materials and kinetic interfaces require a centralized power delivery system in addition to control, which affects their size and limits their portability.

4 PROGRAMMABLE MATTER CHALLENGES

The main challenges associated with programmable matter encompass technical, design, and environmental considerations, which are elaborated upon in the subsequent subsections.

4.1 Technical

Energy efficiency and management: Unlike conventional matter, programmable matter requires an active energy source to process instructions and perform trained behaviors. Hence, their portability and scalability are limited. Furthermore, devices based on programmable materials are not power efficient compared to other approaches since they lose energy to be adapted to the stimuli. To overcome this limitation, several questions should be addressed, such as the possibility of re factorizing programmable matter to harvest energy, embedding power transfer features between the collaborative agents, and triggering the stimuli without employing energy-intensive transformations (e.g. heat by joule effect).

Control Dynamics: Speed and reliability are two key aspects to focus on when working with programmable matter. The goal here is to see how fast a formation can be established without trading-off reliability and how long a shape can be maintained given a reliable loop control model.

Scalability and precision: Rendering fine physical objects out of cyber models requires improvement in the scalability of the matter, which depends on the extent to which the size of the agent is reduced and how it can affect the performance of the system.

4.2 Design

Interaction: Devices based on a kinetic interface integrate interactivity in addition to shapeshifting capabilities, which calls into question the possibility of other approaches to embedding such features. The challenge is to perform reversible modification through sense inputs, haptic feedback, or behavior when needed given certain constraints (e.g., scalability and energy).

Shape: Some devices based on the kinetic interface or programmable materials approach are limited to 2.5D rendering, which cast doubt on their ability to upgrade to superior shapes (3D, 4D).

Manufacturing: Morphable modular components combine shape shifting capabilities with collaborative operations, which implies the use of compact actuators such as smart materials.

Because the goal here is to reach a high level of scalability while maintaining the other features, the challenge is how to deploy an easy and reliable manufacturing process, given the prerequisites.

4.3 Environmental Considerations

Recycling: Failure may occur during the process of shaping an object through deformation or collaborative formations, as usable elements (e.g., materials and robots) are prone to malfunction. This brings recyclability and maintainability into question.

Adaptability: Having sensing and actuating abilities may make rendering formations quite challenging when working in different environments, as it could influence the stimuli or behavior of the active elements. The challenge here is to develop a model that manifests immunity to environmental changes.

Safety: Smart materials, such as ferrofluids, require careful handling due to their toxicity levels (low but present) and potential skin irritant properties, raising considerations about the development of safe and ready-to-handle materials.

5 CONCLUSIONS AND FUTURE WORK

In recent years, there has been a surge in the use of smart materials and programmable materials. However, there is a lack of a systematic overview of different approaches and mechanisms to implement programmable matter-based systems. To fill this gap, this study provides a comprehensive review of the programmable matter paradigm from the perspective of system operation and design. In particular, we identify the existing approaches and mechanisms involved in implementing them, their pros and cons, and point out challenges for future research.

We hope that this article will raise the attention of researchers, designers, and engineers desiring to be introduced to programmable matter with its different approaches. It consists of a classification of various shape-shifting devices, expressed by their quirks and drawbacks, to help design novel programmable matter approach.

In particular, we identified the basic operations of the shape-creation process, which can be performed through multiple mechanisms. In addition, we defined shape creation parameters such as flexibility, recyclability, and morphability, which called into question the possibility of making devices with shape alteration abilities. Then, through an analysis of the different shape shifting devices, we determined a classification of programmable matter, gathering devices that use the collection of modular components, kinetic interfaces, and programmable materials. These approaches were analyzed and compared to determine a suitable approach for a given use case. Finally, we highlight the challenges faced by programmable matter.

Programmable matter approaches define and group devices using similar architectures. The collection of modular components represents components that assemble themselves to make a shape through centralized control (MRB) or decentralized control using robots (MSRR), while other components are equipped with the ability to change their shape locally, which favors motion and ease formations (MSRMR). The kinetic interface consists of deforming an open or closed surface (cell) using actuators in different directions (normal, radial, lateral, articulation) or fluids (inflation). Programmable materials rely on material characteristics to program and perform behaviors using the given stimuli. Materials in this approach can range from conventional to Propitient depending on the number of stimuli, memory, behaviors, and energy consumption.

Our future contributions will target the development of reliable power-efficient devices based on Propitient matter, taking advantage of the drawbacks and challenges provided by this review. Finally, although several advances have been made in existing studies, there are still many challenges concerning the technical level, design level, and environmental aspects.

