Shells and Stages for Actuated TUIs: Reconfiguring and Orchestrating Dynamic Physical Interaction

by

Ken Nakagaki

B.A, Keio University (2013)
M.M.G, Keio university (2014)
M.S, Massachusetts Institute of Technology (2016)

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Author . . . .
Program in Media Arts and Sciences,
School of Architecture and Planning
August 20, 2021

Certified by . . . .
Hiroshi Ishii
Jerome B. Wiesner Professor of Media Arts and Sciences
Thesis Supervisor

Accepted by . . . .
Tod Machover
Academic Head, Program in Media Arts and Sciences

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Abstract

Research on Actuated and Shape-Changing Tangible User Interfaces (TUIs) in the field of Human Computer Interaction (HCI) has been explored widely to design embodied interactions using digital computation has been explored widely. While advanced technical approaches, such as robotics and material science, have led to many concrete instances of Actuated TUIs, a single actuated hardware system, in reality, is inherently limited by its fixed configuration, thus limiting the reconfigurability, adaptability, and expressibility of its interactions.

In my thesis, I introduce novel hardware augmentation methods, Shells and Stages, for Actuated TUI hardware to expand and enrich their interactivity and expressibility for dynamic physical interactions. Shells act as passive mechanical attachments for Actuated TUIs that can extend, reconfigure and augment the interactivity and functionality of the hardware. Stages are physical platforms that allow Actuated TUIs to propel on a platform to create novel physical expression based on the duality of front stage and back stage. These approaches are inspired by theatrical performances, computational and robotic architecture, biological systems, physical tools and science fiction. While Shells and Stages can individually augment the interactivity and expressibility of the Actuated TUI system, the combination of the two enhances advanced physical expression based on combined shell-swaping and stage-transitioning. By introducing these novel modalities of Shells and Stages, the thesis expands and contributes to a new paradigm of Inter-Material / Device Interaction in the domain of Actuated TUIs.

The thesis demonstrates the concepts of Shells and Stages based on existing Actuated TUI hardware, including pin-based shape displays and self-propelled swarm user interfaces. Design and implementation methods are introduced to fabricate mechanical shells with different properties, and to orchestrate a swarm of robots on the stage with arbitrary configurations. To demonstrate the expanded interactivity and reconfigurability, a variety of interactive applications are presented via prototypes, ranging from digital data interaction, reconfigurable physical environment, storytelling, and tangible gaming. Overall, my research introduces a new A-TUI design paradigm that incorporates the self-actuating hardware (Actuated TUIs) and passively actuated mechanical modules (Shells) together with surrounding physical platforms (Stages). By doing so, my research envisions the future in which computational technology is coupled seamlessly with our physical environment. This next generation of TUIs, by interweaving multiple HCI research streams, aims to provide endless possibilities for reconfigurable tangible and embodied interactions enabled by fully expressive and functional movements and forms.

Thesis Supervisor: Hiroshi Ishii
Title: Jerome B. Wiesner Professor of Media Arts and Sciences

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The following people served as readers for this thesis:

Thesis Advisor . . . .

Hiroshi Ishii
Jerome B. Wiesner Professor of Media Arts and Sciences
Massachusetts Institute of Technology

Thesis Reader . . . .

Joseph Paradiso
Alexander W Dreyfoos (1954) Professor
Massachusetts Institute of Technology

Thesis Reader . . . .

Masahiko Inami
Professor
The University of Tokyo
Research Center of Advanced Science and Technology

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- Ken Nakagaki

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Chapter 1

Introduction

Where the sea meets the land, life has blossomed into a myriad of unique forms in the turbulence of water, sand, and wind. At another seashore between the land of atoms and the sea of bits, we are now facing the challenge of reconciling our dual citizenships in the physical and digital worlds.

Hiroshi Ishii, 1997

1.1 Preface

The aesthetic and richness of nature's seashore is predicated on the vibrant ecosystem built on the interactions of growing coral, dynamic sea creatures, and the interplay of water and sand.

In the past quarter of century, research in Tangible User Interfaces (TUIs) and Radical Atoms [54, 52] have blossomed into a variety of forms at the seashore between Bits and Atoms, Art and Science, or Design and Engineering. From the intensive machinery of densely packed vertically actuated pins [33] and modular robotic devices

[93, 74] to organic shape changing material [174] and biologically cultivated morphing matter [175], these examples have shown how dynamic and adaptive digital information can be seamlessly fused with physical objects and materials. Through each of these, people can interact with digital data in the same way we interact with our physical world.

Rather than introduce another type of new hardware in such a vast ecosystem of digital/physical interfaces, my research opens up an opportunity to explore how different building blocks of Radical Atoms - active machines, passive material, and the surrounding environment - could be designed to work together to offer a new level of reconfigurability to enrich and expand the interactivity and expressibility for tangible user interaction design. Thus, my thesis taps into the ecosystem of Radical Atoms through physical prototype examples that demonstrate how these basic machines make up the building blocks of a mechanical ecosystem that, through their versatility and reconfigurability, can produce endless movements and distinctive motions.

1.2 Thesis Statement

Research on actuated and shape changing TUIs have been explored in the field of Human Computer Interaction (HCI) to provide dynamic physical shapes to digital information for tangible and embodied interactions [19, 52]. The power of physically actuated tangible devices has provided novel opportunities for an embodied and physical user experience design through expressive motions and shapes beyond visual-dominant user interfaces (e.g. screens or head-mounted display). This research is often motivated by an ultimate vision of idealized devices or materials that can physically render any shapes in our reality as presented in Ultimate Display [139], Programmable Matter [39], and Radical Atoms [52].

However, such research has been constrained by the limitations of the inherent physical hardware capability, as any physical devices have limitations in terms of actuation capabilities and hardware configurations (ex. degree of freedom, scalability, resolution or texture). Any interactive hardware is limited by its functionality and capability once it is built. While one of the primary motivations for shape changing actuated interfaces is about developing generic platforms that can provide a versatile interactivity through motion and transformation, they still are limited by their form factor and device configuration built into the initial device. Hence, they limit the expression capability of the hardware, to convey people with richer information, including a narrative conveyed through lively motion and shape. This leads to the question: how can Actuated TUI hardwares' overcome the limitations of their unified configuration for greater interactivity and expressibility?

In this thesis, I propose and demonstrate novel hardware augmentation methods for Actuated TUIs including: *Mechanical Shells*, external passive mechanical attachments, and *Stages*, physical surrounding platforms.

Mechanical Shells are add-ons for Actuated TUIs to convert and expand the motion I/O for versatile and reconfigurable interactivity. The shells are designed to be dynamically docked and undocked (either manually or automatically) to the Actuated TUI hardware to provide a versatile interactivity and dynamic physical affordance. *Stages* are physical platforms for the Actuated TUIs to locomote on and to transition in-between *Front and Back Stages*. In combination with *Mechanical Shells* on *Stages*, Actuated TUIs can dynamically reconfigure their interactivity in the *Back Stage* and appear in the *Front Stage* for user interaction. A broad range of inspiration, from classic computer architecture, biology, theater performance, and everyday tools, inspired these concepts and approaches.

In this thesis, I discuss the concept, interaction design role, and the framework of *Shells* and *Stages*. By doing so, I intend to share the vast opportunities for hardware augmentation methods for generic interactive devices to gain a reconfigurable, dynamic and physical interactivity and expressibility. As research examples, I present prototypes of such hybrid architecture based on two existing generic Actuated TUIs: 1) pin-based shape display, and 2) self-propelled swarm TUIs. This will open-up novel interaction design opportunities for dynamic physical interfaces in rich application areas, including digital data representation / interaction, reconfigurable tangible controllers, functional robotic manipulators, or tangible expressive storytelling and

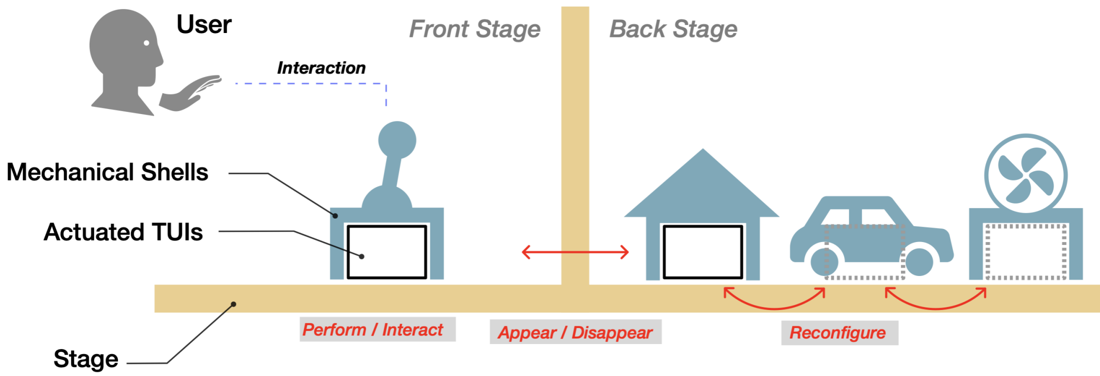


Figure 1-1: *Mechanical Shells* and *Stage* for Actuated TUI

gaming.

Through an investigation into the hardware augmentation methods for A-TUIs, my thesis, in a broader view, introduces a perspective to look at prior research of A-TUIs as building blocks to compose the future of our physical environment, coupled with dynamic computation and digital information. Until now, there have been two major research directions in the research of A-TUIs / Radical Atoms: 1) Active Machines, i.e. self-actuated motorized devices with computational I/O control, and 2) Passive Mechanical Structures, i.e. passively actuated materials / mechanism with computationally fabricated structure. My research, instead of focusing on one or the other, speculates the future of our physical environment where active machines and passive machines are reconfigured to provide versatile interactivity and expressibility. In such a way, my thesis opens up a novel paradigm that gives new perspectives and approaches for fellow researchers and designers to design and develop the next stage of Human-Material / Human-Machine interaction to intersect different modalities of interactive hardware.

1.3 Thesis Contribution

My thesis contributes to the domain of HCI, interaction design and reconfigurable robotics in the following ways:

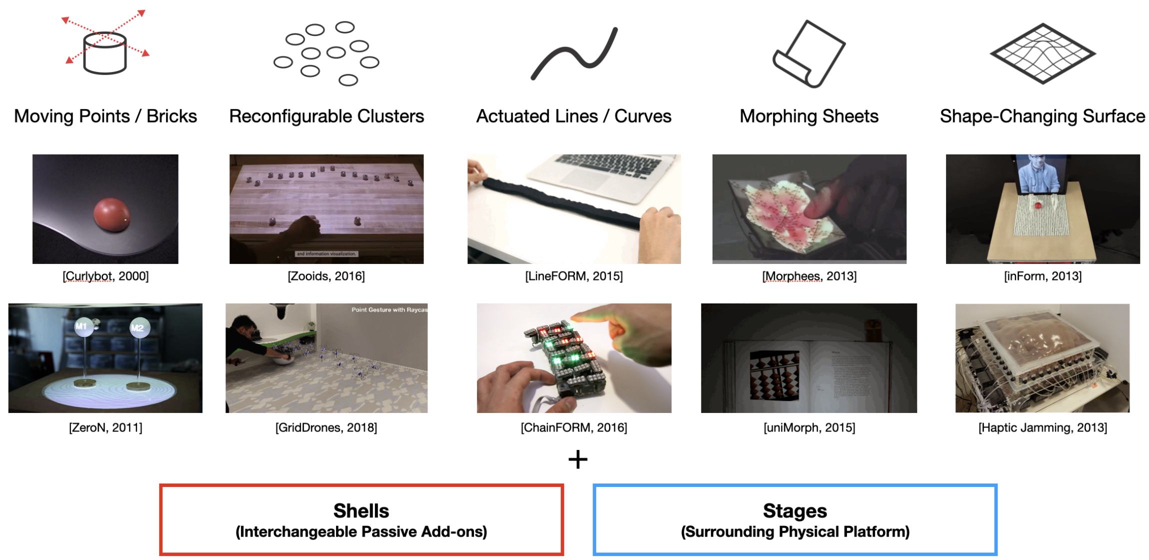


Figure 1-2: *Mechanical Shells* and *Stages* are intended to greatly augment existing types of A-TUI hardware.

1. Introducing Actuated TUI hardware augmentation methods for dynamically reconfiguring their interactivity and expressibility -– to greatly expand the capability of interactive devices. The hardware augmentation methods include:

   - *Mechanical Shells* as interchangeable mechanical add-ons for Actuated TUIs

   - *Stages* as physical platforms for the Actuated TUI systems to locomote on.

2. Demonstrating *Shells* and *Stages* through project examples based on existing Actuated TUI hardware with concrete implementation methods and application examples:

   - *TRANS-DOCK*: reconfiguring the interactivity and functionality of pin-based shape display with manually dockable *Mechanical Shells*

   - *HERMITS*: reconfiguring interactivity of self-propelled TUIs with automated docking Machanical Shells

   - *(Dis)Appearables*: enriching self-propelled TUIs' expressibility with Stages

3. Discussing the challenges and future work for the design and implementation of Shells and Stages to share the research agenda and opportunity for fellow researchers.

