PhD Dissertation Defense
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Dynamic Shape Construction and Transformation with Collective Elements

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This thesis is about an exploration of ways to **dynamically physicalize** digital information from a computer screen, in the real world.
This thesis is about an exploration of ways to **dynamically physicalize** digital information from a computer screen, in the real world.

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**The World of Bits**

**The World of Atoms**

**Graphical Displays**

dynamic but cannot grasp

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**Today**
This thesis is about an exploration of ways to dynamically **physicalize** digital information from a computer screen, in the real world.
Towards Dynamic Physical Media

with which the user can touch, feel, grasp, and manipulate
to think, design, explore, and collaborate.

(dynamic physical object)
to communicate

dynamic physical object
to think with

dynamic physical environment
to think

dynamic physical environment
to explore and collaborate
To achieve this goal, we need to develop

1) **general-purpose methods** to transform arbitrary digital information into tangible, physical forms

2) **interaction models** to program and manipulate the dynamic physical objects and environments

[Images from Victor 2014: Humane Representation of Thought at UIST 2014 Keynote]
As a first step, this thesis explores

1) **dynamic and collective shape construction**
   as a *general-purpose method* to physicalize dynamic digital information

2) **interaction techniques** to program and manipulate dynamic collective elements *through direct physical manipulations*

[Images from Victor 2014: Humane Representation of Thought at UIST 2014 Keynote]
Dynamic Shape Construction and Transformation with Collective Elements

Ryo Suzuki
University of Colorado Boulder
Background

Why This Approach?
Why This Approach?

What is Dynamic and Collective Shape Construction?
Background

Why This Approach?

Concept

What is Dynamic and Collective Shape Construction?

Explorations

Shape Construction with Active Elements

Shape Construction with Passive Elements

Interaction with Collective Elements

- Shape-changing Swarm Robots
- Actuated Swarm Markers
- Modular Inflatable Tiles
- Dynamic Block Assembly
- Swarm Robotic Actuation
- Programming by Demonstration
Background: Why This Approach?

Concept: What is Dynamic and Collective Shape Construction?

Explorations:
- Shape Construction with Active Elements
- Shape Construction with Passive Elements
- Interaction with Collective Elements

Discussion: What's Next?

- Shape-changing Swarm Robots
- Actuated Swarm Markers
- Programming by Demonstration
- Modular Inflatable Tiles
- Dynamic Block Assembly
- Swarm Robotic Actuation
Background

Why This Approach?

Concept

What is Dynamic and Collective Shape Construction?

Explorations

Shape Construction with Active Elements

Shape Construction with Passive Elements

Interaction with Collective Elements

Discussion

What’s Next?
Digital World

Physical World

[Images from Victor 2015: Seeing Spaces]
These two worlds are divided.

Digital World

Physical World
These two worlds are **divided**

**Digital World**

**Physical World**
towards the **seamless integration** of digital and physical worlds
History of Human-Computer Interaction Research

rich history of bringing computation into the real world

Calm Computing
[Ubiquitous Comp., Weiser 1991]

Augmented Reality
[DigitalDesk, Wellner 1993]

Tangible User Interfaces
[SandScape, Ishii 2004]
History of Human-Computer Interaction Research

more recently, researchers started to investigate dynamic physical UI

Augmented Reality
[DigitalDesk, Wellner 1993]

Tangible User Interfaces
[SandScape, Ishii 2004]

Shape-changing Interfaces
[inFORM, Follmer 2013]
History of Human-Computer Interaction Research

Augmented Reality

Tangible User Interfaces

Shape-changing Interfaces

Static Physical Objects + Virtual Objects

Dynamic Physical Objects
shape-changing interface research is inspired by the vision of

“The Ultimate Display would, of course, be a room within which the computer can control the existence of matter.”

“The Ultimate Display” by Ivan Sutherland, 1965
Radical Atoms is a vision for the future of human-material interaction, in which all digital information has a physical manifestation so that we can interact directly with it.