ACKNOWLEDGMENTS

This work was supported by the EIPHI Graduate School.

REFERENCES

[1] D M Addington, D Schodek, and D L Schodek. 2007. Smart Materials and Technologies For the Architecture and Design Professions. In *Smart Materials and Technologies For the Architecture and Design Professions*. Elsevier.

[2] M Bengisu and M Ferrara. 2018. Materials that move. In *Materials that move*. Springer International Publishing, 5–38. https://doi.org/10.1007/978-3-319-76889-2_2

[3] B Buchi, H Mabed, F Lassabe, J Gaber, and W Abdou. 2021. Translation based Self Reconfiguration Algorithm for 6-lattice Modular Robots. In *2021 20th International Symposium on Parallel and Distributed Computing (ISPDC)*. 49–56. https://doi.org/10.1109/ISPDC52870.2021.9521628

[4] A Castano, W M Shen, and Will P. 2000. CONRO: Towards Deployable Robots with Inter-Robots Metamorphic Capabilities Autonomous Robots. *Autonomous robots* 8 (2000), 309–333. https://doi.org/10.1023/A:1008985810481

[5] A A Chafik, J Gaber, S Tayane, and M Ennaji. 2021. Shape-memory programmable device. https://patents.google.com/patent/WO2023066999A1/en?oq=WO2023066999

[6] Ahmed Amine Chafik, Jaafar Gaber, Souad Tayane, and Mohamed Ennaji. 2022. Behavioral modeling of knitted shape memory membrane. In *2022 XXVIII International Conference on Information, Communication and Automation Technologies (ICAT)*. 1–6. https://doi.org/10.1109/ICAT54566.2022.9811236

[7] M Coelho, H Ishii, and P Maes. 2008. Surflex: a programmable surface for the design of tangible interfaces. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems CHI EA '08*. Association for Computing Machinery, 3429–3463.

[8] D Correa, A Papadopoulou, C Guberan, N Jhaveri, S Reichert, A Menges, and S Tibbits. 2015. 3D-Printed Wood: Programming Hygroscopic Material Transformations. , 106-122 pages. https://doi.org/10.1089/3dp.2015.0022

[9] J Daudelin, G Jing, T Tosun, M Yim, H Kress-Gazit, M Campbell, and Science robotics. 2018. An integrated system for perception-driven autonomy with modular robots. https://doi.org/10.1126/scirobotics.aat4983

[10] J Davey, N Kwok, and M Yim. 2012. Emulating self-reconfigurable robots - design of the SMORES system. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 4464–4473. https://doi.org/10.1109/IROS.2012.6385845

[11] M Ennaji, S Tayane, and J Gaber. 2019. Modelling and simulation of the behavior of a shape memory membrane for programmable matter 4D prototyping Systems Research and. *Behavioral Science* 36 (2019), 835–879.

[12] M Ennaji, S Tayane, J Gaber, A A Aziz, A Mouchtachi, and J Saadi. 2018. Membrane flexible composite à mémoire de forme. http://patent.ompic.ma/publication-server/html-document?PN=MA44424%20MA%2044424&iDocId=16035

[13] L Esther, A Piselli, J Faucheu, Delafosse D, Del Curto, and B. 2014. Smart materials: development of new sensory experiences through stimuli responsive materials. In *5th STS Italia Conference A Matter of Design: Making Society through Science and Technology*. 10–10. https://doi.org/10.1016/j.matpr.2020.04.505

[14] S Follmer, D Leithinger, A Olwal, A Hogge, and H Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation . In *Proceedings of the 26th annual ACM symposium on User interface software and technology UIST '13*. Association for Computing Machinery, 417–443. https://doi.org/10.1145/2501988.2502032

[15] M Frey and Snoil. [n.d.]. A Physical Display Based on Ferrofluid. https://web.archive.org/web/20180226210841/http://www.freymartin.de/en/projects/snoil/

[16] Q Ge, A H Sakhaei, H Lee, C K Dunn, N Fang, and M L Dunn. 2016. Multimaterial 4D Printing with Tailorable Shape Memory Polymers. *Scientific Reports* 6 (2016), 31110–31110.

[17] S C Goldstein, J Campbell, and T C. Mowry. 2005. Programmable matter. *Computer* 38 (2005), 99–101. https://doi.org/10.1038/35036656

[18] M Goulthorpe. 2007. Aegis Hyposurface.