4. Laying the foundation for a novel paradigm in Actuated TUI and HCI research to integrate and reconfigure active machines, passive mechanical structures and the surrounding environment to shape a physical ecosystem for inter-device / inter-material interaction.

1.4 Thesis Outline

Figure 1-3 introduces the overall thesis structure. Chapter 2 introduces the context and background in the research domain of Actuated and Modular Tangible User Interfaces, as well as Robotics. In chapter 3, I introduce the concept of the *Mechanical Shell*, a hardware augmentation method for Actuated TUIs with interchangeable passive mechanisms. The overall framework as well as benefits for interaction design are introduced. Chapter 4 and 5 introduce projects for the *Mechanical Shell*: *TRANS-DOCK* and *HERMITS*. In chapter 6, the concept of Stage is introduced. In chapter 7, project *(Dis)Appearables* is introduced as a demonstration of the concept of Stage. This was developed based on the self-propelled system developed in *HERMITS*. Chapter 8 discusses the lessons learned from the exploration of the Shells and Stages, challenges, limitations and future work related to the hardware augmentation methods introduced in the thesis. Chapter 9 concludes the thesis by indicating a novel paradigm of research in the area of Actuated TUIs.

1.5 Terminology Clarification

In this section, I review and clarify the definition of several terminologies I repeatedly use in my thesis.

1.5.1 Actuated TUI Hardware

I refer to Actuated TUI Hardware as "physical devices which have self- actuation capability enabled by a computationally controlled motorized system. It can respond to tangible interactions by users through actuation (shape-changing and motion)."

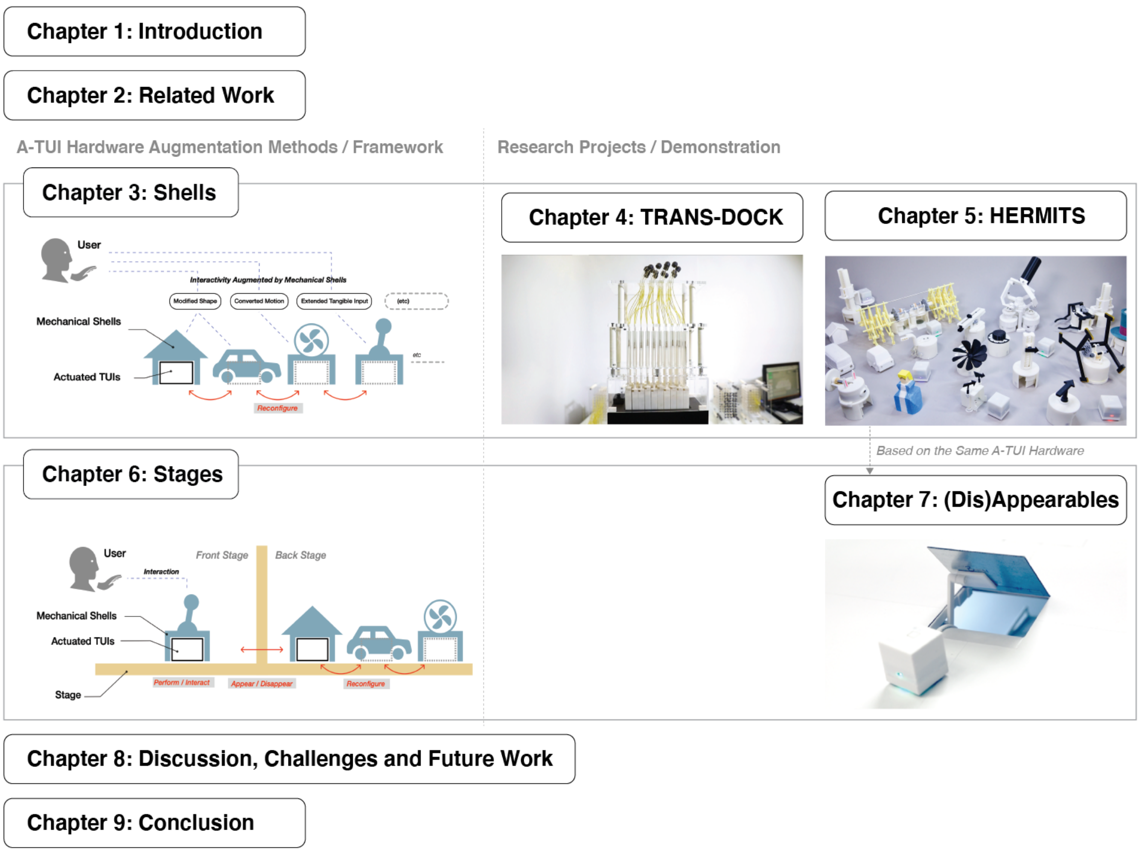


Figure 1-3: Thesis Structure

As shown in Figure 1-2, such devices include: pin-based shape displays, swarm user interfaces, or actuated curve interfaces. Shells and Stages augment such existing interactive hardware.

1.5.2 Interactivity, Reconfigurability, Expressibility

These terms are used when discussing the enrichment of Actuated TUI devices. The term "interactivity" refers to Actuated TUIs' capability to provide input and output capability for user interaction, including display capability for output and controller modality with different affordances for input capability. Also, rich and versatile physical I/O capability is a key criterion. I use "reconfigurability" to refer to how the Actuated TUIs can offer different sets and styles of interactivity through physically interchanging devices and modules so that the system adapts to physical interaction modes and applications. Lastly, "expressibility" describes the capability of Actuated TUIs to convey semantic and narrative expression though motion and shape. As an example, the simple rotation motion of motors can be converted to convey expressibility through a linkage mechanism to express animated motion.

1.5.3 Active Machine and Passive Mechanical Structure

I use the term "active machines" to describe the approach of employing motorized actuated hardware systems that are composed of electrical, computational and mechanical components with self-powered and computationally controlled functionality. Active machines refer to the existing research realm of Actuated TUIs with interactive robotic hardware for pin-based shape display [33, 77] and swarm robotic user interfaces [74]. In contrast, I use "passive mechanical structures" to describe the development of mechanical structural devices that do not have computational and electrical self-actuation elements, but are designed and intended to respond to the external stimuli of force and movement with embedded mechanisms. In terms of existing research, passive machines refer to research in embedding interactivity within physical material structure and mechanisms such as smart materials [37], metamaterial [51] and 4D printing [155]. While the *Mechanical Shell* acts as one of the core concepts presented in this thesis to augment self-actuated TUIs, the terms active machines and passive mechanical structures are used to indicate a broader paradigm of A-TUI research based on two major technical streams in the field.

Chapter 2

Background

This section reviews prior research in HCI and other fields that inform and establish the grounding of this thesis. While in-depth related work related to each research project is introduced in later sections (e.g. Shape Display research for *TRANS-DOCK*, Swarm User Interface research for *HERMITS)*, this chapter contextualizes the overall research paradigm and positioning of my research in a broader context.

2.1 Ubiquitous Computing, TUI, and Radical Atoms

While the Graphical User Interface (GUI) has long been established as the essential mode of interaction for computer interfaces, researchers have long sought to bring the computers out from flat 2D displays and into 3D physical space and real objects. In 1991, in his paper "The Computer for the 21st Century" [166], Mark Weiser coined the term "Ubiquitous Computing", where he envisioned computers being merged into physical environments when computers were still in bulky form factors. Hiroshi Ishii and Brygg Ullmer then established their vision of Tangible User Interfaces (TUIs) in 1997 [54], where they envisioned the integration of digital information into physical objects where users can grasp, touch and manipulate, just as we play with blocks. One of the primary forms of TUIs is combining passive tangible 'pucks' with overlaid graphics where users can manipulate the pucks which are then interpreted by computers to update the dynamic information on the projected images [32, 160].

While the vision of TUIs led to the integration of atoms and bits, the interactive modalities of TUI instances were constrained into inert tangible controllers with dynamic projection. While the graphics were dynamically rendered, the physical matter remained passive, thus researchers aimed to develop and research actuated tangible interfaces [114]. One of the first actuated TUIs developed was an array of electromagnets that controlled the position of tangible pucks [110]. Researchers also began exploring the idea of tangible interfaces that can transform their own shape, which became known as shape-changing interfaces [137, 19]. Following his TUI vision paper, Ishii et al. developed a new vision of "Radical Atoms" later in 2012 [52], which envisions a material with physical transformation / adaptation capabilities. His team presented the vision together with a concept video, named 'Perfect Red', where they demonstrated the concept of digital clay that users tangibly interact with for 3D CAD applications.

2.1.1 Two Major Approaches in Radical Atoms informing Shells

Towards such a vision, researchers have explored and proposed concrete instances with technical implementation methods in the past two decades. I categorize the approaches of this research realm into two technical methods: "active machines" which employ self-powered and computationally controlled electromagnetic motors, and "passive mechanical structures," which make use of the inherent material structure and physical mechanisms that are set in motion by external forces, such as by user manipulation.

The first approach utilizes computationally controlled electric motors to render dynamic shapes and motion. This approach provides a robust and versatile transformation and actuation capability to quickly and dynamically actuate. While this method is far from regarded as organic 'material' due to its own nature (i.e.bulky, heavy or rigid), it has greatly helped researchers to explore the ultimate future of interaction scenarios because of their accurate, dynamic and responsive shape con-

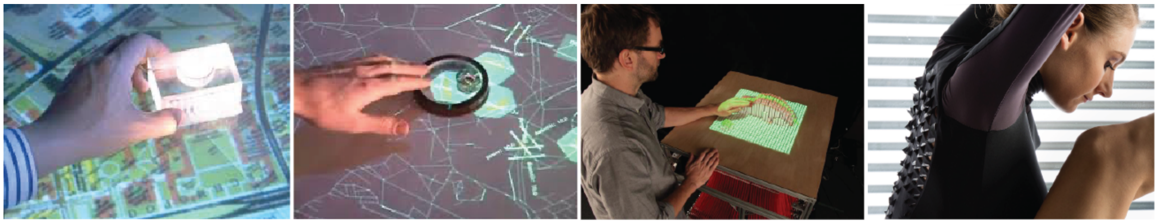


Figure 2-1: Research Related to TUI and Radical Atoms (metaDesk [160], PICO [111], inForm [33], and bioLogic [175])

trol capabilities combined with sensors computationally. Examples of this approach include pin-based shape displays [33, 77], actuated curve interfaces [96, 95] and self-propelled (wheeled/swarm) interfaces [35, 74].

On the other hand, the second approach, the development of programmable material, is a method that explores embedding transformation and interactive functionality into material themselves. This research realm attempts to embed the interactivity into the material structure or property itself through means of digital fabrication, computational simulation, and material science [9, 51, 175], which enable them to react to external mechanical stimuli via passive actuation. While this approach has limitations in terms of the speed of transformation as well as the versatility of shapes, it has the advantages of merging interactive functionality into organic material that can provide high-fidelity organic shapes that are soft, flexible, light, and low-cost compared to motorized methods.

By looking at the field through the lens of this active and passive categories of implementation methods for Radical Atoms, I considered how the next generations of research could make use of a hybrid architecture of active and passive modules to reconfigure dynamically. This hybrid architecture has been manifested in my work "Shell," a physical augmentation method. Shell explores augmenting active machines with passive machines to speculate how the next paradigm of Actuated TUI research may be developed using the combination of these two major approaches.

2.2 Ambient Media and Spatial User Interfaces informing Stages

In the original paper of Tangible Bits [54], one key concept was Ambient Media, an approach to merge computational information into our physical environment via atmospheric examples, such as air, water and wind. Ambient Media combines foreground tangible objects with an environment-based background or atmosphere that provides small bits of information as enriching context. This way of thinking about our physical world in combination with graspable objects and the surrounding environment largely informed the way I have developed the concept of Stages, which acts as an immersive physical space and platform for A-TUIs. The stage allows A-TUIs to transition between the foreground (interactive) and background (ambient) of the user's attention.

While the recent Actuated TUI and Radical Atoms research have successfully developed advanced actuated objects, with the concept of Stage, I intend to create an opportunity to design the surrounding environment, which has the potential to enhance the actuated abilities and interactivity of Actuated TUIs.

2.2.1 Modularity in Tangible Interface Design

To explore modular architecture for actuated TUIs, the modular tangible interface is another important research realm to be mentioned within HCI. As we have learned to construct overall shapes with building blocks, researchers of TUIs have developed integrating computation / digital information with such building blocks. Such research enabled users to reconfigure and construct different shapes while the constructed shapes have been captured by computers. This approach is gaining attention in shape changing / actuated interface research circles in recent years as it allows for customizable robotic / actuated devices and crafts [81, 93, 115].