“Radical atoms” by Ishii et al., 2012
Shape-changing Interfaces

- **PneUI** [Yao, UIST’13]
- **Inflatable Mouse** [Kim, CHI’08]
- **Thrifty Faucet** [Togler, TEI’09]
- **Bendi** [Park, CHI’15]
- **inFORM** [Follmer, UIST’13]
- **BMW Museum** [Art+Com ’08]
- **Lumen** [Poupyrev ’04]
- **HypoSurface** [Goulthorpe ’01]

**special-purpose shape-changing interfaces** ↔ **general-purpose shape-changing interfaces**
Shape-changing Interfaces

special-purpose shape-changing interfaces

PneUI [Yao, UIST'13]
Inflatable Mouse [Kim, CHI'08]
inFORM [Follmer, UIST'13]
Thrifty Faucet [Togler, TEI'09]
Bendi [Park, CHI'15]
Lumen [Poupyrev '04]

general-purpose shape-changing interfaces

BMW Museum [Art+Com '08]
HypoSurface [Goulthorpe '01]

inFORM: Dynamic Physical Affordances and Constraints, Follmer et al, UIST 2013
These systems require a large, mechanically complex device, which is difficult to deploy into existing environments.

general-purpose but not deployable
I propose collective shape construction as a way to achieve this goal.
Background

Why This Approach?

Concept

What is Dynamic and Collective Shape Construction?

Explorations

Shape Construction with Active Elements

Shape Construction with Passive Elements

Interaction with Collective Elements

Discussion

What's Next?
Dynamic Physical UI

Shape-changing UI

- Single materials
- Monolithic devices
Dynamic Physical UI

Shape-changing UI

Shape Change with Collective Elements
The focus of this thesis is on a shape that consists of a set of physical units that are separable from each other. These units can be either discrete or non-discrete elements.

- **Discrete Elements**: e.g., LEGO Blocks
- **Non-discrete Elements**: e.g., 3D Printed Objects

**Dynamic Physical UI**

Shape Change with Collective Elements
I argue there are two ways to construct dynamic shape:

1. **Dynamic shape** made of **discrete** collective elements

2. **Active** collective elements
   - **self-actuated** elements that can move or reconfigure themselves with internal actuation

The focus of this thesis is on dynamic shape made of discrete collective elements.
I argue there are two ways to construct dynamic shape.

**Dynamic shape made of discrete collective elements**

The focus of this thesis.

### Active collective elements

- **self-actuated** elements that can move or reconfigure themselves with internal actuation

### Passive collective elements

- **externally-actuated** elements that can move or reconfigure through external actuation

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**Dynamic Physical UI**

Shape Change with Collective Elements
Dynamic Physical UI

Shape Change with Collective Elements

The focus of this thesis is Dynamic shape made of discrete collective elements.

I argue there are two ways to construct dynamic shape:

- **Active** collective elements
  - self-actuated elements that can move or reconfigure themselves with internal actuation

- **Passive** collective elements
  - externally-actuated elements that can move or reconfigure through external actuation
Universal shape transformation with discrete collective elements has been explored in the context of robotics:

- **Self-reconfigurable robots** (e.g., [Yim et al. 2007])
- **Swarm robots** (e.g., [Rubesnstein et al. 2014])
- **Programmable matter** (e.g., [Gilpin et al. 2010])
This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

For information display

(e.g., [Suzuki et al., UIST 2018])

For tangible user interfaces

(e.g., [Suzuki et al., UIST 2019])

Interaction with collective elements

(e.g., [Suzuki et al., CHI 2018])
Dynamic Physical UI

Shape Change with Collective Elements

This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

- For information display (e.g., [Suzuki et al., UIST 2018])
- For tangible user interfaces (e.g., [Suzuki et al., UIST 2019])
- Interaction with collective elements (e.g., [Suzuki et al., CHI 2018])
This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

For information display
(e.g., [Suzuki et al., UIST 2018] )

For tangible user interfaces
(e.g., [Suzuki et al., UIST 2019] )

Interaction with collective elements
(e.g., [Suzuki et al., CHI 2018] )
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For information display
(e.g., [Suzuki et al., UIST 2018])

For tangible user interfaces
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Interaction with collective elements
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For information display (e.g., [Suzuki et al., UIST 2018]).
This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

For information display (e.g., [Suzuki et al., UIST 2018])

In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**.
Dynamic Physical UI

Shape Change with Collective Elements

This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

For information display (e.g., [Suzuki et al., UIST 2018])

Q. Are there any other ways or approaches to construct and represent a physical shape?

In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**
This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

For information display (e.g., [Suzuki et al., UIST 2018])

Q. Are there any other ways or approaches to construct and represent a physical shape?

In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**

To answer this question, I systematically explore a range of possible representations for dynamic physical shape.
This thesis investigates **HCI aspects** of this dynamic and collective shape construction.

For information display
(e.g., [Suzuki et al., UIST 2018])

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**Q. Are there any other ways or approaches to construct and represent a physical shape?**

In robotics, self-reconfigurable robots or programmable matter research often assume **lattice or voxel-like structure**

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Before jumping in, I’d like to first explain with a metaphor to think about how we can render information.

