Collective Shape-changing Interfaces

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ABSTRACT

In this paper, I introduce *collective shape-changing interfaces*, a class of shape-changing interfaces that consist of a set of discrete collective elements. Through massively parallel transformation, locomotion, and connection of individual building blocks, the overall physical structure can be dynamically changed. Given this parallel change of individual elements, I propose three approaches for user interaction: dynamic, improvised, and actuated collective shape transformation. I exemplify each approach through my own work and possible future work.

CCS Concepts

•Human-centered computing → Human computer interaction (HCI);

Author Keywords

collective shape-changing interfaces; tangible bits; modular robots; swarm robots; programmable matter

INTRODUCTION

Today, we live between two realms; the world of bits and the world of atoms [1]. The permeation of ubiquitous computers attempts to bring these two worlds closer—laptops, tablets, smartphones, smartwatches, and public displays now exist almost everywhere, and it would seem these two worlds are almost merged.

However, the *interface* between these two realms has not changed much. Over the last decades, we still use a tiny rectangle window to access the digital world—graphical displays. Through this rectangle window, a user can interact with the world of bits, sometimes with mouse and keyboard or sometimes with a gesture or touch inputs. No matter what the user interface is, these two worlds are still largely divided; the user can never reach inside the window. After all, we still live in a world of atoms, and the digital information still lives in a world of bits (Figure 1).

Tangible bits aims to consolidate this dual citizenship by enabling to "grasp and manipulate bits" and making "the world as an interface" [1]. Since then, research in human-computer interaction has explored how we can merge the bits and atoms. It originally starts from leveraging *static* physical objects to embody digital information (tangible user interfaces), but then gradually introduces the notion of leveraging *dynamic* physical materials to fully represent the dynamics and fluidity of the digital world—so-called shape-changing user interfaces.

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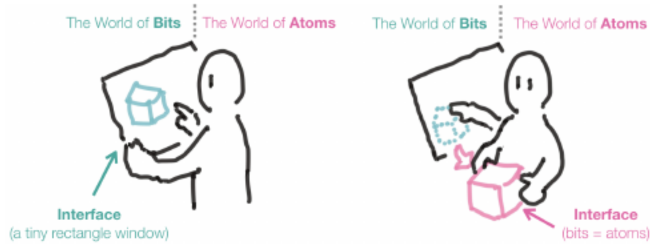

Figure 1. An "interface" between the bits and atoms. A rectangle window is an interface to access the bits (left). Atoms themselves are an interface of bits (right).

Traditionally, shape-changing interfaces are mostly examined through a single-purpose shape transformation of a monolithic material (Figure 2). However, the ultimate vision of shape-changing interfaces lies in reprogrammable, general-purpose shape transformation. Ivan Sutherland, a founding father of virtual and augmented reality, once envisioned such a hypothetical capability as a computer that "can control the existence of matter" [3]. Similar visions have been sought after—Toffoli's Programmable Matter, Goldstein's Claytronics, and Ishii's Radical Atoms. Despite the differences, these visions all coalesce towards one ultimate goal; bringing the limitless capability of the digital bits into the world of atoms.

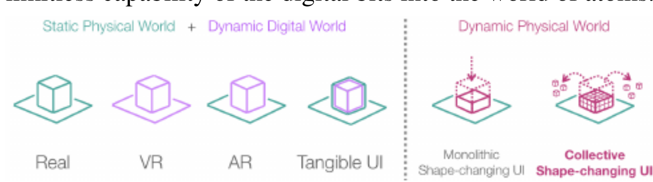

Figure 2. The scope and relationship between existing concepts. The focus of this paper is on dynamic physical interfaces constructed from discrete collective elements.

Throughout my Ph.D., I have explored how to bring this vision closer to reality. My approach is to reconstruct shape-changing interfaces with a discrete set of dynamic materials (Figure 2 right). The aim of this paper is to provide a foundation for this new class of shape-changing interfaces, which I call *collective shape-changing interfaces*.

COLLECTIVE SHAPE-CHANGING INTERFACES

The collective shape-changing interface is a class of shape-changing interface that consists of a set of discrete elements. Each individual element can dynamically change its physical property so that they can collectively transform the overall physical structure.