The idea of extending digital devices using passive objects and materials has been previously explored in HCI. An example of this is how the optical output of a display

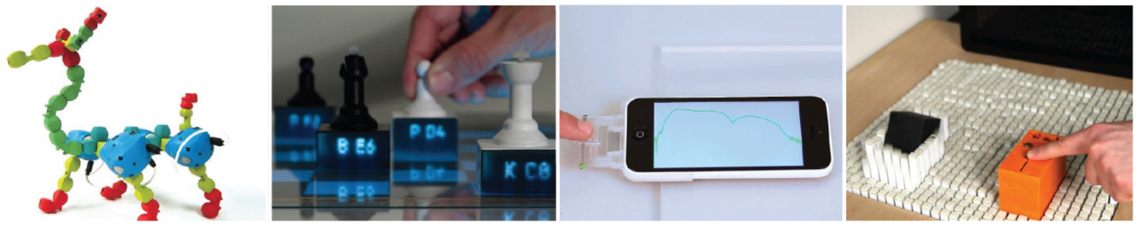


Figure 2-2: Interactive Devices Extended with Passive Tangible Objects (Topobo [115], Printed Optics [169], Acoustruments [73], Kinetic Blocks [125])

was extended using optical fibers to project the displayed images onto other physical surfaces [8, 169]. To extend the input of touch-sensitive surfaces, passive objects with conductive pathways expanded the interaction surface from the touch screens to other physical, tangible surfaces [50, 117]. As for mechanical systems, PrintMotion proposes a unique approach of converting the motion of a 3D Printer with mechanical parts fabricated by the printer itself [64, 63] and extending the shape display's motion with assembly blocks and passive mechanisms [125, 144].

My thesis, with the concept of Shell, introduces a framework and method of augmenting interactive devices using passive mechanical modules. While my research projects focus on translating motion and dynamic shapes of Actuated TUIs with mechanical devices, the framework of Shell can be widely applicable to bring general interactive devices together to form a coherent design.

2.3 Robotics, Modularity and User Interaction Design

The technological prototypes I have developed for my research are based on the motorized mechanical systems of robotics. Robotics, as a field itself, is an interdisciplinary domain that develops physical systems that can locomote through actual environments and manipulate real objects. While a variety of technological areas (e.g. control system, electrical and mechanical engineering, computer vision, etc) support this domain of research, a significant amount of hardware research in this field is related to my thesis work to develop actuated machines with reconfigurable modular

Figure 2-3: Modular, Reconfigurable and Swarm Robotics (Programmable Matter / Claytronics [39, 40], m-blocks [121], Zooids [74], omniSkins [13])

architecture (Figure 2-3).

Robotics researchers have developed modular hardware systems for designing locomotive devices, swarm robots for reconfigurable shapes, and functionalities [61]. Various projects explore the concept of Programmable Matter, with the aim of inventing the ultimate material that can dynamically reconfigure its shapes with magnetically controlled hardware [39, 40]. m-Blocks are modules of cubic blocks with inertia force for self-reconfiguration [121]. Swarm robotics have also been explored to reconfigure to a variety of shapes with multiple self-propelled collectively-controlled hardware [122], which has been extended into HCI research, defined as Swarm User Interfaces (SUIs) [74]. Recently, fabric-shaped robots have been developed by the team of Prof. Kramer-Bottiglios to augment wrapped passive deformable objects with uniquely positioned and shaped hardware [15, 13]. Using the hardware design with the capability of re-configuring and customizing multiple-robotic hardware, the team has demonstrated how a hybrid combination of general-purpose hardware and passive deformable materials could accomplish versatile tasks for robots that can adapt to diverse and unknown natural environments. While their approach focuses on robotic applications, including locomotion, object manipulation and other natural field tasks, my thesis intends to apply such a hybrid research methodology for designing interaction for versatile users' requirements and digital applications with enriched physical interactivity.

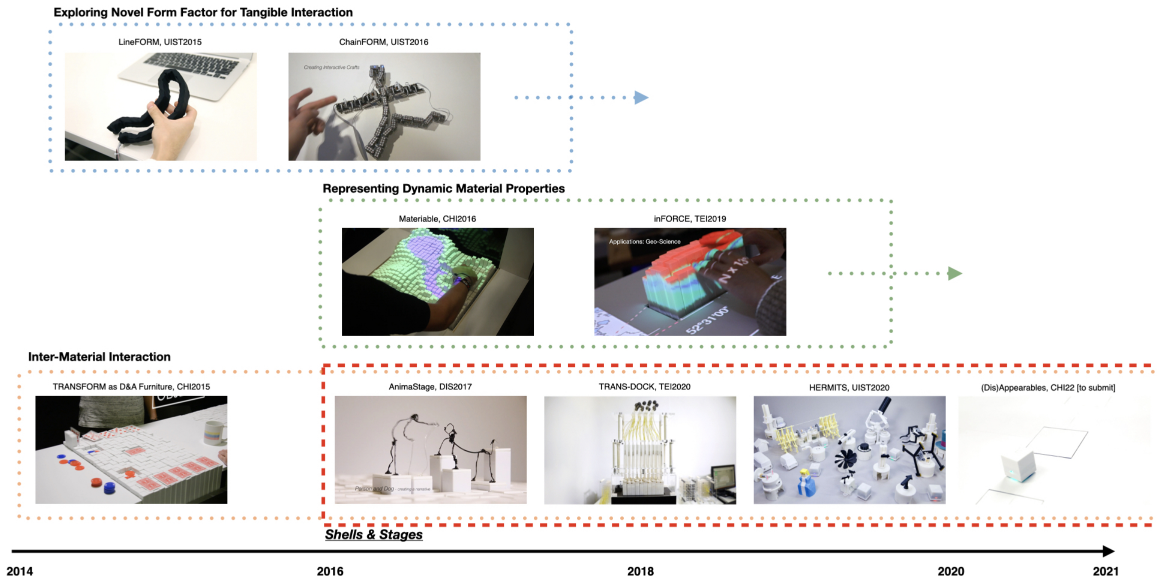


Figure 2-4: My research at the MIT Media Lab on Shape Changing / Actuated TUIs

2.4 My Research at the MIT Media Lab and Positioning of My Approach

For the past 7 years at the MIT Media Lab, I have been exploring the research space of Actuated Tangible User Interfaces in multiple research realms, which has greatly informed my thesis topic (Figure 2-4). With projects like *LineFORM* and *ChainFORM*, I have explored and defined interaction design with a novel form factor of 'Line' for actuated TUIs [96, 93, 95]. With *Materiable* and *inFORCE* projects, I invented software and hardware techniques to enable Shape Changing Interfaces to represent dynamic material properties [100, 94].

In this thesis, Shell and Stages, the hardware augmentation methods I introduce are developed from my prior exploration of inter-material interaction in the domain of Actuated TUIs. Inter material interaction was a concept proposed in *inFORM* [33], as an interaction modality with Actuated TUIs via passive material. I have investigated this realm of research first with the project *TRANSFORM as dynamic and adaptive furniture* to utilize the pin-based shape display as furniture, and demonstrated how the hardware can manipulate objects expressively by flipping cards or moving fruits [164] (Figure 2-5 a,b). *AnimaStage* is another project in this realm that explored the

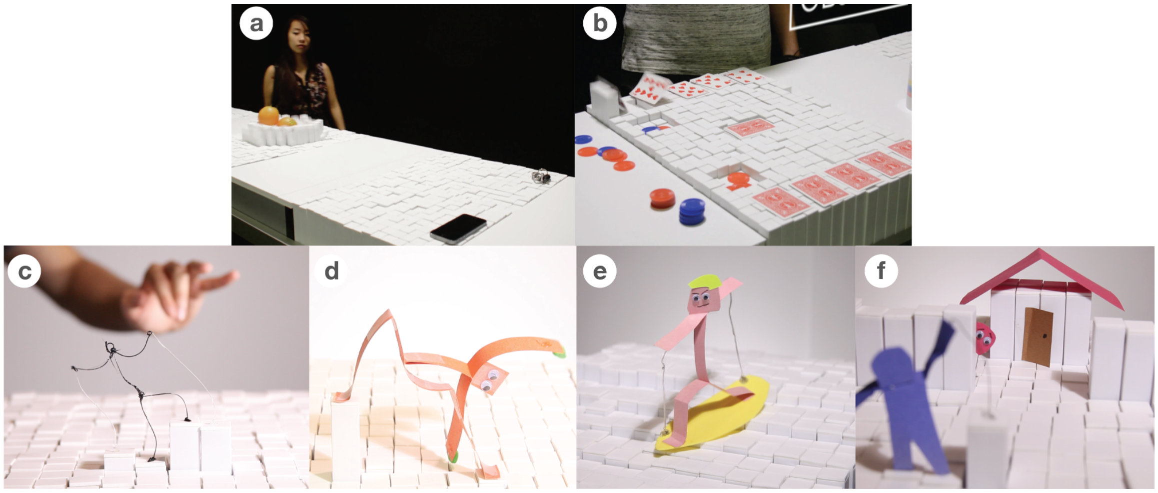


Figure 2-5: My prior research in inter-material interaction with A-TUIs that informs the concepts and methods proposed in this thesis (a, b: TRANSFORM as Adaptive and Dynamic Furniture [164], c-f: AnimaStage [99])

use of pin-based shape displays to give motion to hand-made crafts. This project led to this thesis by informing both concepts of Shells and Stages. One of this work's findings was that using pin-based shape displays' plain vertical pin motions could be translated into fully expressive motions through flexible materials (Figure 2-5 c, d). Also, AnimaStage has demonstrated how the pin-display platform can be used as a stage allowing the materials on-top of the stage to hide materials below, and further augment them for expression (Figure 2-5 e, f). I introduce the concept of Shells and Stages as an extension of these projects in exploring the relationship of active machines and passive material, in combination with the surrounding environment. Finally, this thesis introduces the added contribution of a generalizable framework for other researchers to apply to their work.

Chapter 3

Mechanical Shell: Passive Mechanical Add-ons

3.1 Basic Concept

I define the Mechanical Shell as "an external passive attachment to an existing actuated tangible interface that can be manually or automatically attached and detached, that can adaptively extend, convert and reconfigure the hardware interactivity for versatile tangible applications."

The diagram in Figure 3-1 graphically describes this concept. The shell is an attachment that can modify, convert or extend the interactive functionalities of an A-TUI. For example, *Mechanical Shells* can modify the interactive property of 'shape', convert the 'motion' with a transmission mechanism, or extend other I/O capabilities by taking advantage of installed sensors and actuators in the device of A-TUIs. The *Mechanical Shells* can be designed using a combination of these tangible augmentation capabilities.

As for the role of *Mechanical Shells*, they can serve multiple purposes. By reconfiguring its shape and converting mechanical I/O motion, the *Mechanical Shells* can enhance the dynamic physical affordances to offer a variety of rich interaction capabilities to users such as tangible and haptic controllers as well as shape/data representation. Reconfiguring the shell with expressive and iconic shapes and mo-

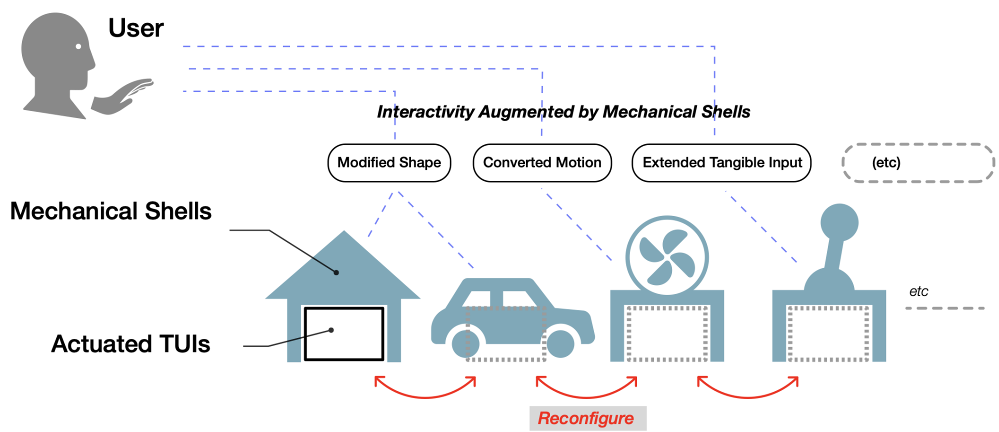


Figure 3-1: Concept of *Mechanical Shell*

tions would enhance its communication capability to users, which can be a great tool for storytelling. Furthermore, the motion conversion capability allows the A-TUI to gain robotic functionality to affect the physical environment as manipulators and locomotors.

3.2 Inspiration - Shell and Architecture Design

The concept of *Mechanical Shell* is developed based on a variety of inspirations including classic computer architecture, industrial mechanical systems, everyday tools, even science fiction and myths. This section overviews those inspirations that informed the concept and design of *Mechanical Shell*.

3.2.1 Inspiration from Computer Architecture

The terminology of mechanical 'shell' is partially inspired from the computer architecture of 'shell', which is a term for one of the most fundamental concepts of a UI coined in the 1960s by Louis Pouzin. 'Shell' was originally developed for users to communicate with the OS (Operating System) of computers for commanding instruction and receiving results through predefined commands for specific and conversation-like interactions. 'Shell' was one of the first concepts of 'interface' which was designed

Figure 3-2: Architectural Inspiration from shell of computer architecture for *Mechanical Shells*

for interfacing between generic computation systems and operating users [92] (Figure 3-2a).