(e.g., Stanford bunny)
how can we *physically* render information?  
(e.g., Stanford bunny?)
**Metaphor:** Representations in Computer Graphics

In Computer Graphics, these are many different ways to render and represent information:

- **Original Information**
- **Point Cloud**
- **Mesh Surface**
- **Voxels**
- **Wireframe**
**Metaphor:** Representations with **Static** Physical Elements

In the same way, there are many ways to *physically* render and represent with **static** elements.

- **original information**
- **voxel** (e.g., LEGO Blocks)
- **surface** (e.g., Origami)
- **connected line** (e.g., 3D Printed Chain)
- **wireframe** (e.g., Zome Tools)
- **sliced layers** (e.g., 123D Make)
How can we **physically** render and represent information with **dynamic** collective elements?
How can we physically render and represent information with dynamic collective elements?

To answer this question, I explored eight possible representations for dynamic and collective shape construction.
I explored eight possible representations for dynamic and collective shape construction:

- Sparse Dots
- Sparse Lines
- Pin Array
- Single Line
- Voxel
- Layers
- Surface
- Hub and Struts

Images and references:
- Reactile [Suzuki 2018]
- ShapeBots [Suzuki 2018]
- LiftTiles [Suzuki 2019]
- ChainFORM [Nakagaki 2016]
- Dynablock [Suzuki 2018]
- Additive Folding [Yim 2018]
- MORI [Beike 2017]
- Morphys [Takei 2012]
Hub and Struts
Surface
Layers
Voxel
Single Line
Pin Array
Sparse Lines

Sparse Dots

[Zooids, LeGoc 2016] [ART+COM 2008] [Reactile, Suzuki 2018]
Sparse Lines

[ShapeBots, Suzuki 2018]

[Torres 2014]
Sparse Dots  Sparse Lines  Single Line  Voxel  Layers  Surface  Hub and Struts

Pin Array

[ShapeBots, Suzuki 2018]  [LiftTiles, Suzuki 2020]  [ShapeCanvas, Everitt 2016]
Sparse Dots  Sparse Lines  Pin Array

Voxel  Layers  Surface  Hub and Struts

Single Line

[Cubimorph, Roudaut 2016] [ChainFORM, Nakagaki 2016] [M-TRAN, Murata 2002]
Layers

[Additive Folding, Yim 2018]  [BendingArches, Morten 2016]
Sparse Dots
Sparse Lines
Pin Array
Single Line
Voxel
Layers
Hub and Struts

Surface

[MORI, Belke 2017] [Morphees, Roudaut 2013] [CurveUps, Guseinov 2017]
Sparse Dots  Sparse Lines  Pin Array  Single Line  Voxel  Layers  Surface

Hub and Struts

[Hammond 2020]  [KineReels, Takei 2011]  [Swaminathan 2019]
Active Elements

Passive Elements

Sparse Dots
Sparse Lines
Pin Array
Single Line
Voxel
Layers
Surface
Hub and Struts
I demonstrate and explore new representations to expand the current scope.
I demonstrate and explore new representations to expand the current scope also discuss future research opportunities and exploration strategies to fill the gap
What is Dynamic and Collective Shape Construction?

- Shape-changing Swarm Robots
- Actuated Swarm Markers
- Modular Inflatable Tiles
- Dynamic Block Assembly
- Swarm Robotic Actuation

Explorations

Interaction with Collective Elements

- Programming by Demonstration

Discussion

What’s Next?
Background:
Why This Approach?

Concept:
What is Dynamic and Collective Shape Construction?

Explorations:
Shape Construction with Active Elements
- Shape-changing Swarm Robots
- Modular Inflatable Tiles

Shape Construction with Passive Elements
- Actuated Swarm Markers
- Dynamic Block Assembly

Interaction with Collective Elements
- Programming by Demonstration

Discussion:
What’s Next?
The focus of this thesis is on Dynamic and collective shape construction. This involves Active and Passive collective elements.

**Active collective elements** are self-actuated elements that can move or reconfigure themselves with internal actuation.

**Passive collective elements** are externally-actuated elements that can move or reconfigure through external actuation.

Shape Change with Collective Elements
The focus of this thesis is on Dynamic and collective shape construction.

**Active** collective elements are self-actuated, meaning they can move or reconfigure themselves with internal actuation. An example of this is shown in the image.

**Passive** collective elements are externally-actuated, meaning they can move or reconfigure through external actuation. Another example is also shown in the image.