[19] G Grassi, B Sparrman, I Paoletti, and S Tibbits. 2022. 4D Soft Material Systems. In *The International Conference on Computational Design and Robotic Fabrication*, and others (Ed.). 201–211.

[20] E Hawkes, B An, N M Benbernou, H Tanaka, S Kim, E D Demaine, Rus D Wood, and R J. 2010. Programmable matter by folding. , 12441-12446 pages. https://doi.org/10.1073/pnas.0914069107

[21] J L Huang, Z Zhakypov, H Sonar, and J Paik. 2018. A reconfigurable interactive interface for controlling robotic origami in virtual environments. *The International Journal of Robotics Research* 37 (2018), 629–676.

[22] H Iwata, H Yano, F Nakaizumi, and R Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques SIGGRAPH '01*. Association for Computing Machinery, 469–76. https://doi.org/10.1145/383259.383314

[23] H Iwata, H Yano, and N Ono. 2005. Volflex. In *ACM SIGGRAPH 2005 Emerging technologies SIGGRAPH '05*. Association for Computing Machinery, 31–31. https://doi.org/10.1145/1187297.1187329

[24] M W Jorgensen, E Ostergaard, and H H Lund. 2004. Modular ATRON: modules for a self-reconfigurable robot. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566)* 2 (2004), 2068–73.

[25] V L Kalyani. 2015. Claytronics - An Unimaginable Shape Shifting Future Tech. *Journal of Management Engineering and Information Technology* 2 (2015), 2394–8124.

[26] Y Kawaguchi. 2008. Gemotion Screen: A Generative, Emotional, Interactive 3D Display. https://api.semanticscholar.org/CorpusID:111621852

[27] E F Keller. 2011. Towards a science of informed matter Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of. *Biological and Biomedical Sciences* 42 (2011), 174–183. https://doi.org/10.1016/j.shpsc.2010.11.024

[28] D Kirchner, S Niemczyk, and K Geihs. 2014. RoSHA: A Multi-robot Self-healing Architecture. 304–315. https://doi.org/10.1007/978-3-662-44468-9_27

[29] A Kochan. 2000. Rapid prototyping gains speed, volume and precision. *Assembly Automation* 20 (2000), 295–299. https://doi.org/10.1108/01445150010378425

[30] S Kodama and M Takeno. 2001. Sound-Responsive Magnetic Fluid Display. In *IFIP TC13 International Conference on Human-Computer Interaction*, ed M Hirose (Ed.). IOS Press, 737–745.

[31] J Koh, K Karunanayaka, and R Nakatsu. 2013. Linetic: Technical, Usability and Aesthetic Implications of a Ferrofluid-Based Organic User Interface. In *IFIP Conference on Human-Computer Interaction*, and others (Ed.), Vol. 8119.

[32] H Kurokawa, K Tomita, A Kamimura, S Kokaji, T Hasuo, and S Murata. 2008. Distributed Self-Reconfiguration of M-TRAN III Modular Robotic System. *The International Journal of Robotics Research* 27 (2008), 373–86. https://doi.org/10.1177/0278364907085560

[33] D Lakatos. 2012. AMPHORM : form giving through gestural interaction to shape changing objects. https://dam-prod.media.mit.edu/x/files/thesis/2012/dlakatos-ms.pdf

[34] R Landauer. 2008. Information is Physical. *Physics Today* 44 (2008), 23–23. https://doi.org/10.1063/1.881299

[35] D Leithinger and H Ishii. 2010. Relief: a scalable actuated shape display. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction TEI '10*. Association for Computing Machinery, 221–223. https://doi.org/10.1145/1709886.1709928

[36] J Leng, H Lu, Y Liu, W Huang, and S Du. 2009. Shape-Memory Polymers—A Class of Novel Smart Materials. *MRS Bulletin* 34 (2009), 848–55.

[37] Y Liu and H Hu. 2010. A review on auxetic structures and polymeric materials Scientific research and essays. , 1052-63 pages. https://doi.org/10.5897/SRE.9000104

[38] P S Lobo, J Almeida, and L Guerreiro. 2015. Shape Memory Alloys Behaviour: A Review. *Procedia Engineering* 114 (2015), 776–83.