Inspired by the historical, conceptual and systematical role of 'shell' in computer architecture, which acted as an interface which fills in the gap between users and OS, *Mechanical Shell* similarly fills in the gap between A-TUIs (capable of generic but limited interactivity) and users' diverse and specialized needs / requirements (see Figure 3-3). Unlike the original shell (including CLI or GUI shell), the *Mechanical Shell*'s role is not served as an interface to an OS but acts as a literal/tangible 'shell' to interface with generic A-TUI hardware.

"The things that I liked enough to actually take were the hierarchical file system and the shell—a separate process that you can replace with some other process." – Ken Thompson, the first Unix Shell developer [126].

As represented in this quote, one of the most essential values of the original shell concept is the interchangeability to interact with OS with extended and configured commands. This interchangeability is quite inspiring that while relying on the power of OS with general computation capability, the peripheral shell is being replaced to provide very much a different interactive experience depending on users' preferences and requirements. I'm very much inspired by and admire this fundamental concept from the 1960s, and intend to explore this architecture in tangible ways to overcome the essential limitation of the concept of shape-changing and A-TUIs (as in hardware and interactivity constrain).

Other than the shell, in software architecture, it is a common method to use software modules for extending the utility of general-purpose applications (e.g. add-ons or extensions for browsers) (Figure 3-2b). More recently, people customize and

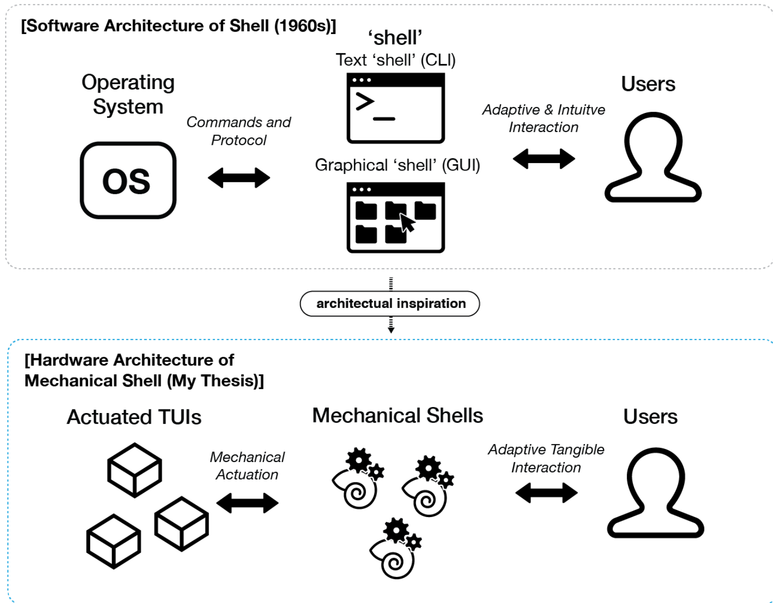


Figure 3-3: Architectural Inspiration from shell of computer architecture for *Mechanical Shells* (a. Shell as in computer architecture, b. Browser Extension, c. Smartphone and apps)

personalize their smartphones functionality with a variety of Apps (Figure 3-2c).

3.2.2 Inspirations from Biology

There are other inspirations in the physical world around us for the concept of *Mechanical Shells* in my thesis. In the world of nature and biology, hermit crabs are known to actively and adaptively switch their shells throughout their lifetimes according to their sizes of bodies for protection (Figure 3-4a). Another example from biology is Parasitism, which is the relationship of an organism in which a parasite lives on another organism, the host, to take over their body (Figure 3-4b) [25]. Such an inter-organism relationship can act as a reference for how different types of A-TUI devices work reconfigurably in the future.

Additional inspiration from biology is metamorphosis in insects - e.g., insects shed their old 'shells' to inhabit new ones when they grow or go from one stage of life form into another (e.g., larva or caterpillar into mature insect or butterfly/moth).

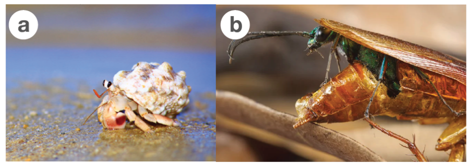


Figure 3-4: Biological Inspiration of *Mechanical Shell* (a. Hermit Crab and Shell, and b. Wasp parasitizing a cockroach [4])

3.2.3 Inspirations from Mechanical System

The interchangeable system, similar to *Mechanical Shell*, is also utilized in industrial engineering machinery. For example, for machining material, automated CNC routers handle versatile tasks only by switching the cutting bits reconfigurably (Figure 3-5a). For motion conversions, the ideas and project examples in my thesis are also heavily inspired by mechanical automata. Mechanical automata are machines that use a combination of mechanical parts to convert driving force for expressive and complicated motions. A variety of mechanical automata artworks greatly extend a simple motion of driving force (e.g. rotation input by a user), to expressive, enjoyable and playful physical motions (Figure 3-5b,c). Using the approach of *Mechanical Shell*, I intend to utilize the power of mechanical conversion to greatly expand the expressibility of A-TUIs for interaction design.

The Turk, or mechanical Turk, is another instance of mechanical machinery from the 18th century, which was designed to trick people into believing that a machine automatically plays chess while it was actually controlled by humans inside (Figure 3-5d). This work provokes novel interaction design opportunities with the hybrid relationship of shell and A-TUIs to trick users' perception of an interactive system. Additionally, an inspiration from Greek Mythology, the Trojan horse, had a shell-like structure to trick its opponent, by controlling a large wooden horse gimmick in which humans can control the motion from inside (Figure 3-5e).

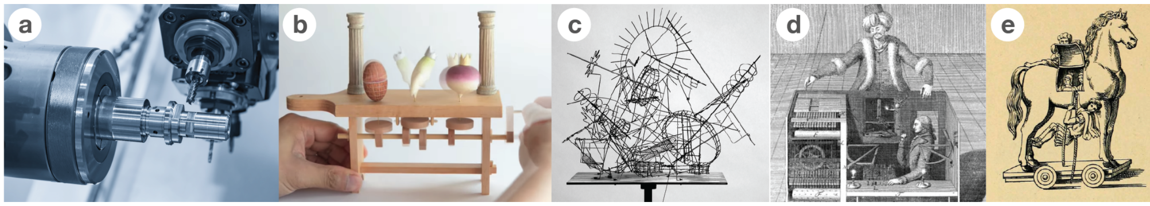


Figure 3-5: Inspiration for *Mechanical Shells* from Mechanical System (a. multi-tool machining center, b. mechanical automata by kazuaki harada [66], c. kinetic art by Arthur Ganson [38], d. mechanical turk, e. Trojan Horse)

Figure 3-6: The inspiration for *Mechanical Shells* from everyday tools and human augmentation (a. electric drill and drill bits, b. camera and lenses, c. hand tools, d. Skeltonics Exoskeleton [23]).

3.2.4 Inspiration from Everyday Tools and Human Augmentation

In our everyday life, we utilize tools with interchangeable architecture similar to shells. For example, electric drills have the core motor and battery whose functionality can be reconfigured for specific function with drill bits (Figure 3-6a). SLR Cameras have lens changing functionality, to expand and reconfigure the optic-capturing capabilities (Figure 3-6b).

When we look at the relationship of human and tools, they have a very similar relationship to A-TUI and Shells. We utilize and interchange tools to accomplish certain tasks, but tools help us to translate our kinetic action to perform certain tasks (Figure 3-6c). In such way, human augmentation is one of the important inspiration source for *HERMITS*. An advanced example of this realm is the design of exoskeleton human augmentation devices, as shown in the Figure 3-6d. While there are a variety of motorized exoskeletons, passive exoskeletons, like *Skeletonics* [23], convert and extend motor skills of human with mechanical transmission systems, which are lighter and cheaper when compared to motorized ones.

Figure 3-7: The inspiration for *Mechanical Shells* from Sci-Fi (a. Mobile Suit Gundam, b. Neon Genesis Evangelion, c. Attack on Titan, d. Ghost in the Shell).

3.2.5 Inspiration from Science Fiction and Other Sources

Lastly, there are numerous inspirations for shells from Science Fiction, including novels, movies and anime. For example, there are many Japanese animations themed on piloting robots that have a similar modality to Mechanical Shell where humans ride in the larger bodies of the machine to control and fight (e.g. Gundam, Figure 3-7a). In Neon Genesis Evangelion, or Attack on Titan, the core human and larger control bodies are biologically connected, providing the kinesthegia and senses being felt by the larger body to the nerves of the core human body (Figure 3-7b, c). The metaphor of shell is also used to install human minds and conciousness to a body (shell), to imagine how our minds can be easily translated in different bodies as in the works of Ghost in the Shell or the Matrix (Figure 3-7 d). Some novels and SciFi themes also explore robots parasitizing each other - for example, in Clifford D. Simak's classic novel 'City' from 1952 [130], he postulated an ant-sized robot that would bore into a larger robot and make its way to its artificial brain, causing the large robot to leave its current job and go off to work for the owners of the ant robot 'parasites'.

3.3 Roles and Benefits of Mechanical Shells

While the modular architecture can be seen in computer architecture, nature, and other artifacts, I would like to categorize its value in this section from the perspective of interaction design and user utilities. Mechanical Transducers extend the interactive device in the categories described below.

3.3.1 Adaptation for Human Interaction (Display / Affordance)

Firstly, the adaptability of direct human interaction can be enriched with the hybrid modularity of *Mechanical Shells*. The way interactive devices interact with humans can be adaptively interchanged with the *Mechanical Shells*. This capability brings the interactive devices to display information in more expressive ways, where the modality can be interchanged depending on the displaying contents. For human interaction, affordances are also an important interactive concept. With the interchangeable transducers, the physical affordances can be dynamically interchanged with the hybrid modularity.

3.3.2 The Versatility of Functionalities (Tasks and Locomotion)

Secondly, functional tasks can be extended with the hybrid modular architecture. Similar to the case of drill bits, the extending transducer defines the functionality of the interactive device (drill holes / tie screws). This provides the capability of interactive devices to have functions that the device itself would not be able to do. The types of functionality would include the way devices interact with other objects (tasks to handle / detect other objects) or the way the device locomotes in the field in the case of robotic systems.

3.3.3 Other Logistical Utilities

Thirdly, by letting interactive devices handle versatile tasks and human adaptation, the hybrid architecture with *Mechanical Shells* would provide multiple logistical utilities. For example, the Mechanical Shell approach would contribute to saving space, cost, and materials by taking advantage of its modular reconfiguration capability. While a number of interactive hardware is usually required depending on the purpose to provide versatile interactivity, our approach may contribute to the sustainability aspect which is listed as one of the grand challenges in shape-changing actuated tangible interfaces in the field [1]. Thus, the hybrid modular architecture also has the advantage of saving space / cost / materials, by off-loading the expensive / bulky parts to the core interactive devices while the *Mechanical Shells* convert their interactive capability. Similar to the way smartphones are well-customized with interchangeable cases, *Mechanical Shells* may also benefit the future of actuated tangible interfaces for protection or personal expression.

3.4 Design Framework and Implementation Strategy

This section overviews the basic design framework related to the Mechanical Shell that extends the interactivity of A-TUIs. This diagram defines the research strategies and opportunities for extending the interactivity of generic interactive devices.

Figure 3-8 shows the research framework which defines the research space of the overall interaction architecture with *Mechanical Shells*. This framework can be a strategic guideline for researchers and designers to develop their own Mechanical Shell system, to augment generic A-TUI for versatile interactive functions. Overall, the left gray box represents interactive hardware of A-TUIs which contain a set of potential interactive properties beyond actuation/shape-change (such as how *HERMITS' Mechanical Shells* utilized the illumination of LED.) The *Mechanical Shells* have to be designed in consideration with these properties of the designated general-purpose A-TUIs to be extended to achieve specific interaction purposes.

This framework is also composed of multiple design elements for developing the interactive architecture, including Mechanical Shell's functionalities, docking protocol, design and fabrication methods, interaction targets, and control methods. In my thesis projects, I have partially investigated different aspects of this framework, while there are other opportunities which I wish to explore in future projects.