Shape Change with Collective Elements

Dynamic Physical UI
Active

collective elements

self-actuated elements
that can move or reconfigure themselves with internal actuation

Zoooids
[Le Goc UIST 2016]

UbiSwarm
[Kim UbiComp 2017]

GridDrones
[Braley UIST 2018]

Rovables
[Dementyev UIST 2016]

PICO
[Patten CHI 2007]

Rolling Pixels
[Lee TEI 2020]
Swarm User Interfaces: Using Swarm Robots as Displays and Tangible User Interfaces
Swarm User Interfaces: Using Swarm Robots as Displays and Tangible User Interfaces
What if these swarm robotic elements can not only represent a shape with sparse dots but also through lines, or pins, or connected lines to expand a range of expressions?
This new type of representations can not only **improve expressions** but also **expand a range of applications** and interaction space.

What if these swarm robotic elements can not only represent a shape with spatially aligned dots but also through lines, or pins, or connected lines to expand a range of expressions?
Collective Shape Transformation

Swarm Robots
Collective
Shape Transformation

Swarm Robots

Individual
Shape Transformation

Shape-changing UI
Collective and Individual Shape Transformation

Collective Shape Transformation

Individual Shape Transformation

Swarms Robots

Shape-changing Swarm Robots

Shape-changing UI
ShapeBots: Shape-changing Swarm Robots

by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
ShapeBots is a demonstration of swarm robots that can both individually and collectively transform their shape. We explore how shape-changing swarm robots can expand a range of expressions for information display as well as application space for tangible user interfaces.

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Miniature Reel Actuator

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Types of Transformation

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Interactive Information Display

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Dynamic Physical Affordances

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Object Actuation

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Adaptive Physical Tools

[UIST 2019] ShapeBots: Shape-changing Swarm Robots by Suzuki, Zheng, Kakehi, Yeh, Do, Gross, and Leithinger
Tabletop-scale

ShapeBots
Tabletop-scale

ShapeBots

Room-scale
LiftTiles: Modular Inflatable Tiles

by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger
Reconfigurable Modular Inflatable Tiles
for Room-scale Shape Transformation

[TEI 2020] *LiftTiles: Constructive Building Blocks for Prototyping Room-scale Shape-changing Interfaces*
by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger
Reconfigurable Modular Inflatable Tiles for Room-scale Shape Transformation

[TEI 2020] LiftTiles: Constructive Building Blocks for Prototyping Room-scale Shape-changing Interfaces by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger
User-customizable and reconfigurable Shape-changing Elements

[TEI 2020] LiftTiles: Constructive Building Blocks for Prototyping Room-scale Shape-changing Interfaces by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger
User-customizable and reconfigurable
Shape-changing Elements

[TEI 2020] LiftTiles: Constructive Building Blocks for Prototyping Room-scale Shape-changing Interfaces
by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger
Dynamic Shape Construction with Active Collective Elements

Dynamic Shape made of Shape-changing Swarm Robots
[Suzuki et al., UIST 2019]

Dynamic Shape made of Modular Inflatable Tiles
[Suzuki et al., TEI 2020]
Shape Construction with **Active** Elements
- Shape-changing Swarm Robots
- Modular Inflatable Tiles

Shape Construction with **Passive** Elements
- Actuated Swarm Markers
- Dynamic Block Assembly

**Interaction** with Collective Elements
- Programming by Demonstration

**Why This Approach?**
- What is Dynamic and Collective Shape Construction?

**What’s Next?**
Background: Why This Approach?
Concept: What is Dynamic and Collective Shape Construction?
Explorations: Shape Construction with Active Elements
Discussion: What's Next?

- Shape-changing Swarm Robots
- Actuated Swarm Markers
- Modular Inflatable Tiles
- Dynamic Block Assembly
- Swarm Robotic Actuation

Interaction with Collective Elements: Programming by Demonstration
The focus of this thesis

**Dynamic** shape made of **discrete** collective elements

**Active**
- collective elements
- self-actuated elements that can move or reconfigure themselves with internal actuation

**Passive**
- collective elements
- externally-actuated elements that can move or reconfigure through external actuation

**Shape Change with Collective Elements**

Dynamic Physical UI
The focus of this thesis

**Dynamic** shape made of **discrete** collective elements

**Active** collective elements

self-actuated elements that can move or reconfigure themselves with internal actuation

**Passive** collective elements

externally-actuated elements that can move or reconfigure through external actuation

Shape Change with Collective Elements
Passive collective elements

externally-actuated elements that can move or reconfigure through external actuation

PixieDust [Ochiai 2014]
Aerial Assembly [Tibbits 2014]
SoftCubes [Yim 2014]
Morphing Cube [Yamaoka 2014]
Actuated Lattice [Torres 2014]
Timber Construction [Leder 2018]
Three Benefits
1. **Scalability**
does not require electro-mechanical components, thus become simple inexpensive

2. **Resolution**
overall size can become small and support large number of elements

3. **Robustness**
provide structural stability that can decrease mechanical breakdown

Passive collective elements

*externally-actuated* elements that can move or reconfigure through external actuation

PixieDust [Ochiai 2014]
Aerial Assembly [Tibbits 2014]
SoftCubes [Yim 2014]
Morphing Cube [Yamaoka 2014]
Actuated Lattice [Torres 2014]
Timber Construction [Leder 2018]
Challenges:
How can we dynamically construct a shape?
Challenges:
How can we dynamically construct a shape?

