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.

Today

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

Tomorrow

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

This is not AR, not VR, just R or Dynamic Reality

[Images from Victor 2014: Humane Representation of Thought at UIST 2014 Keynote]

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?

Background

Why This Approach?

Concept

What is
Dynamic and Collective
Shape Construction?

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Why This Approach?

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What is
Dynamic and Collective
Shape Construction?

Explorations

Shape Construction
with **Active** Elements

Shape Construction
with **Passive** Elements

Interaction with
Collective Elements

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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

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

shape-changing interface research is inspired by the vision of

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]

inFORM [Follmer, UIST'13]

BMW Museum [Art+Com '08]

Thrifty Faucet [Togler, TEI'09]

Bendi [Park, CHI'15]

Lumen [Poupyrev '04]

HypoSurface [Goulthorpe '01]

special-purpose
shape-changing interfaces

general-purpose
shape-changing interfaces

Shape-changing Interfaces

PneUI [Yao, UIST'13]

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Bendi [Park, CHI'15]

Lumen [Poupyrev '04]

HypoSurface [Goulthorpe '01]

special-purpose
shape-changing interfaces

general-purpose
shape-changing interfaces

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**

deployability
?
?
special-purpose
general-purpose

deployability
Collective Shape Construction
I propose collective shape construction as a way to achieve this goal
special-purpose
general-purpose

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Dynamic Physical UI

Shape-changing UI

Single materials

Monolithic devices

Dynamic Physical UI

Shape-changing UI

Shape Change with
Collective Elements

Dynamic Physical UI

Shape Change with
Collective Elements

The focus of this thesis

Dynamic shape made of
discrete collective elements

||

a shape that consists of a set of physical units
that are separable from each other

||

(Static) **Discrete** Elements

e.g., LEGO Blocks

≠

(Static) **Non-discrete** Elements

e.g., 3D Printed Objects

Dynamic Physical UI

Shape Change with
Collective Elements

The focus of this thesis

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

Dynamic Physical UI

Shape Change with
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Dynamic Physical UI

Shape Change with
Collective Elements

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])

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])

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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?

To answer this question,
I systematically explore a range of possible representations for dynamic 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?

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

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

(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

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]

Sparse Lines

Pin Array

Single Line

Voxel

Layers

Surface

Hub and Struts

Sparse Dots

[Zooids, LeGoc 2016]

[ART+COM 2008]

[Reactile, Suzuki 2018]

Sparse Dots

Pin Array

Single Line

Voxel

Layers

Surface

Hub and Struts

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]

Sparse Dots

Sparse Lines

Pin Array

Single Line

Layers

Surface

Hub and Struts

Voxel

[Dynablock, Suzuki 2018]

[Zhao 2017]

[M-Blocks, Romanishin 2013]

Sparse Dots

Sparse Lines

Pin Array

Single Line

Voxel

Surface

Hub and Struts

Layers

[Additive Folding, Yim 2018]

[BendingArches, Morten 2016]

Sparse Dots

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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]

Sparse Dots

Sparse Lines

Pin Array

Single Line

Voxel

Layers

Surface

Hub and Struts

Active Elements

Passive Elements

Active Elements

This thesis

This thesis

Passive Elements

This thesis

This thesis

I demonstrate and explore new representations to expand the current scope

Active Elements

This thesis

This thesis

Passive Elements

This thesis

This thesis

I demonstrate and explore new representations to expand the current scope

also discuss future research opportunities and exploration strategies to fill the gap

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Shape Change with
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The focus of this thesis

Dynamic and **collective**
shape construction

Active
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self-actuated elements
that can move or reconfigure
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Active
collective elements

self-actuated elements
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themselves with internal actuation

Zooids
[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

Zooids [Le Goc UIST 2016]

UbiSwarm [Kim UbiComp 2017]

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Rovables [Dementyev UIST 2016]

PICO [Patten CHI 2007]

Rolling Pixels [Lee TEI 2020]

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?

Swarm Robots

Collective

Shape Transformation

Swarm Robots
Shape-changing UI
Collective
Shape Transformation
Individual
Shape Transformation

Collective and Individual
Shape Transformation
Swarm Robots
Shape-changing Swarm Robots
Shape-changing UI
Collective
Shape Transformation
Individual
Shape Transformation

[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

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

Interactive Information Display

[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

[TEI 2020]

LiftTiles: Modular Inflatable Tiles

by Suzuki, Nakayama, Liu, Kakehi, Gross, and Leithinger

[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*
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User-customizable and **-reconfigurable**
Shape-changing Elements

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User-customizable and **-reconfigurable**
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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]

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Shape Change with
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The focus of this thesis

Dynamic shape made of
discrete collective elements

Active
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PixieDust
[Ochiai 2014]

Aerial Assembly
[Tibbits 2014]

SoftCubes
[Yim 2014]

Morphing Cube
[Yamaoka 2014]

Actuated Lattice
[Torres 2014]

Timber Construction
[Leder 2018]

Passive
collective elements

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

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

PixieDust
[Ochiai 2014]

Aerial Assembly
[Tibbits 2014]

SoftCubes
[Yim 2014]

Morphing Cube
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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**?