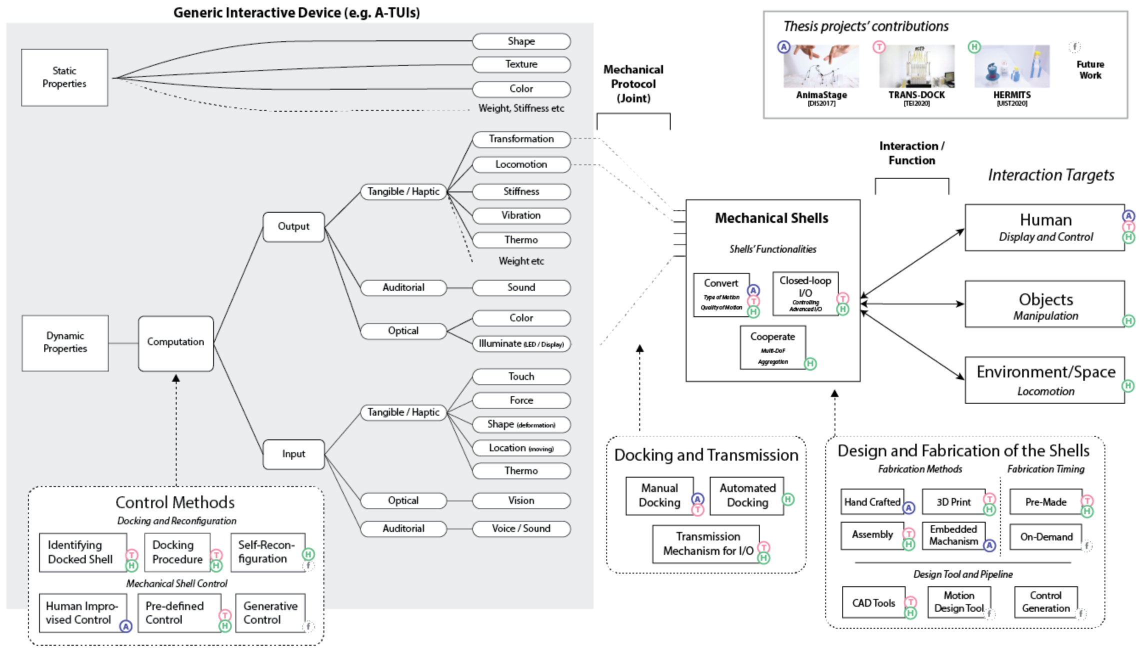


Figure 3-8: Research Framework to Extend the Interactivity of A-TUIs with *Mechanical Shells*

3.4.1 Mechanical Shell Functionalities

In terms of Mechanical Shell functionality, they can, first, convert the interactivity of the device by extending the primitive physical interactive properties, including shape, motion, and optics. Secondly, utilizing this conversion, they can make a reconfigured closed-loop input/output relationship by taking advantage of the sensor and actuator combinations. With this combination of input and output, versatile interactivity can be developed and defined through the shells. Thirdly, for generic actuation devices that are capable of collectively controlled or equipped with multiple actuators for large numbers of degrees of freedom (DoFs), the Mechanical Shell can be designed to be activated through the cooperation of multiple actuation units. This feature enables the Mechanical Shell to let A-TUIs achieve complex interactive properties the device itself cannot accomplish.

3.4.2 Docking and Transmission

How docking works between *Mechanical Shells* and A-TUIs is a necessary design criterion to be considered. They can either be manually docked or automatedly docked depending on the capability of A-TUIs. The transmission mechanism for I/O is another criteria for making a robust connection to transmit the interactivity well.

3.4.3 Design and Fabrication of Shells

The design and fabrication of shells provide many research opportunities to extend the interactivity of a system. For example, the shell can be fabricated in different ways, either manually crafted (as in AnimaStage), pre-fabricated, or on-demand fabrication. While relying only on prefabricated shells would limit the versatility of the interactivity, I think the on-demand fabrication method (e.g. rapid and instant fabrication machine) would expand the versatility of the system. The mechanics of the shell can also be crafted with assembled parts but has the potential to be applied with smart material / meta-material approaches. Additionally, design tools could be improved for the system to let users design their own shells that meet their needs / or full automated design to achieve optimized shell design.

3.4.4 Interaction Target

The *Mechanical Shells*, as a result of the whole interaction architecture, can dynamically and adaptively interact with different interaction targets. Designing for the human is the primary focus of my thesis to provide different display capabilities, dynamic physical affordances, or direct haptic interactions including force control. Other targets include objects for A-TUIs to manipulate them adaptively and environment/space for the devices to locomote through. Through interacting with objects and space through *Mechanical Shells*, the A-TUIs gain an inter-mediated interaction with humans.

3.4.5 Control Methods

Lastly, the control methods of A-TUIs for interaction architecture are an important topic to be considered. Control methods can be divided into two major modes. The first one is the control in docking and reconfiguration. How would the system or individual actuated devices be controlled to dock to the appropriate *Mechanical Shells* by adapting to users' needs or digital applications? While such reconfiguration control is a primary research challenge in automated docking, the manual docking would require control in docking for passive docking. Secondly, the mode of control for A-TUIs when being attached to specific *Mechanical Shells* is a research opportunity and crucial for this interaction architecture. This mode is important for the A-TUIs to adaptively switch the control for creating intended output and detecting input depending on the docked *Mechanical Shells*. As different types of *Mechanical Shells* would require different control modes, the approach to develop such a control in a customizable manner is a relevant area of study. It may be able to be programmed in code beforehand by users, perhaps even using a tangible programming method (kinetic programming) for the system to record intended motion / input patterns by users. Once the *Mechanical Shells* are designed with specialized design software, such controls could be generated automatically, as the software interprets the interaction control based on the mechanical design.

Chapter 4

TRANS-DOCK

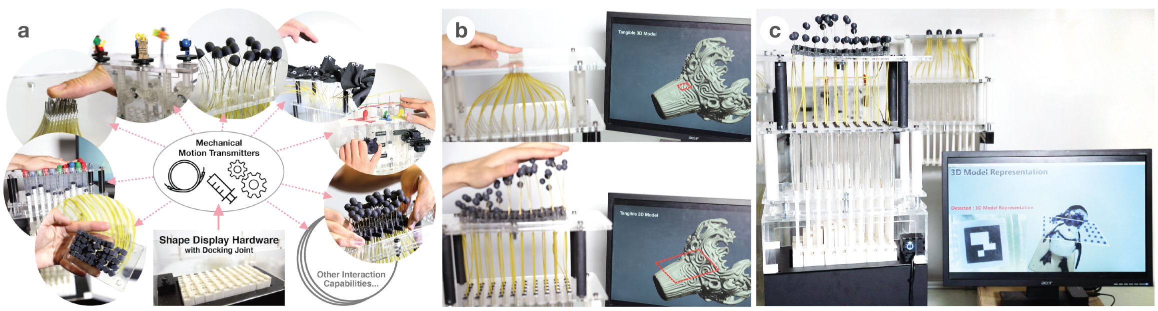


Figure 4-1: TRANS-DOCK: *Mechanical Shells* for Pin-based Shape Display.

Contributors in this project: Ken Nakagaki, Yingda (Roger) Liu, Chloe Nelson-Arzuaga, and Hiroshi Ishii.

Abstract

This chapter introduces *TRANS-DOCK*, a docking system for pin-based shape displays that enhances their interaction capabilities for both the output and input. By simply interchanging the *Mechanical Shell* transducer module, composed of passive mechanical structures, to be docked on a shape display, users can selectively switch between different configurations including display sizes, resolutions, and even motion modalities to allow pins moving in a linear motion to rotate, bend and inflate. We introduce a design space consisting of several mechanical elements and enabled interaction capabilities. We then explain the implementation of the docking system and transducer design components. Our implementation includes providing the limitations and characteristics of each motion transmission method as design guidelines. A number of transducer examples are then shown to demonstrate the range of interactivity and application space achieved with the approach of *TRANS-DOCK*. Potential

use cases to take advantage of the interchangeability of our approach are discussed. Through this exploration, we intend to expand expressibility, adaptability and customizability of a single shape display for dynamic physical interaction. By converting arrays of linear motion to several types of dynamic motion in an adaptable and flexible manner, we advance shape displays to enable versatile embodied interactions.

4.1 Introduction

Shape Changing Interfaces, a rapidly growing research area in the field of HCI over the past decade, enable tangible, embodied and haptic interactions with dynamically rendered physical shapes [19, 116, 52]. While various kinds of actuation techniques and form factors have been introduced to explore their capabilities and applications [96, 74, 174], pin-based shape displays have become one of the most popular approaches [77]. This type of shape display is composed of arrays of vertically actuated pins that can dynamically render entire 2.5D shapes and motions.

A great number of applications using this type of display have been introduced, including remote collaboration [76], material simulation [100], data physicalization [148], animated craft [99], assembly [125, 144], VR [131, 31], AR [78], artistic expression [53], and adaptive furniture [164]. Simultaneously, a range of technical implementations have also been developed, including resolution improvement [178], scaling to room size [60], adding a movable-base [131, 31], detecting or representing variable force [94], and developing a mobile system [57, 12]. In this previous research, different configurations of shape display hardware have been developed to explore, prototype, and evaluate specific applications and interactions. Yet, the hardware setup of each shape display is often fixed or limited to a single kind of configuration (e.g. display-size, resolution, pin-alignment, and linear pin-movement), thus restricting the potential interaction capability enabled by a single system.

To enhance the capability of pin-based shape displays, we propose a method of using interchangeable *Mechanical Shell* transducers that can be docked on a shape display (Figure 4-1a). Using this approach, shapes and motions rendered by a pin-based shape display can be converted into a range of varied configurations, including pin-spacing, shape rendering area and pin-alignment. Additionally, even types of motion can be converted from linear motion to other modalities like bending, inflation, and rotation. Prototypes for our transducers were designed for a 10x5 shape display that is capable of both shape rendering (output) and force and position detection (input). Based on this idea, we prototyped a variety of example transducer modules that demonstrate the expanded interactivity and application space for pin-based shape display research (Figure 4-1b and c).

This work intends to contribute not only to pin-based shape display research but also to shape changing interface research in general, with the approach of broadening the hardware capability of a single shape changing interface through docking interchangeable passive mechanical systems. The expanded interaction capabilities based on this approach enhances three aspects of functionality for actuated interfaces: ***expressibility*** of the display and representation of digital models with extended actuation modalities, ***adaptability*** of a system that conforms to a range of user requirements and applications, and ***customizability*** of the configurations for users and designers to choose their preference of physical interfaces. Our contribution in this project includes:

- A general method to expand display and interaction capabilities of pin-based shape displays by docking passive *Mechanical Shell* transducers.
- Design space for the *Mechanical Shell* of TRANS-DOCK to enable a range of configuration and motion modalities based on three basic motion transmitters.
- Technical implementation of the docking system and mechanical transducers with a design guideline on mechanical configuration methods.
- Examples of transducer prototypes and potential use cases to motivate the proposed method.

In TRANS-DOCK, I refer to the Mechanical Shell as "transducers" or "mechanical transducers" in the writings and figures, as it was originally defined in our pub-

lished paper [98]. While transducers are used to be intended for motion transmission system, the defined concept largely overlaps with Mechanical Shells.

4.2 Related Work

The idea of extending digital devices using passive objects and materials have been previously explored in HCI. An example of this is how the optical output of a display was extended using optical fibers to project the displayed images onto other physical surfaces [8, 169]. For the purpose of extending the input of touch sensitive surfaces, passive objects with conductive pathways expanded the interaction surface from the touch screen to other physical, tangible surfaces [117, 177, 65]. As for mechanical systems, there are industrial robotic arms with a reconfigurable end effector system that adapts to a range of object handling tasks [120]. PrintMotion proposes a unique approach of converting the motion of 3D Printer with mechanical parts fabricated with the printer itself [64]. Our approach is to specifically extend pin-based shape displays to expand their actuation and tangible interaction capabilities.

One of the first pin-based shape displays, *FEELEX*, developed by Iwata [55], aimed to provide haptic sensation to computer graphics by projecting video onto an actuated surface. Based on their vision of *Radical Atoms* [52], Follmer et al. developed *inFORM*, 30x30 pin-based shape display hardware to explore novel interaction techniques, including dynamic physical affordances, object manipulation and remote collaboration [33, 76]. The idea of utilizing shape displays to manipulate the surface of physical objects was further explored using assembled passive blocks [125, 144], animated crafts [99] and dynamic furniture applications [164]. Among them, Schoessler et al.'s *Kinetic Blocks* project partially explored how passive blocks with integrated mechanical gears can translate the vertical motion of shape display pins to horizontal and rotational motions [125]. In comparison, our approach further explores this method by using a variety of mechanical elements, including Bowden cables and pneumatics. Different types of passive transducers have pre-designed pin and motion-configurations that can be replaced on-demand. The most important and original aspect of our research is the conversion of multiple pin configurations (pin-alignments, resolutions etc.) enabled through passive transducers and a docking-system which physically connects all pins at once.

To enrich the adaptability and customizability of shape changing interfaces, some researchers have proposed using modular actuated hardware [93, 115]. *ShapeClip* was proposed for designers, particularly for pin-based shape display systems, to design their own shape displays with custom configuration including resolutions, pin-alignments, number of pins and deformation of flexible surfaces [47, 29]. *TRANS-DOCK* takes a different approach in that it adds passive transducers to the existing hardware of shape displays with fixed configurations. Additionally, a recent review paper [1] highlights that one of the grand challenges for Shape Changing Interfaces is sustainability, stating that their "morphing ability should ultimately reduce the need for multiple instances of similar devices and therefore reduce long-term resource requirements." We believe that our method in *TRANS-DOCK*, with its interchangeable passive structure, may contribute to this effort.