Example:
Assembling blocks with a robotic is slow because it is Serial process.
Challenges:
How can we dynamically construct a shape?

Serial
only one element is dynamically moving

Parallel
all elements are dynamically moving
how can we apply this for collective shape construction of an arbitrary 3D shape?
Dynablock: Dynamic 3D Printing

by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, Kakehi
Inspiration

Parallel Material Solidification of DLP 3D Printer

[UIST 2018] Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi
Proposed Approach

Parallel Block Assembly with Shape Display
assemble each layer at once

[UIST 2018] Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation
by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi
Proposed Approach

Parallel Block Assembly with Shape Display
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[UIST 2018] Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation
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by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi
Proposed Approach

Parallel Block Assembly with Shape Display
assemble each layer at once
Dynablock: Dynamic 3D Printing
Parallel assembly of collective passive blocks

[UIST 2018] Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation
by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi
3D Shape Construction by Selectively Actuating the Pins

[UIST 2018] Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi
[UIST 2018] Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation
by Suzuki, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and Kakehi
Dynamic Shape Construction with Passive Collective Elements

Parallel actuation of passive building blocks for voxel representation

[Suzuki et al., UIST 2018]
Dynamic Shape Construction with **Passive** Collective Elements

**Parallel actuation** of passive building blocks for **voxel** representation

**Parallel actuation** of passive swarm markers for **sparse dots** representation
Dynamic Shape Construction with **Passive** Collective Elements

- **Parallel actuation** of passive building blocks for **voxel** representation
- **Parallel actuation** of passive swarm markers for **sparse dots** representation
- Externally actuated collective elements with **electromagnetic coil arrays**


Dynamic Shape Construction with **Passive** Collective Elements

Parallel actuation of passive building blocks for **voxel** representation

Parallel actuation of passive swarm markers for **sparse dots** representation

Externally actuated collective elements with **electromagnetic coil arrays**


Dynamic Shape Construction with **Passive** Collective Elements

**Parallel actuation** of passive building blocks for **voxel** representation

**Parallel actuation** of passive swarm markers for **sparse dots** representation

**Parallel actuation** of passive existing objects for **spatial reconfiguration**
Dynamic Shape Construction with **Passive** Collective Elements

**Parallel actuation** of passive building blocks for voxel representation

**Parallel actuation** of passive swarm markers for sparse dots representation

**Parallel actuation** of passive existing objects for spatial reconfiguration

Externally actuated existing static objects with **swarm robotic actuation**

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**RoomShift:** Room-scale Dynamic Haptics for VR with Furniture-moving Swarm Robots

Dynamic Shape Construction with **Passive** Collective Elements

- **Parallel actuation** of passive building blocks for **voxel** representation
- **Parallel actuation** of passive swarm markers for **sparse dots** representation
- **Parallel actuation** of passive existing objects for **spatial reconfiguration**
Actuated Swarm Markers

Background
Why This Approach?

Concept
Introducing Dynamic and Collective Shape Construction

Explorations
Shape Construction with Active Elements
- Shape-changing Swarm Robots
- Modular Inflatable Tiles

Shape Construction with Passive Elements
- Dynamic Block Assembly
- Actuated Swarm Markers
- Swarm Robotic Actuation

Interaction with Collective Elements
- Programming by Demonstration

Discussion
What's Next?
Background

Why This Approach?

Introducing Dynamic and Collective Shape Construction

Concept

Shape Construction with Active Elements

Shape Construction with Passive Elements

Explorations

Shape-changing Swarm Robots

Dynamic Block Assembly

Modular Inflatable Tiles

Actuated Swarm Markers

Swarms Robotic Actuation

Interaction with Collective Elements

Programming by Demonstration

What's Next?
Using dynamic collective elements as an information display or a tool to interact with.
Using dynamic collective elements as an information display or a tool to interact with.

But, collective elements could be more than just a tool or an information display, but also a medium to create or animate through exploration, like clay or building blocks.
how can we use these collective elements as a **medium** to create and explore dynamic motions? what would be the interaction look like?