The promise of the collective shape-changing interface is its generalizability for universal shape transformation. In contrast

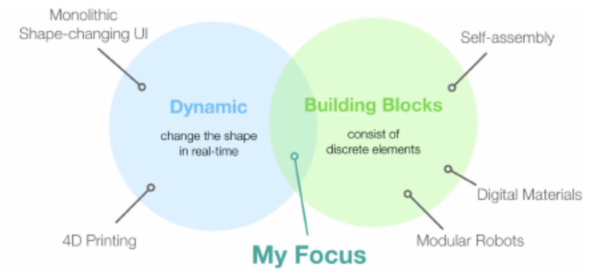

Figure 3. Two key aspects of collective shape-changing interfaces: dynamic and discrete building blocks.

to monolithic, single-purpose shape-changing materials, collective elements can theoretically transform into an arbitrary physical shape, which provides almost limitless expression—just like pixels on a graphical display. To achieve this goal, there are two key aspects; 1) **dynamic:** shape change is done in real time (Figure 3 left), and 2) **discrete elements:** the shape is constructed from discrete building blocks (Figure 3 right).

Figure 4. The vision of dynamic and universal shape transformation: Microbots in Disney's Big Hero 6 (left). Claytronics concept (right).

Towards Dynamic and Universal Shape Transformation

Making shapes with discrete elements is not a new idea. There is a long history of modular self-reconfigurable robots and digital materials to explore this idea for general-purpose shape construction and transformation. However, despite the decades of research, this approach is rarely seen in interactive systems, as it suffers from a key limitation: slow transformation speed. In existing systems, the overall shape change often takes minutes to hours. This is not acceptable for an interactive system, as real-time interaction happens in the span of seconds, not minutes or hours.

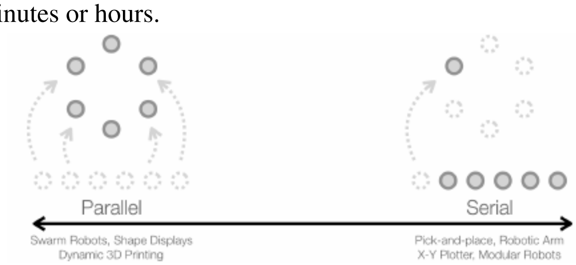

Figure 5. Parallel vs serial shape construction.

The key to achieving this goal is parallelism (Figure 5 left). For example, consider a pick and place machine to assemble LEGO blocks. While it has the capability to create almost arbitrary physical shapes, the serial assembly process will never be done in real time (Figure 5 right). Although existing modular robotics research has taken this parallelism in mind, the actual prototypes are often far from massively parallel shape transformation due to the mechanical complexity. We need to reconsider how to achieve the massively parallel shape construction to apply this notion for dynamic and interactive systems.

Parallel Transformation, Locomotion, and Connection

To this end, I formalize the following three elements for collective parallel changes: 1) transformation, 2) locomotion, and 3) connection.

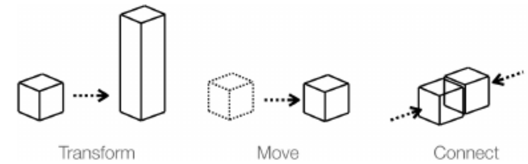

Figure 6. Three changes of each building block: transform, move, and connect.

- **Parallel Transformation:** The first aspect is transforming the individual form of elements. By individually transforming their change, they can achieve the overall shape transformation. This type of collective behavior can be seen in, for example, shape displays or actuated line based interface, whose individual elements cannot move freely but can individually transform to form an overall shape.
- **Parallel Locomotion:** The second aspect is changing the position. This is the most common approach for collective shape formation. For example, swarm robots or drone displays leverage this positional change of many individual elements. Since elements are spatially distributed, this allows the manipulation of overall shape in fast and parallel ways. The degree of freedom of positional change includes 1D, 2D, or 3D.
- **Parallel Connection:** The third aspect is to change the physical property. This can include color, functionality, texture, and connection capability, but this paper focuses on connection between elements. Such a connection capability is leveraged in modular self-reconfigurable robots or digital materials. Connection with nearby elements enables to create a graspable 3D object, which is difficult to achieve with spatially distributed elements.