4.2.1 Pin-based Shape Display Hardware Review

We briefly overview the properties and configuration of previously proposed shape display hardware to characterize their versatility and how each are designed for specific applications. With this, we emphasize how our method of expanding shape display capabilities may adapt to a variety of applications / interaction scenarios. This review is also intended to build the foundation for our design space of transducers which is discussed in a later section (Figure 4-4).

In his PhD thesis, Leithinger identified comprehensive properties of pin-based shape displays as Area, Pin Spacing, Pin Diameter, Vertical Range, Speed, and Haptic Feedback [75]. We refer to these characteristic properties and utilize them in our transducer design space. In previous research, higher resolution (small pin size, and spacing) is often preferred to provide high density shape representation [178, 12] while others prioritized a large area (larger pin size and spacing) for bodily / room scaled interaction and furniture applications [80, 164, 60].

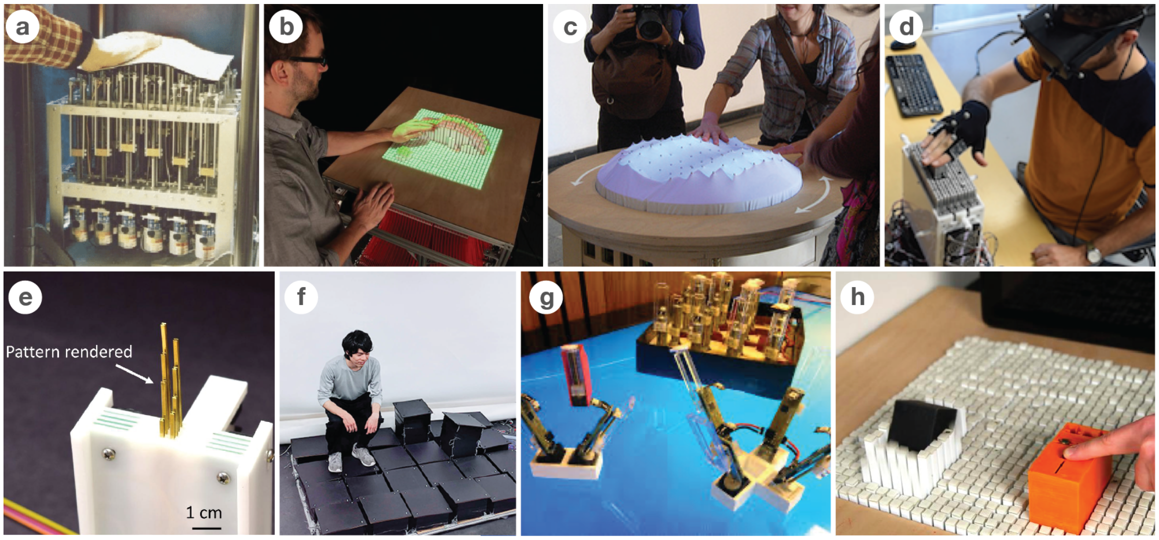


Figure 4-2: Related Work of TRANS-DOCK (a. FEELEX [55], b. inForm [33], c. Relief [79]), d. ShapeShift [131], e. High Resolution Shape Displays [178], f. LiftTiles [142], g. ShapeClip [47], h. KineticBlocks [125])

While Leithinger's review was sufficient for standard shape display conditions, other types of unique shape display parameters have been explored. Other than basic primitive motions, non-linear motions such as inflation [106, 36] and bending [103, 105] was explored for artistic representation and organic transformation. While pin-based shape displays are often configured with a horizontal plane, vertical planes are also used to compose shape changing walls [18, 60]. Non-constrained planes with 2D and 3D movable pin displays were proposed for spatial and mobile interaction [131, 12]. Overlaying a continuous material such as a sheet of fabric on pin-based shape displays is another unique configuration to render smooth shape especially to compensate for the coarseness of low-resolution displays [79, 55, 165, 29]. Variable force control was added to expand the haptic interaction with shape displays [94].

4.3 TRANS-DOCK

4.3.1 Overall Design

By introducing passive mechanical transducers, we intend to broaden the interaction capabilities of shape display hardware by enhancing its expressibility, adaptability,

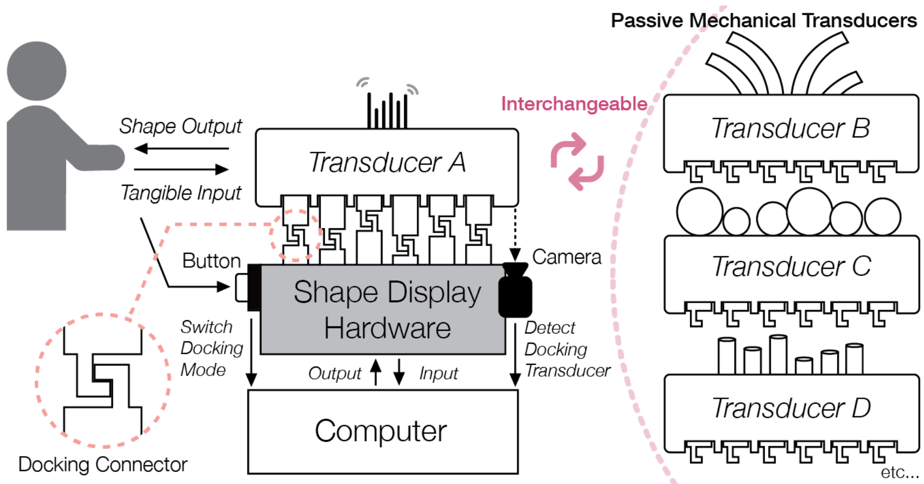


Figure 4-3: Overview of *TRANS-DOCK* configuration composed with interchangeable transducers, shape display, computer, camera and button.

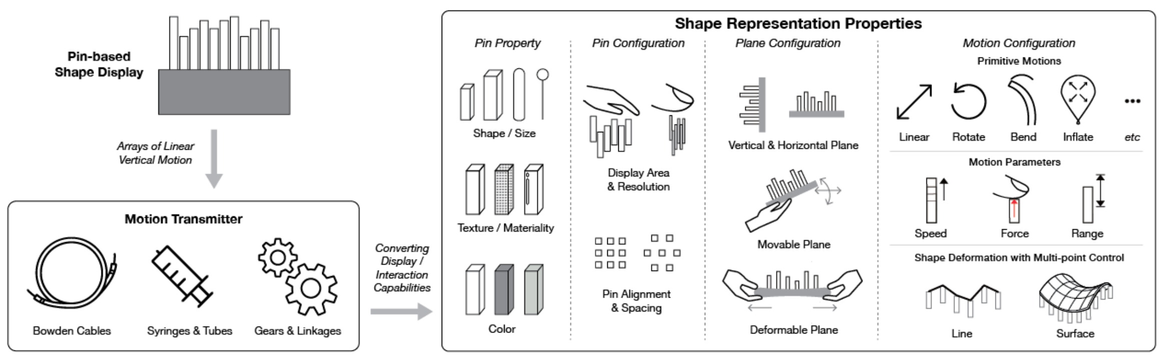


Figure 4-4: Design Space of Transducers; Linear Motion of Pin-based Shape Display being converted through Several Types of Motion Transmitters to Variety of configurations.

and customizability. Figure 4-3 shows the overall design configuration of *TRANS-DOCK*, which demonstrates how multiple interchangeable transducers can be docked to the existing shape display hardware. Each transducer converts the linear actuation of shape display pins into other actuation modalities and configurations with the docking joints. The camera and button are used to support the computer to moderate the docking process. Design space, implementation, and technical design guidelines are described in the following section.

4.3.2 Transducers Design Space

Figure 4-4 presents the design space for *TRANS-DOCK* transducers. This design space is developed based on a reference to previous shape display hardware (discussed in 4.2.1). We intend to develop this design space to be a comprehensive list of properties that can be used when designing and developing transducers.

For each transducer to provide different types of display and interaction capabilities, transducers are mechanically composed with one or more types of *Motion Transmitters*. By composing these transmitters, the original shape display's pin can be converted into other properties. *Shape Representation Properties* presents the comprehensive list of properties including pin properties, and pin, plane and motion configurations.

Motion Transmitters

Motion transmitters are enabling elements that convert the vertical linear motion of the shape display into other configurations and motion modalities. For example, a **Bowden cable** is a flexible cable that can transmit linear motion and force into a spatially distant and extended point from the actuator unit [162]. Just like the brake mechanics of a bicycle, the cable is composed of an outer tube and inner wire to transmit motion. The flexibility of this cable enables us to reconfigure the linear motion of shape display pins to other pin-alignments and motion directions. A **Syringe and Tube** can be used to transmit the linear motion of a shape display pin into air pressure, which allows control of the pneumatic system using a shape display. Similar to the Bowden cable, flexible tubes can also be used to reconfigure the spatial configuration and path for the pneumatic system. Lastly, **Gears and Linkages** can convert linear motion into rotary motion, for example by using rack and pinion mechanics. Gears and Linkages have further potential to convert the linear motion of pins, including transmitting the motion of a single pin into multiple rotating objects by connecting multiple gears, and the maximum moving distance of pins can be increased by using gears with different ratios. Multiple Motion Transmitters can be combined in single transducer to provide rich interactivity.

Shape Representation Properties

Pin Properties - Multiple properties of individual pins can be converted with the transducers, including **shape / size**, **texture / materiality** and **color**. This can be utilized to provide different haptic experiences and aesthetics. These properties are not something that can be converted dynamically within single transducers, but by switching transducers, users can selectively change.

Pin Configuration - Positional relationship among multiple pins is a primary factor to be considered for shape display hardware. **Display area** and **resolution** are important factors when displaying information with a shape display for display quality, texture, and affordance across finger / hand / body interaction. In addition, the common XY grid *pin alignment* and *spacing* can be converted, for example, to diagonal alignments, depending on usability or for aesthetic purposes.

Plane Configuration - While shape display pins are usually constrained to a fixed **horizontal** plane, this can be reconfigured to other types of plane such as the **vertical**, **movable** (hand-held) or even **deformable** (flexible) plane, which can dynamically affect pin configurations.

Motion Configuration - Regarding the transmission of motion, the vertical linear motion of a shape display pin can be converted to other linear directions such as **horizontal** and **diagonal**. For non-linear motions, **rotary motion**, **bending motion** and **inflation** are enabled with the specific configuration of motion transmitters. Among them, inflation itself has great potential in enabling a range of organic motion including expand/shrink, stretch, fold, curl or change stiffness by utilizing a custom pneumatic composite [174, 108, 147, 159], which we do not explore in-depth in this project. For each motion primitives, there are parameters that can be converted: **speed**, **force**, and **range**. Additionally, by combining multiple actuators, deforming continuous material is also possible including continuous **lines** and **surfaces**, by using strings and fabrics.

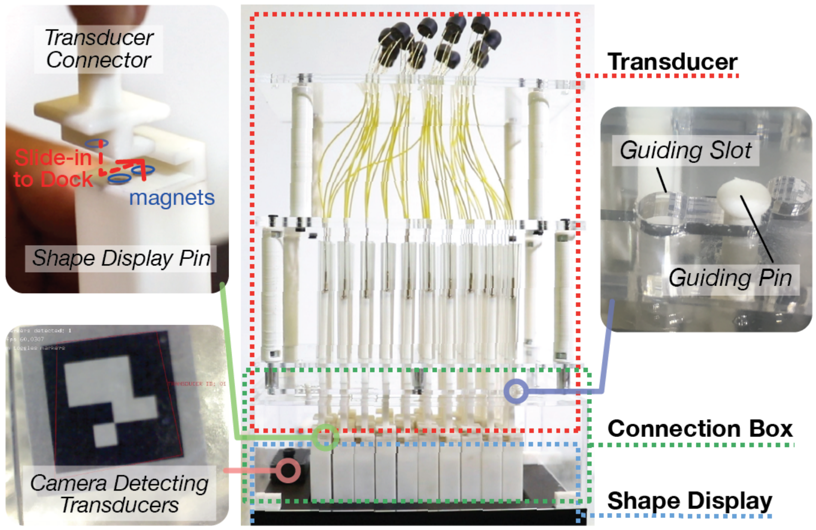


Figure 4-5: Transducer Structure and connection with the Shape Display (Top Left: Close-up view of Docking Connection for shape display pins, Bottom Left: Detection of Transducer with a Camera, Right: Guiding slot and pin for jointing transducers).

4.4 Implementation

In this section, we describe the implementation of our prototype that demonstrates the concept of *TRANS-DOCK*. As shown in Figure 4-3, the system is composed of shape display hardware, a computer, camera, button and, the transducers. Each component and its connection with each other are described below.

4.4.1 Pre-developed Shape Display Hardware

For the pin-based shape display, we used a hardware named *inFORCE* [94] that is composed of 10 x 5 pins (19.2mm square each with 0.8mm spacing, total of 200 x 100 mm display area). For the actuator, 50 of the *Quickshaft LM 1247 Linear DC-Servomotors* produced by Faulhaber were installed. The actuator enabled a vertical motion distance of 100mm, continuous force of 3.6 N, peak force 10.7 N, actuation and sensing precision of 120 μm and maximum speed of 3.2 m/s. This shape display also had the capability of identifying the vertical force applied on individual pins by analyzing the driving current of the motor. The detail of hardware and software implementation as well as specification are reported in [94]. Compared to other shape displays, *inFORCE*'s stronger force control and smaller number of pins was suited to explore and prototype the idea of *TRANS-DOCK*.