[39] F Luigi and B Arturo. 2022. Smart Materials. *Materials* 15, 18 (2022). https://doi.org/10.3390/ma15186307

[40] S Malik, K Muhammad, and Y Waheed. 2009. Nanotechnology: A Revolution in Modern Industry. *Molecules* 28, 2 (2009), 661–661. https://doi.org/10.3390/molecules28020661

[41] R Moeckel, C Jaquier, K Drapel, E Dittrich, A Upegui, A ; M O Ijspeert, G Tokhi, M A Virk, and Hossain. 2006. YaMoR and Bluemove - An Autonomous Modular Robot with Bluetooth Interface for Exploring Adaptive Locomotion. In *International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, Berlin, Heidelberg*. Springer, 685–92. https://doi.org/10.1007/3-540-26415-9_82

[42] S Murata, E Yoshida, A Kamimura, H Kurokawa, K Tomita, and S Kokaji. 2002. M-TRAN: self-reconfigurable modular robotic system. *IEEE/ASME Transactions on Mechatronics* 7 (2002), 431–472. https://doi.org/10.1109/TMECH.2002.806220

[43] K Nakagaki, S Follmer, and H Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint . In *UIST '15: Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 333–342. https://doi.org/10.1145/2807442.2807452

[44] K Nakagaki, L Vink, J Counts, D Windham, D Leithinger, S Follmer, and H Ishii. 2016. Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces . In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems CHI '16*. Association for Computing Machinery, 2764–72. https://doi.org/10.1145/2858036.2858104

[45] Y Nakagawa, S Yonekura, and Y Kawaguchi. 2011. Super thin 3D form display for multimodal user experiences using vertically deformation of leaf spring and SMA. *IEEE International Symposium on VR Innovation (ISVRI)* (2011), 63–69.

[46] M Nakashige, K Hirota, and M Hirose. 2004. Linear actuator for high-resolution tactile display RO-MAN 2004. 13th IEEE International Workshop on Robot and Human Interactive Communication (IEEE Catalog No.04TH8759) RO-MAN 2004. *13th IEEE International Workshop on Robot and Human Interactive Communication* (2004), 587–90.

[47] M Nakatani, H Kajimoto, D Sekighuchi, N Kawakami, and S Tachi. 2004. Pop Up! a novel technology of shape display of 3D objects. In *ACM SIGGRAPH 2004 Emerging technologies SIGGRAPH '04*. Association for Computing Machinery, 21–21.

[48] M Nakatani, H Kajimoto, D Sekiguchi, N Kawakami, and S Tachi. 2003. 3D Form Display with Shape Memory Alloy .

[49] M Park and M Yim. 2009. Distributed control and communication fault tolerance for the CKBot. In *2009 ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots*. 682–690.

[50] A Parkes and H Ishii. 2010. Bosu: a physical programmable design tool for transformability with soft mechanics. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems DIS '10*. Association for Computing Machinery, 189–98.

[51] B Piranda and J Bourgeois. 2018. Designing a quasi-spherical module for a huge modular robot to create programmable matter. *Autonomous Robots* 42 (2018), 1619–1652. https://doi.org/10.1007/s10514-018-9710-0

[52] B Piranda and J Bourgeois. 2020. Datom: A Deformable modular robot for building self-reconfigurable programmable matter. In *International Symposium on Distributed Autonomous Robotic Systems*. https://doi.org/10.1007/978-3-030-92790-5_6

[53] I Poupyrev, T Nashida, S Maruyama, J Rekimoto, and Y Yamaji. 2004. Lumen: interactive visual and shape display for calm computing. In *ACM SIGGRAPH 2004 Emerging technologies SIGGRAPH '04*. Association for Computing Machinery, 17–17.

[54] J W Romanishin, K Gilpin, S Claici, and D Rus. 2015. 3D M-Blocks: Self-reconfiguring robots capable of locomotion via pivoting in three dimensions . , 1925-1957 pages. https://doi.org/10.1109/ICRA.2015.7139450

[55] P Schoessler, D Windham, D Leithinger, S Follmer, and H Ishii. 2015. Kinetic Blocks: Actuated Constructive Assembly for Interaction and Display . In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology UIST '15*. Association for Computing Machinery, 341–350. https://doi.org/10.1145/2807442.2807453

[56] A F Siu, E J Gonzalez, S Yuan, J Ginsberg, and S Follmer. 2018. shapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems CHI '18*. Association for Computing Machinery, 1–13. https://doi.org/10.1145/3173574.3173865

[57] A Stanley, J Gwilliam, and A Okamura. 2013. Haptic jamming: A deformable geometry, variable stiffness tactile display using pneumatics and particle jamming.