[Images from Victor 2014: Humane Representations of Thoughts]
constructing dynamic motions often requires programming

interaction happens in real world

programming happens on a computer screen

[Image from Le Goc et al. 2016: Zooids: Building Blocks for Swarm User Interfaces]
How can we enable the end user to create and explore dynamic motions, not through coding on a computer screen, but through direct physical manipulation in the real world?

Reactile: Swarm UI Programming

by Suzuki, Kato, Gross, and Yeh
We propose the following workflow to program dynamic motions through direct physical manipulation:

**Step 1**
Create Elements

**Step 2**
Abstract Attributes

**Step 3**
Specify Behaviors

- user input
- data change
- time

**Step 4**
Propagate Changes

---

Inspiration

Constraint-based Programming
1. Define
2. Bind
3. Propagate

Input Real-time Data Stream Output

Tracking and Parameterization

Input: position, distance, angle, area

Real-time Data Stream: pos = [1.2, 0, 1.5], distance = 1.5, angle = 45, area = 2.2

Output: bind to a graph axis, record and replay

pos = [1.2, 0, 1.5]
distance = 1.5
angle = 45
area = 2.2

Inspiration: Input Real-time Data Stream Output

Tracking and Parameterization

Input: position, distance, angle, area

Real-time Data Stream: pos = [1.2, 0, 1.5], distance = 1.5, angle = 45, area = 2.2

Output: bind to a graph axis, record and replay

RealitySketch: Sketching Embedded and Responsive Graphics in Augmented Reality by Suzuki, Habib, Wei, Diverdi and Leithinger
Inspiration

Constraint-based Programming
1. Define
2. Bind
3. Propagate

<table>
<thead>
<tr>
<th>Input</th>
<th>Real-time Data Stream</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking and Parameterization</td>
<td>pos = [1.2, 0, 1.5]</td>
<td>Binding and Motion Playback</td>
</tr>
<tr>
<td>position</td>
<td>distance = 1.5</td>
<td>bind as a function</td>
</tr>
<tr>
<td>distance</td>
<td>angle = 45</td>
<td>record and replay</td>
</tr>
<tr>
<td>angle</td>
<td>area = 2.2</td>
<td>bind to a graph axis</td>
</tr>
</tbody>
</table>

RealitySketch: Sketching Embedded and Responsive Graphics in Augmented Reality by Suzuki, Habib, Wei, Diverdi and Leithinger
Step 1. Create a shape by sketching
Step 2. Define a parameter to use it as a dynamic variable

Step 3. Bind two parameters to make the shape dynamic

Example:
Creation of dynamic data visualization

Example:
Creation of dynamic data visualization or interactive simulation, gaming, etc

Background

Why This Approach?

Concept

What is Dynamic and Collective Shape Construction?

Shape Construction with Active Elements

Explorations

Shape Construction with Passive Elements

Interaction with Collective Elements

Discussion

What's Next?

- Shape-changing Swarm Robots
- Actuated Swarm Markers
- Modular Inflatable Tiles
- Dynamic Block Assembly
- Swarm Robotic Actuation

Programming by Demonstration
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- Programming by Demonstration
Discussion and Design Implications

1. **Active Collective Elements**
   How can we combine individual transformation as building blocks for various representations?

2. **Passive Collective Elements**
   How can we combine both active and passive elements to construct a dynamic shape?

3. **Collective Actuation**
   How can we leverage multiple active elements to collectively actuate passive materials?
1 - Active Collective Elements

How can we combine individual transformation as building blocks for various representations?
Active Collective Elements

How can we combine individual transformation as building blocks for various representations?

Case Study: ShapeBots
Active Collective Elements

How can we combine individual transformation as **building blocks** for various representations?

Case Study: ShapeBots
Active Collective Elements
How can we combine individual transformation as **building blocks** for various representations?

Horizontal Movement  Vertical Movement  Horizontal Extension  Vertical Extension  Bending  Climbing  Connection  Transformation  Spacing  Pivoting
Pivoting
Connection
Vertical Movement
Horizontal Movement
Horizontal Extension
Vertical Extension
Bending
Climbing
Connection
Transformation
Spacing
Pivoting

extend

bend

: Active Elements
Pivoting
Connection
Vertical Movement
Horizontal Movement
Horizontal Extension
Vertical Extension
Bending
Climbing
Connection
Transformation
Spacing
Pivoting

: Active Elements

bend
extend
shrink
Pivoting
Connection
Vertical Movement
Horizontal Movement
Vertical Extension
Horizontal Extension
Bending
Climbing
Connection
Transformation
Spacing
Pivoting

: Active Elements
Active Collective Elements

How can we combine individual transformation as **building blocks** for various representations?
2 - Passive Collective Elements

How can we combine both active and passive elements to construct a dynamic shape?
Passive Collective Elements

How can we combine both active and passive elements to construct a dynamic shape?