4.4.2 Joint Docking System

Based on the *inFORCE* hardware, we modified the tip of its pins into a mechanical joint to enable docking for different kinds of transducers. The design criteria of the connector included **easy to dock on and off on users' demand**, and **robust force transmission for both pushing and pulling**. Thus, we designed a *docking connector* shown on Figure 4-5, top-left. The pair of connectors have interlocking hooks which can slide in and out only when moved in the horizontal direction. Small magnets were used to snap together compatible pins to secure a robust connection during the actuation. The magnetic force was weak enough such that the pins could be easily slid off when a horizontal force was applied by a user to interchange the transducer.

Having this connector design for all 50 pins, we designed a *connection box* mounted on the shape display to secure connection for all pins. This connection box had four guiding pins on the corners (Figure 4-1a and 4-5 right) which fit into guiding slots on the transducers. These guiding slots help users to appropriately place and slide the transducers on the shape display to secure all 50 pin connections. In this way, all 50 pins were able to be connected to the transducer pins at once with a simple action. During the docking of the transducers, all pins had to be set to the same height using software on the computer.

A camera mounted on the connection box was used to detect the markers attached to the bottom of the transducer to identify the type of transducer being docked or removed. With the system knowing the transducer status, it can switch between different compatible actuation modes. Also, all of the pins had to be set to the same height while dismounting the transducers, so that the joints could be slid out all at once. For this reason, we attached a button that a user can press when he/she wanted to replace the transducer.

4.4.3 Transducers' Components

For the general fabrication of transducers, we utilized laser-cut acrylic boards to compose structures and layers of the transducers assembled with spacers and screws. For clarity in this project, we used transparent acrylic sheets with an open side to reveal the internal structure. However, in actual uses and applications, they should be hidden so that users can focus on the converted configuration rather than the internal mechanics.

Regarding the three motion transmitters, for the **Bowden Cable** we utilized Gold-N-Rod "*.032 Brass Plated SS Very Flexible*" produced by Sullivan Products, which are usually used for RC plane control. Thicker Gold-N-Rod was used in inFORM to maximize the resolution [33]. This cable was composed of a 1.9mm diameter nylon tube, and 0.85mm steel wire. The tubes and wires were able to be cut for customized length and the wires were mounted on other components with brass couplers. For the **syringes**, we tested the use of 10ml syringes which were able to be aligned with same spacing as our 10x5 shape display. Tubes can be used to configure the actuated composite alignments (e.g. balloon). For the **mechanical gears**, we designed them with CAD software, SOLIDWORKS, and fabricated using 3D printers (FDM or SLA). We designed a rack and pinion mechanism as a basic conversion mechanism from linear motion of shape display pins to ration. Based on this, we developed other types of mechanics (e.g. bevel gears) to translate motion modalities. All of these motion transmitter components were fixed (with screws or glue) to the joint connector (3D printed) to make a connection to the shape display pins.

4.4.4 Technical Limitation and Design Guideline

There are a number of technical limitations to be considered when composing transducers with each motion transmitter. Here, we summarize such requirements through a general comparison of the motion transmitters, a force transmission efficiency and the relationship between display area and resolution. This section is intended for future researchers and designers to build upon our research as a reference design guideline.

Comparison of Motion Transmitters' Characteristics

Figure 4-6 shows a table of general comparison for the three motion transmitters. This table overviews both enabled motion modalities with each transmitter, and, more importantly, the pros and cons of them from four functional aspects. As for *force transmission efficiency*, gears and linkages provide rather high efficiency, while the other two methods have higher friction of force transmission loss due to cable / wire and syringe friction. Because of its thinness, Bowden cables are particularly good for their *compactness* which enables them to be used in high resolution configurations, while, generally, gears and linkages are rather difficult to scale down to millimeter scale. Also, Bowden cables and syringe / tubes are great for their *flexibility* which enables movable plane configurations by separating the actuation unit of a shape display with the interaction surfaces. Lastly, pneumatics has the worst *durability* in comparison to others because air leaks are a critical issue as inflatable composites get damaged.

This comparison is rather generic and approximate which can be updated with advanced mechanical engineering technique (e.g. micro-scale gears [45], high efficiency pneumatic joints [168]), while our intention here is to give an overall comparison as a reference guideline.

Furthermore, by connecting multiple types of motion transmitters in a series, a transducer could gain advantage of multiple transmitters; for example, using Bowden cable to actuate rack / pinion gears to create a hybrid configuration of movable plane and rotary motions. However, in this case, force transmission efficiency need to be considered because the efficiency can drop when doing so, which is further described below.

Force Transmission Efficiency

As one of the key aspects for designing the transducers, taking force transmission efficiency into consideration is important. During our prototyping process, we found that, depending on the motion transmitter configuration and state, it becomes difficult to actuate transmitters with the shape display actuator once it reaches the maximum force limit. For example, in the case of the Bowden cables, by increasing cable length and curvature, the friction force becomes larger so that if the cable is too long and curved, it becomes unable to actuate with the shape display pins as shown in the technical evaluation on Figure 4-7. Generally, the mechanical relationship needs to satisfy the following formula:

$$F_{SD} > F_s^{max} + F_{ex} + (F_{touch}) \tag{4.1}$$

Here, F_{SD} is the maximum continuous force of the shape display actuator, F_s^{max} is the maximum force of static friction of the specific motion transmitter, and Fex represents extra force that is applied to the actuation unit (e.g. weight of an object attached to the converted pin). If a designer wants to design actuation as opposed to human force or detect human force input, F_{touch} also needs to be considered. Designers of *TRANS-DOCK* should do their best to minimize F_s^{max}, to reduce the loss of power transmission with a higher efficiency technique [135].

Display Area vs Resolution

Another technical limitation that needs to be considered for shape display-like configuration is the relationship between Number of Pins, Display Area, and Display Resolution. As the number of pins is constant and cannot be converted for single shape display, when increasing the display area, the display resolution ($cm^2/pixel$) would also increase; which can be represented as an equation $DisplayArea = PinNumber * DisplayResolution$. The graph on Figure 4-8 shows an example of such a relationship for the inFORCE shape display with the actual Transducers we have developed.

Motion Transmitters	*Types of Enabling Motion*	**Transmission Efficiency** For Force I/O	**Compactness** For Resolution and Bulkiness	**Flexibility** For Arrangibility and Movability	**Durability** For Robustness
Bowden Cables	Bend	*[Push]* Poor *[Pull]* Good	Good	Good	Fair
Gears & Linkages	Linear (*Direction can be Changed*) Rotate	Good	Poor	Poor	Fair
Syringes & Tubes	Inflate	Fair	Fair	Good	Poor

Figure 4-6: Comparison of motion transmitters, representing general characteristics of each transmitter.

[Unit: N]		***Cable Curvature*** *(Number of Loops around 3.5cm Diameter Cylinder)*				
		Straight	1 Loop	2 Loops	3 Loops	4 Loops
Cable Length	0.5m	0.10	0.48	1.13	2.33	3.48
	1.0m	0.25	0.61	1.08	2.18	3.58
	1.5m	0.38	0.73	1.38	2.22	3.93
	2.0m	0.37	0.85	1.6	3.23	5.35
	2.5m	0.7	0.97	2.0	3.6	6.1

Does not Satisfy the requirement on Eq (1) (shaded cells: 3.93, 5.35, 6.1)

Figure 4-7: Technical Evaluation of Bowden cable's friction in relation to the cable length and curvature. When the friction force is greater than the Shape Display (in our case, 3.6N), it will not satisfy the Eq (1).

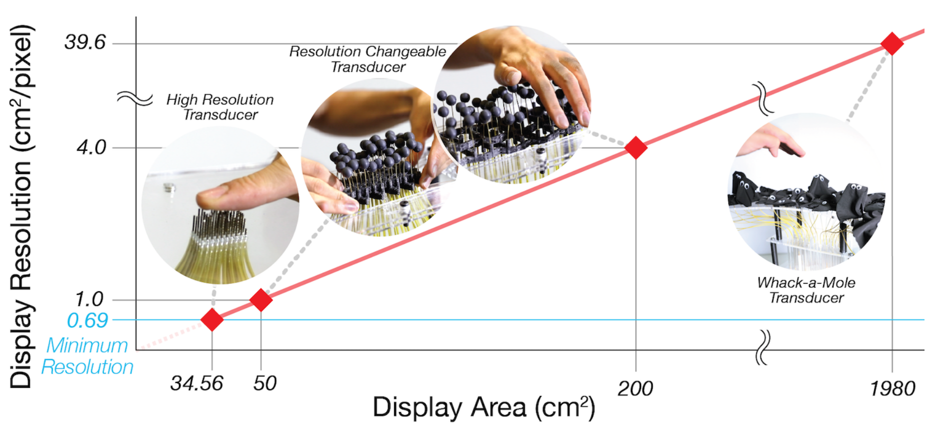


Figure 4-8: Graph of Display Area vs Resolution with inFORCE shape display as an example. As the number of pin is constrained, the transducers are generally constrained on the redline. Four prototype transducers (shown in Figure 4-9) are mapped on the red line as a reference.

4.5 Example Prototypes

Our example prototypes are intended to demonstrate how shape displays can be both expanded to gain a range of capabilities and applied to a variety of interaction scenarios with our approach. For each application or functionality, there are other enabling systems used to achieve similar goals (cited along the following sections), while our contribution here is the capability of switching between different actuation configurations with a single pin-based shape display, rather than claiming the superiority of our approach. Our prototype transducers had a range of height in 27-42cm. Some of the prototypes below present transducers with general functionalities, while few others present application-specific transducers.

4.5.1 Transducers with General Functionalities

One of the unique contributions of *TRANS-DOCK* is to convert the shape display *resolution*. Using the Gold-N-Rod cables, we developed a **High Resolution Transducer** which converts the shape display resolution to 2.4mm pitch high resolution with 0.8mm diameter pins (Figure 4-9a). This can be utilized to convey the fine textured shape of a 3D model. This transducer enables users to choose their preferred shape display resolution depending on their requirements and applications. Moreover, in order to let users variably adjust the resolution without switching transducers, we also developed a **Resolution Changing Transducer** that allows the resolution to be manually and variably controlled (Figure 4-9b). Utilizing the 3D printed auxetic structure [107], this transducer can change its pin resolution from 10 to 20 mm pitch. With this structure, our prototype maintains the uniform distance between pins while the entire size of the display is changed. With these, users can selectively choose different resolution / display area depending on the content they would like to touch and feel. Figure 4-1c present such application usage.

Figure 4-9c shows **Balloon Display Transducer** which actuates arrays of balloons by utilizing the *inflation* capability with syringes. With this, we were able to compose an interactive surface with organic and flexible transformations [106]. Bal-

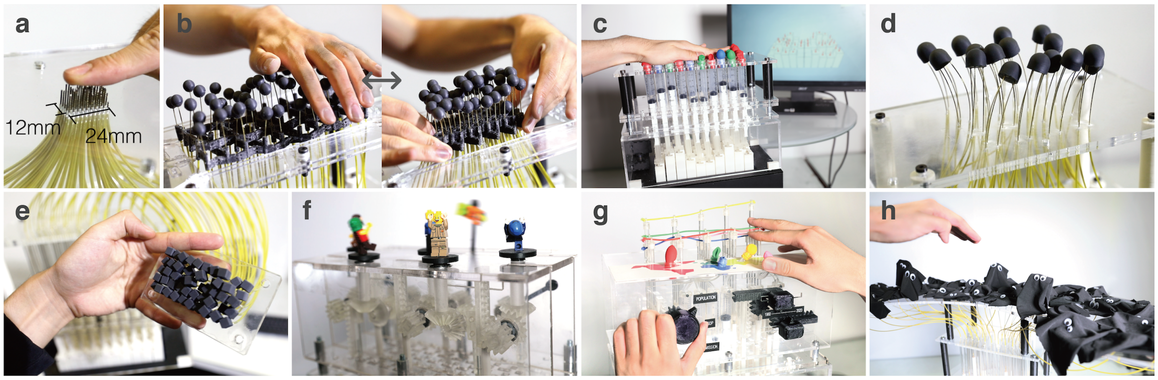


Figure 4-9: *TRANS-DOCK* Transducers for General Functionalities (a: High Resolution Transducer, b: Resolution Changeable Transducer, c: Balloon Array Transducer, d: Bending Pin Transducer, e: Movable Plane Transducer) and for Specific Applications (f: Story-telling and Animation, Data Physicalization, g: Whack-a-Mole)

loons can detect being pressed as the air pressure is transmitted to affect the position of shape display pins. Hence, these balloons can provide a bi-directional tangible interaction capability of squeezing or compressing soft objects [101].