[UIST 2018]

Dynablock: Dynamic 3D Printing

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

[UIST 2018] *Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation*

by **Suzuki**, Yamaoka, Leithinger, Yeh, Gross, Kawahara, and 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*
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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

Vision

[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**

[ASSETS 2017] *FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers* by **Suzuki**, Stangl, Gross, and Yeh

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

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

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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**

[CHI 2020] *RoomShift: Room-scale Dynamic Haptics for VR with Furniture-moving Swarm Robots*
by **Suzuki**, Hedayati, Zheng, Bohn, Szafir, Do, Gross, and Leithinger

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**

Background

Why This Approach?

Concept

Introducing Dynamic and Collective Shape Construction

Explorations

Shape Construction with **Active** Elements

Shape Construction with **Passive** Elements

Interaction with Collective Elements

Discussion

What's Next?

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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

[Images from Bit Planner, LEGO, Zome Tools]

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?

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

[CHI 2018]

Reactile: Swarm UI Programming

by Suzuki, Kato, Gross, and Yeh

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* 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

Step 4
Propagate Changes

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Inspiration

Constraint-based Programming

1. Define
2. Bind
3. Propagate

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

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

Step 1. Create a shape by sketching

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Step 2. Define a parameter to use it as a dynamic variable

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Step 3. Bind two parameters to make the shape dynamic

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

Example:
Creation of dynamic data visualization

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

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

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by **Suzuki**, Kato, Gross, and Yeh

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What's Next?

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?

● : Active Elements

● : Active Elements

● : Active Elements

● : 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**

● : Active Elements

● : Passive Elements

● : Active Elements

● : Passive Elements

Active Elements

This thesis

This thesis

Passive Elements

This thesis

This thesis

Active Elements

This thesis

This thesis

In this way, we can start **exploring new domains** and **filling these gaps**

Passive Elements

This thesis

This thesis

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 **collectively actuate** passive materials?

swarm robots + magnets

as a prototyping environment for
passive shape-changing interfaces

Collective Actuation

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

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?

Thank My Advisors and Thesis Committee

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Dynamic Shape Construction and Transformation with Collective Elements

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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

Case Study: **Dynablock**

Case Study: **RoomShift**

Q&A: Representations

Q&A: Representations

Q&A: Representations

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

Q&A: Representations

Is this pin-array?

Resolution: 5mm 0.05mm

Is this still voxel?

Q&A: Limitations and Future Work

Information Display vs Fabrication

Dynamic → **Static**

Q&A: Limitations and Future Work

Information Display vs Fabrication

swarm construction

Q&A: Limitations and Future Work

Technical Limitations

computation / communication	*central control vs local control (all projects)*
sensing / tracking	*only support position tracking (e.g., ShapeBots)*
power supply	*only last less than hours (e.g., ShapeBots)*
connection / disconnection	*not very stable (e.g., Dynablock)*

Q&A: Limitations and Future Work

Technical Limitations

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.

electro-permanent magnets

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

Q&A: Limitations and Future Work

Technical Limitations

on-body (magnet)

[UIST'16] Rovables: Miniature On-Body Robots as Mobile Wearables, Dementyev et al.

wall-climbing (gecko-inspired dry adhesion)

[ICRA'07] Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot, Kim et al.

Q&A: Human in the Loop vs Autonomous

human-robot collaboration

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

robotic construction

[AIAA'17] BILL-E: Robotic platform for locomotion and manipulation of lightweight space structures, Jenett

Q&A: Deployable / General-purpose

Q&A: Applications for Data Physicalization

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

Parallel Actuation

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

Application: Tactile Assistant for Blind People

[ASSETS 2017] *FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers* by Suzuki, Stangl, Gross, and Yeh

[CHI 2018] *Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation* by Suzuki, Kato, Gross, and Yeh

Q&A: Dynamic Physical Affordances

Q&A: Dynamic Physical Affordances

Q&A: Global vs Local Computation

computation / communication	*central control vs local control (all projects)*
sensing / tracking	*only support position tracking (e.g., ShapeBots)*
power supply	*only last less than hours (e.g., ShapeBots)*
connection / disconnection	*not very stable (e.g., Dynablock)*

Q&A: Global vs Local Computation

distributed control

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

global-to-local compiler

[Science'14] Designing Collective Behavior in a Termite-inspired Robot Construction Team, Werfel et al.

Q&A: Alternative Programming

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

Q&A: Soft vs Rigid

swarm soft robots

[PLoS ONE'17] Soft Modular Robotic Cubes: Toward Replicating Morphogenetic Movements of the Embryo, Vergara et al.

modular soft robots

[DIS'19] MorphIO: MorphIO: Entirely Soft Sensing and Actuation Modules for Programming Shape Changes through Tangible Interaction, Nakayama et al.

Q&A: Embedded vs Augmented

swarm robots

that are seamlessly blended
and integrated into everyday life

Q&A: Embedded vs Augmented

Immersive Analytics: Definition

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.

electro-permanent magnets

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

Q&A: Miniaturization: Towards mm-scale

e.g., Universal Planar Manipulator by Dan Reznik

e.g., SRI micro factory

Q&A: Interactions

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

self actuation ⟷ *external actuation*

[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