Case Study: Dynablock

Case Study: RoomShift
Passive Collective Elements

How can we combine both active and passive elements to construct a dynamic shape?

Case Study: Dynablock

Case Study: RoomShift
swarm robots that crawl on a passive tube
Pivoting Connection

Horizontal Movement
Vertical Movement
Horizontal Extension
Vertical Extension
Bending
Climbing

Connection
Transformation
Spacing
Pivoting

swarm robots that rotate a passive tube

passive timber

pivot
Hub and Struts
connect

: Active Elements
: Passive Elements
Active Elements
- Sparse Dots
- Sparse Lines
- Pin Array
- Single Line
- Voxel
- Layers
- Surface
- Hub and Struts

Passive Elements
- This thesis
- This thesis
- This thesis
- This thesis
- This thesis
- This thesis
- This thesis
- This thesis
In this way, we can start **exploring new domains** and **filling these gaps**
3 - **Collective Actuation**

How can we leverage multiple active elements to *collectively actuate* passive materials?
Collective Actuation
How can we leverage multiple active elements to collectively actuate passive materials?

Case Study: RoomShift
Collective Actuation

How can we leverage multiple active elements to collectively actuate passive materials?
Collective Actuation

How can multiple active elements collectively actuate passive materials?
Collective Actuation

How can multiple active elements \textit{collectively actuate} passive materials?

\textbf{swarm robots + magnets}

as a prototyping environment for passive shape-changing interfaces
Collective Actuation

How can multiple active elements **collectively actuate** passive materials?

*swarm robots*

that actuate transformable furniture
Collective Actuation

How can multiple active elements collectively actuate passive materials?

swarm robots that are seamlessly blended and integrated into everyday life
Background

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What’s Next?

Modular Inflatable Tiles

Actuated Swarm Markers

Swarm Robotic Actuation
Thank My Advisors and Thesis Committee

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CMU

Rubaiat Habib
Adobe Research

Stephen DiVerdi
Adobe Research

Michael Bernstein
Stanford
Dynamic Shape Construction and Transformation with Collective Elements

Ryo Suzuki
University of Colorado Boulder / @ryosuzk / http://ryosuzuki.org/
Additional Slides
Q&A: Contributions

1.2 Thesis Contributions

This thesis makes contributions to the field of Human-Computer Interaction in the following areas:

1. A design space exploration of dynamic shape construction with collective elements

2. Taxonomy and investigation of active shape construction and transformation with collective elements

3. Techniques for creating a dynamic shape with shape-transformable swarm robots

4. Techniques for constructing 3D shapes with an assembly of passive connectable blocks

5. Techniques for actuating existing objects to reconfigure spatial layouts

6. Techniques for programming the dynamic shape construction on a 2D surface with direct physical manipulation

High-level

1. Exploration of representations

2. Exploration strategy 1: combining building blocks

3. Exploration strategy 2: combining active & passive
Q&A: Representations

Sparse Dots  Sparse Lines  Pin Array  Single Line  Voxel  Layer  Surface  Hub and Struts

Representation

Element

Examples

Reactile  ShapeBots  LiftTiles  ChainFORM  Dynablock  Additive Folding  MORI  Morphys
[Suzuki 2018]  [Suzuki 2018]  [Suzuki 2019]  [Nakagaki 2016]  [Suzuki 2018]  [Yim 2016]  [Beke 2017]  [Takei 2012]
This Thesis  This Thesis  This Thesis  This Thesis  This Thesis  This Thesis  This Thesis
Q&A: Representations

voxel surface line wirefram sliced layers
How can we combine individual transformation as building blocks for various representations?
Q&A: Representations

Is this pin-array? Is this still voxel?

Resolution: 5mm 0.05mm
Q&A: Limitations and Future Work

Information Display vs Fabrication

Dynamic

Static

B
C
D
E
Q&A: Limitations and Future Work

Information Display vs Fabrication

swarm construction
## Q&A: Limitations and Future Work

### Technical Limitations

<table>
<thead>
<tr>
<th>Category</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>computation / communication</td>
<td>central control vs local control (all projects)</td>
</tr>
<tr>
<td>sensing / tracking</td>
<td>only support position tracking (e.g., ShapeBots)</td>
</tr>
<tr>
<td>power supply</td>
<td>only last less than hours (e.g., ShapeBots)</td>
</tr>
<tr>
<td>connection / disconnection</td>
<td>not very stable (e.g., Dynablock)</td>
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Q&A: Limitations and Future Work

Technical Limitations

- **wireless power transformation**
- **electro-permanent magnets**

[IMWUT’18] Luciola: A Millimeter-Scale Light-Emitting Particle Moving in Mid-Air Based On Acoustic Levitation and Wireless Powering, Uno et al.