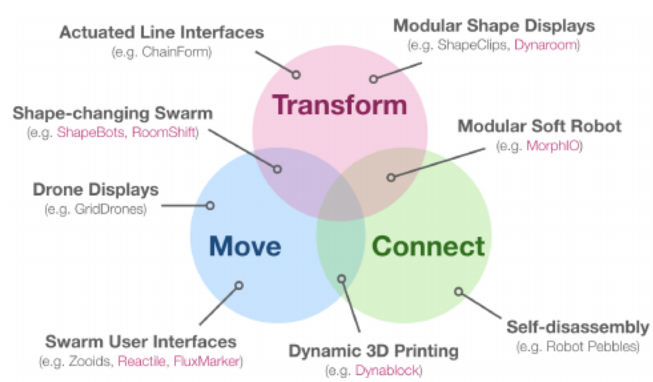

Figure 7. Categorization of the approaches.

Design Space of Collective Shape-changing Interfaces

Previously, each element is spontaneously explored through different systems (Figure 7). However, through identifying the building blocks for collective shape-changing interfaces, we can now explore a broader design space of such interfaces. One of the key contributions of this paper is to provide a holistic view to unify the collective shape-changing interface systems. To this end, I propose the following three approaches:

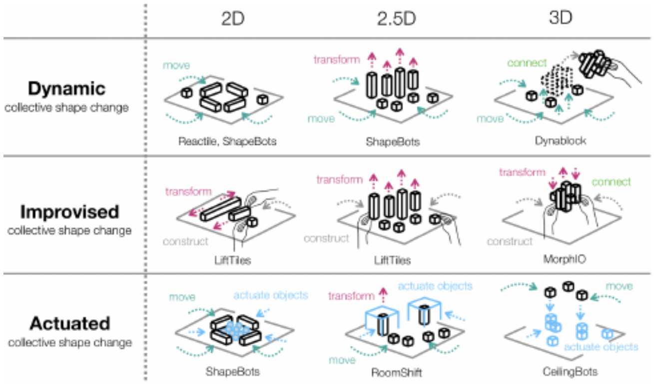

Figure 8. Design space of collective shape-changing interfaces: dynamic, improvised, and actuated collective shape changes.

- **Dynamic**: Dynamic collective shape change is an approach to construct shape through the transformation of many system elements. Such shape formation and transformation is done in seconds by leveraging parallel manipulation.
- **Improvised**: Improvised collective shape change lets the user manually construct and rearrange the elements by hand, and then transform the overall shapes based on the structure.
- **Actuated**: Another interesting aspect of collective shape-changing interfaces is the ability to actuate existing objects in the users environment. This way, the interface can be seamlessly integrated and distributed in the real world.

Figure 8 illustrates each approach with different dimensions. In the following sections, I exemplify each approach with my previous and future work.

DYNAMIC COLLECTIVE SHAPE CHANGE

Dynamic + 3D = Dynablock [UIST 2018]

Dynablock [7] is a system for dynamic 3D shape construction (Figure 8 top right). It can assemble an arbitrary 3D shape with collective building blocks in seconds, by leveraging shape displays as a parallel assembler of tiny blocks.

Figure 9. Dynablock: constructing an arbitrary 3D shape in seconds.

A prototype consists of 3,000 9mm blocks which can be assembled and disassembled using magnetic connections. Dynablock demonstrates the parallel connection and parallel vertical movement can achieve the instant and reconstructable shape formation.

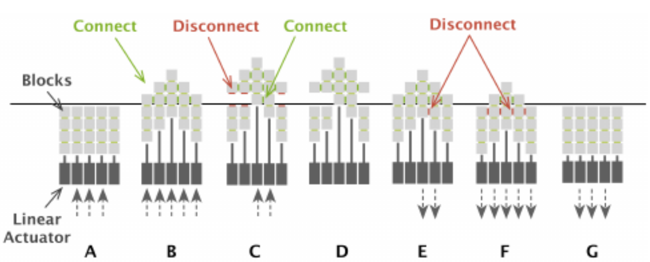

Figure 10. Dynamic shape formation with a parallel assembler.

Dynamic + 2D/2.5D = ShapeBots [UIST 2019]

ShapeBots [8] aims to explore dynamic collective transformation for 2D and 2.5D shape. Traditionally, wheeled swarm robots have difficulty representing shapes beyond 2D. ShapeBots demonstrate parallel locomotion and self transformation to overcome this limitation (Figure 8 top center).

Figure 11. ShapeBots: dynamic collective shape change for 2.5D transformation.