[58] R Suzuki, J Yamaoka, D Leithinger, T Yeh, M D. Gross, Y Kawahara, and Y Kakehi. 2018. Dynablock: Dynamic 3D printing for instant and reconstructable shape formation. , 99-111 pages. https://doi.org/10.1145/3242587.3242659

[59] F Taher, J Hardy, A Karnik, C Weichel, Y Jansen, K Hornbæk, and Alexander J. 2015. Exploring Interactions with Physically Dynamic Bar Charts . In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems CHI '15*. Association for Computing Machinery, 3237–3283. https://doi.org/10.1145/2702123.2702604

[60] Y Tahouni, I P S Qamar, and S Mueller. 2020. NURBSforms: A Modular Shape-Changing Interface for Prototyping Curved Surfaces . In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction TEI '20*. Association for Computing Machinery, 403–412.

[61] P M Taylor, A Moser, and A Creed. 1998. A sixty-four element tactile display using shape memory alloy wires. *Displays* 18 (1998), 163–171.

[62] P Thalamy, B Piranda, F Lassabe, and J Bourgeois. 2020. Deterministic Scaffold Assembly By Self-Reconfiguring Micro-Robotic Swarms. *Swarm and Evolutionary Computation* 58 (2020), 100722–18. https://doi.org/10.1016/j.swevo.2020.100722

[63] T Toffoli and N Margolus. 1991. Programmable matter: Concepts and realization. *Physica D: Nonlinear Phenomena* 47, 1-2 (1991), 263–272. https://doi.org/10.1016/0167-2789(91)90296-L

[64] Y Tokuda, J L B Moya, G Memoli, T Neate, D R Sahoo, S Robinson, J Pearson, M Jones, and S Subramanian. 2017. Programmable Liquid Matter: 2D Shape Deformation of Highly Conductive Liquid Metals in a Dynamic Electric Field. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces ISS '17*. Association for Computing Machinery, 142–50. https://doi.org/10.1145/3132272.3134132

[65] M T Tolley, S M Felton, S Miyashita, D Aukes, Rus D Wood, and R J. 2014. Self-folding origami: shape memory composites activated by uniform heating Smart Mater. *Struct* 23 (2014), 94006–94006.

[66] A M Vijaykumar. 2015. A Scalable and Low-Cost Interactive Shape-Changing Display. https://tigerprints.clemson.edu/all_theses/2498

[67] A Wakita and A Nakano. 2012. Blob manipulation . In *TEI '12: Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, Vol. 12. Association for Computing Machinery, 299–302. https://doi.org/10.1145/2148131.2148193

[68] A Wakita, A Nakano, and N Kobayashi. 2010. Programmable blobs: a rheologic interface for organic shape design. In *TEI '11: Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*. Association for Computing Machinery, 273–279. https://doi.org/10.1145/1935701.1935760

[69] A Wakita, A Nakano, and M Ueno. 2011. SMAAD surface: A tangible interface for smart material aided architectural design Circuit Bending, Breaking and Mending . In *Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia*. 355–64. https://doi.org/10.52842/conf.caadria.2011.355

[70] P White, V Zykov, J C. Bongard, and H Lipson. 2005. Three Dimensional Stochastic Reconfiguration of Modular Robots. In *Robotics: Science and Systems I, June 8-11, 2005, Massachusetts Institute of Technology, Cambridge, Massachusetts,*

{USA}, Sebastian Thrun, Gaurav S. Sukhatme, and Stefan Schaal (Eds.). The MIT Press, 161–168. https://doi.org/10.15607/RSS.2005.I.022

[71] P. J. White, K. Kopanski, and H. Lipson. 2004. Stochastic self-reconfigurable cellular robotics. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, Vol. 3. https://doi.org/10.1109/ROBOT.2004.1307499

[72] F Witz, B Buchi, H Mabed, F Lassabe, Jr Gaber, and W Abdou. 2022. Deep Learning for the selection of the best modular robots self-reconfiguration algorithm. In *2022 IEEE Symposium on Computers and Communications (ISCC)*. 1–6. https://doi.org/10.1109/ISCC55528.2022.9912849

[73] L Yao, R Niiyama, J Ou, S Follmer, Della Silva, C Ishii, and H. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces . In *Proceedings of the 26th annual ACM symposium on User interface software and technology UIST '13*. Association for Computing Machinery, 13–22.

[74] M Yim, P White, P Michael, and Jimmy Sastra. 2009. Modular Self-Reconfigurable Robots. In *Encyclopedia of Complexity and Systems Science*. Springer, 5618–5631. https://doi.org/10.1007/978-0-387-30440-3_334

[75] V Zykov and H Lipson. 2007. Experiment Design for Stochastic Three-Dimensional Reconfiguration of Modular Robots.