[ICRA’10] Robot pebbles: One centimeter modules for programmable matter through self-disassembly, Gilpin
Q&A: Limitations and Future Work

Technical Limitations


Q&A: Human in the Loop vs Autonomous

human-robot collaboration

robotic construction

[UIST’16] Autodesk Hive - Crowdsourced Fabrication, Lafreniere et al.

[AIAP’17] BILL-E: Robotic platform for locomotion and manipulation of lightweight space structures, Jenett
Q&A: Deployable / General-purpose

Deployability

Special-purpose

General-purpose

Collective Shape Construction

swarm / modularity

distributed autonomous
Q&A: Applications for Data Physicalization
Q&A: Applications for Accessibility

using robots as both inputs and outputs to help users construct

[CHI’16] Tangible Reels: Construction and Exploration of Tangible Maps by Visually Impaired Users, Ducasse et al.
Q&A: Applications for Accessibility

Application: Tactile Assistant for Blind People

Parallel Actuation
Parallel actuation of a swarm of magnetic markers for sparse dots representation

Point out the location on the map?

Q&A: Dynamic Physical Affordances
Q&A: Dynamic Physical Affordances
<table>
<thead>
<tr>
<th>Feature</th>
<th>Central Control vs Local Control (All Projects)</th>
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Q&A: Global vs Local Computation

distributed control

Robots on the outer edge of the arbitrarily shaped starting group take turns starting motion.

[Science’14] Programmable Self-Assembly in a Thousand-Robot Swarm, Rubenstein et al.

global-to-local compiler

Q&A: Alternative Programming

Object-oriented programming: each element can memorize property so that the user can combine.

Each cube is an object that represents:
- color
- shape
- sound
- expression
- texture
- animation
- ...

change object color to purple

synthesize expression to $\sin(x) + \cos(2x)$

change object animation to $\sin(x) + \cos(2x)$
Q&A: Soft vs Rigid

swarm soft robots

Inflating two central modules results in 3-module shift

Bottom center inflated


modular soft robots

Q&A: Embedded vs Augmented

swarm robots that are seamlessly blended and integrated into everyday life
Q&A: Embedded vs Augmented

Augmenting Desktop Workstation with Actuated Devices

Gilles Bailly
Salvatore Evola
Vincent Valtard
Thomas Pachit
Q&A: Things vs Stuff

The continuum between “things” and “stuff” [source: Zooids, Le Goc et al. 2016]
Q&A: Miniaturization: Towards mm-scale

wireless power transformation

[IMWUT’18] Luciola: A Millimeter-Scale Light-Emitting Particle Moving in Mid-Air Based On Acoustic Levitation and Wireless Powering, Uno et al.

[ICRA’10] Robot pebbles: One centimeter modules for programmable matter through self-disassembly, Gilpin

electro-permanent magnets
Q&A: Miniaturization: Towards mm-scale

e.g., Universal Planar Manipulator by Dan Reznik

e.g., SRI micro factory

Robot B also taps its rod to register it, and then both robots rotate to their original orientations and return to their queues.
Q&A: Interactions

- Inter-robot interaction
- Robot selection
- User-centered navigation

Getting attention:
- Get attention:
  - wave

Move to a specific location:
- Move to a specific location:
  - point with a hand
  - push a robot with a finger

Stop:
- stop:
  - make a stop gesture with 2 hands

Speed up:
- speed up:
  - quickly move palms up and down

Navigation in the environment:
- move:
  - push a robot with a finger
  - push the roav with 1 finger
  - guiding gesture with 2 hands

Stop:
- stop:
  - pull palms on the table
  - quickly rotate one hand
  - quickly rotate both hands

- e.g., Kim et al. User-defined Swarm Robot Control [CHI'20]
Q&A: Design / Technology Choice

Ochiai, Graphics by Computational Acoustic Fields
Q&A: Self-assembly vs External Assembly

[ICRA’09] Roombots: Mechanical design of self-reconfiguring modular robots for adaptive furniture, Sprowitz et al.

BioMolecular Self-Assembly, Tibbits et al.
Q&A: Self-assembly vs External Assembly

[ISS’17] Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality, Zhao et al.
Q&A: Collective Actuation