A system consists of a swarm of self-transformable robots with extendable reel actuators. Our actuator can extend from 1.5 cm to 20 cm, which enables large shape transformation of tiny 3 cm robots in both vertical and horizontal directions. By leveraging this capability, ShapeBots can be used for line-based swarm displays and distributed 2.5D shape displays.

Figure 12. ShapeBots: dynamic collective shape change for 2D animation.

Dynamic + 2D = Reactile [CHI 2018]

Reactile [4] is a swarm user interface system leveraging external actuation (Figure 8 top left). It actuates a swarm of small magnets (8 mm) using PCB-based electromagnetic coil arrays which is a thin (3 mm thickness) and has a large (80 cm x 40 cm with 3,200 coils) effective area.

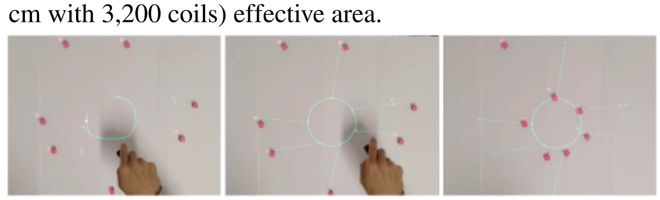

Figure 13. Reactile: swarm UI programming.

In this project, we explore tangible interaction to program the behavior of swarm elements. Users can construct a shape, parameterize, and transform through direct manipulation in the real world, instead of coding on a computer screen.

Dynamic + 2D = FluxMarker [ASSETS 2017]

Figure 14. FluxMarker: collective shape change for blind people.

With FluxMarker [6], we apply dynamic shape construction for accessibility use (Figure 8 top left). The interface provides dynamic physical haptics for blind people, such as data physicalization, location finding on a tactile map, and feature identification for tactile graphics. We evaluated the prototype with six blind users and identified the interaction model for swarm user interfaces.

IMPROVISED COLLECTIVE SHAPE CHANGE

Improvised + 3D = MorphIO [DIS 2019]

MorphIO [2] is a modular soft robotic system (Figure 8 middle right). Its modular design allows an expressive transformation by combining multiple elements. The entirely soft sensing and actuation unit enables the user to program transformation through physical demonstration.

Figure 15. MorphIO: modular soft robot with soft material I/O.

Improvised + 2D/2.5D = LiftTiles

LiftTiles [5] is a modular and reconfigurable shape display (Figure 8 middle left and center). By leveraging discrete, compact, and highly extendable actuators, the user can construct a large-scale shape display.

Figure 16. LiftTiles: modular and reconfigurable shape display.

Our prototype consists of a retractable inflatable actuator, which can extend from 15 cm to 150 cm. We demonstrate an application in shape-changing wall displays, adaptive furniture appearance, and environmental-scale dynamic haptics.

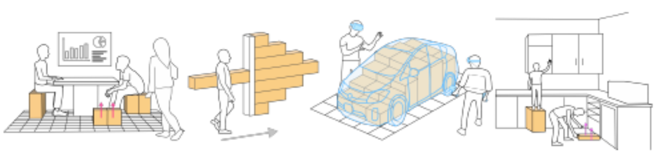

Figure 17. Applications in display, adaptive furniture, and haptics

ACTUATED COLLECTIVE SHAPE CHANGE

Actuated + 2D = ShapeBots

In addition to dynamic shape change, ShapeBots can also be used for actuating existing objects to construct a shape on the 2D surface (Figure 8 bottom left).

Figure 18. Leveraging ShapeBots to actuate existing objects.

Actuated + 2.5D = RoomShift

RoomShift is a swarm of self-transformable robots for collective object actuation (Figure 8 bottom center).

Figure 19. RoomShift: collective actuation for haptics and affordances.

By leveraging the locomotion and transformation, each robot carries existing furniture to reconstruct the spatial layout of a room. This enables a dynamic haptic interface for virtual environment and provides an adaptive spatial reconstruction.

CONCLUSION

In summary, the contributions of this paper are:

1. **A concept of collective shape-changing interfaces:** a definition, scope, and the goal
2. **A formalization of the strategy to achieve the goal:** parallel transformation, locomotion, and connection of collective building blocks
3. **An exploration of the design space:** dynamic, improvised, and actuated collective shape change in different dimensions
4. **Demonstration of each category** through my own practices and future work

For future work, I will develop a system to exemplify the other dimensions (e.g., bottom right), complete the current work-in-progress projects, and discuss the benefits and limitations of each approach to identify future research opportunities.

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