Another kind of organic transformation is demonstrated with the **Bending Pin Transducer**. The motion of *bending* is enabled by combining three flexible Gold-N-Rod wires. For each pin, the tips of the three wires are fixed with a solid piece, and by controlling the respective height of each wire, we can control the bending angle, bending direction, and pin height. With our setup of a 50 pin shape display hardware, we constructed 16 bending pins aligned in a 4x4 grid (Figure 4-9f). The behavior of bending motion adds interesting opportunities for interaction with shape displays including conveying impression of living creature (like tentacles or tails) [105, 157], recreating overhanging structure which are difficult to do with pin-based shape display, or grabbing and holding objects or hands [146].

The **Movable Plane Transducer** demonstrates the *movable plane* configuration, which provides a hand-held shape changing surface (Figure 4-9g). By using a longer Gold-N-Rod cable (approx. 450mm for our prototype), this transducer can be held and moved in 3D space. This kind of configuration can be utilized for prototyping / assessing shape changing interfaces for mobile interaction [57] and spatial tangible / haptic interfaces [5, 12].

4.5.2 Application-Specific Transducers

Beyond generic shape display-like transducers, we've also prototyped Application-specific ones to demonstrate its versatile nature. Figure 4-9f shows a Transducer for **Story-telling / Dancing Figures** which demonstrates the use of *rack and pinion* mechanisms to translate linear motion to *rotations*. In this case, rotational movements are used to represent expressive motion. By expanding the types of motion created with shape displays, *TRANS-DOCK* has a potential application space in story-telling or expressive animatronics [99].

Figure 4-9g shows the **Data Physicalization Transducer** which is designed to convey complex data in the world over several decades by dynamically rendering physical charts [148, 84]. With this transducer, users can dynamically select, view and touch changing world-scale data (e.g. population, GDP, and Co2 emission) across the five continents. Knob and slider inputs on the *vertical plane* allow users to select a time period and the type of data to render with the tangible charts. Colorful rubber strings connected to vertically moving pins are used to create a dynamic line chart, while balloons are used to render specific data points in time. As this demonstrates, a transducer can be combined with multiple types of motion transmitters and primitive motions.

Lastly, the **Whack-A-Mole Transducer** extends the interaction area of shape displays to a much larger area (approx. 900mm wide) to allow an upper-body-scale interaction of the whack-a-mole game (Figure 4-9h). This was also developed using a Gold-N-Rod cable, but, in this case, to expand the interaction area. A piece of small fabric with googly eyes was placed on top of each wire so that it looked like a tiny creature appears as the pins move up.

4.6 Discussion of Potential Use Cases

While we demonstrated the variety of possible transducers to convert the shape display motions and expand its interactivity, there is an important question left: "How the 'interchangeability' of *TRANS-DOCK* can be useful / practical?" While there is

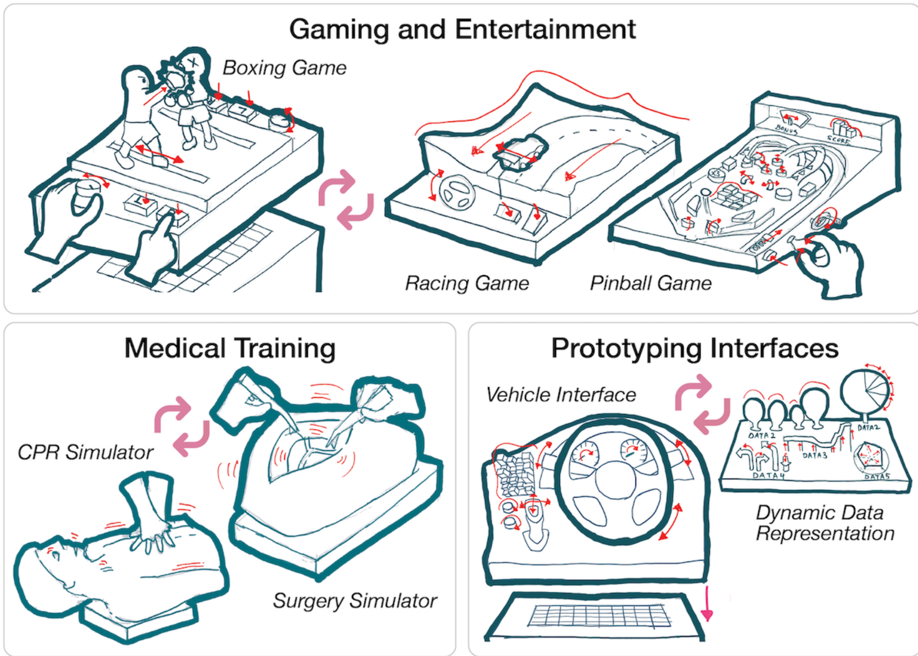


Figure 4-10: Sketches of Potential Use Cases. (Boxing, racing and pinball transducers for Gaming and Entertainment, surgery and CPR simulator for Medical Training, and automobile interface and data display for Prototyping Interfaces.

a lot of potential for each transducer, we would like to introduce several imagined use cases that may utilize the interchangeability of *TRANS-DOCK* (see Figure 4-10).

4.6.1 Entertainment and Learning

Under the context of entertainment and gaming (Figure 4-9h for our prototype), an individual transducer can provide unique content for gaming – similar to how game cartridges can be installed in video game consoles, or how sheets can be swapped in some magnetic board games[1]. As shown in Figure 4-10, both tangible output and input can be configured with *TRANS-DOCK*.

Learning is another specific task where researchers have explored the importance of tangibility with dynamic actuated interfaces [58]. In such context, *TRANS-DOCK* could be installed in museums and schools which require a variety of tangible learning contents where different transducers can be selected depending on the types of data physicailization. For example, transducers with different display area / resolution

[1]https://www.amazon.com/Kidsthrill-Magnetic-Travel-Board-Adults/dp/B013TNVKTE

can be used for presenting the shape of historical objects / sculptures (Figure 4-1b), and different types of Data Physicalization Transducers (Figure 4-9g) can be used to present abstract information in tangible way.

Specifically, medical training (e.g. palpation, CPR, etc) requires a lot of tangible exercises and currently a variety of actuated medical simulators are used in medical schools and hospitals [72, 17]. While, with such simulators, a single simulator is used for a single or few types of medical training, the interchangeability of *TRANS-DOCK* could be used to simulate different medical conditions depending on the transducer with a single actuated platform to reduce the cost.

4.6.2 Prototyping Actuated Systems

When prototyping interfaces with actuation or haptic feedback, it requires time and knowledge for planning the design, choosing actuators, fabricating, assembling, and wiring. Especially when designers or researchers want to compare between multiple different configurations of actuated interfaces, it becomes more difficult to implement a number of complex actuated systems all from scratch. This also requires more materials and cost as they build more prototypes. The approach of *TRANS-DOCK* can be beneficial at such an early stage for the prototyping of actuated interfaces (e.g. automobile interfaces, robotic system or haptic feedback devices) by helping designers and researchers to quickly prototype, test and compare [116, 59].

4.7 Future Work

In *TRANS-DOCK*, we have introduced the new design space of expanding shape display capabilities as well as implementation methods and a variety of examples, there are many challenges and questions that need to be tackled in the future.

4.7.1 Transducer Design Pipeline

While the idea of *TRANS-DOCK* has a potential for people to prototype interactive actuated systems, the design process itself should be improved on for a range of users to design their own transducer. Developing three-step design pipeline supported by computational fabrication is one preferable example for future research (Figure 4-11) including **Design**, **Fabrication / Assembly**, and **Control**.

First, for **Design**, there could be a custom built CAD software which allows users to easily customize a transducer. For example, such software could be designed in a way that users first design the overall shape of the transducer, then pick location for different motion modalities (rotation, inflation etc). With such user input, taking the technical limitations into consideration, the software could automatically generate a digital model of the mechanics. For **Fabrication / Assembly**, the current fabrication process is relying heavily on manual assembly which may take more time for other shape displays with a larger number of pins. Rather, 3D printing or other digital fabrication techniques could be utilized to fabricate fully assembled transducers with mechanical structures to save time and provide accurate composition [89]. To reduce the cost of transducers, cardboard crafting can be a promising approach similar to Nintendo Labo [104]. Lastly, for **Control**, how to let designers create motion and interaction for a fabricated transducer is another challenge. With the custom CAD software described above, control software could be automatically generated to let designers design the motion while abstracting out the motion of individual pins.

We can learn from previous research on computational fabrication to develop such pipeline [20, 138, 71, 87]. Once such design pipeline is built, we also hope to conduct a workshop as a user study to observe how a range of users with different backgrounds may make for their own practical and artistic use cases.

4.7.2 Technical Improvements

The prototypes in our exploration focused specifically on the conversion of primitive motion and pin alignments with mechanical transmissions, while other properties in

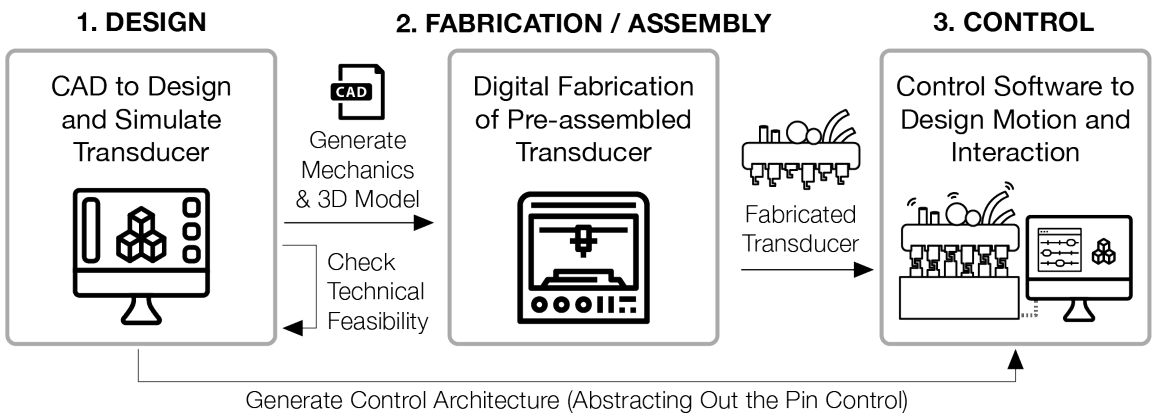


Figure 4-11: Future Design, Fabrication and Control Pipeline for *TRANS-DOCK*.

the design space are not demonstrated within our prototypes. The motion parameters (force, speed and range) can be converted with the knowledge of mechanical engineering techniques and mechanical impedance transformation [85]. For example, increasing maximum force by compromising the speed and travel range using gears is a common mechanical engineering practice. Such properties should be able to be converted depending on the demanded transducer design and limitation of the shape display hardware, and such designs should be applied for the future research space of *TRANS-DOCK*.

Other than the above challenges, the bulkiness and thickness of our transducer prototypes should be tackled with a precise and intelligent mechanical design, and the size can be minimized depending on the requirements for each application.

4.8 Conclusion

In summary, we introduced a novel approach for extending the interaction capabilities of pin-based shape displays with passive mechanical transducers that can be docked to the display. We outlined the design space to comprehensively define the range of potential configuration, introduced a variety of example transducer prototypes, and discussed potential use cases. The range of enabled configuration and motion modalities with the transducers extended the expressibility, adaptability and customizability of shape display interactions. We envision that once pin-based shape displays become more accessible in the future, the value and capabilities of shape displays can be fully extended with *TRANS-DOCK* by adapting to user requirements, conveying rich information, and being customized as a creative platform.

Chapter 5

HERMITS

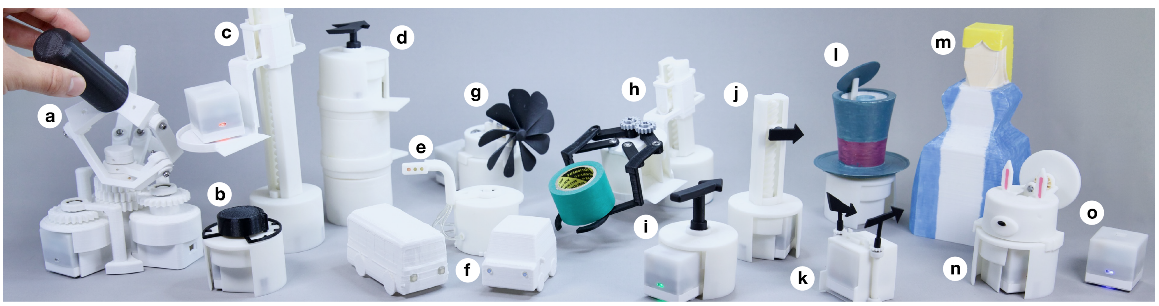


Figure 5-1: HERMITS: *Mechanical Shells* for Self-propelled TUIs.

Contributors in this project: Ken Nakagaki, Joanne Leong, Jordan L Tappa, Joao Wilbert, and Hiroshi Ishii.

Abstract

We introduce *HERMITS*, a modular interaction architecture for self-propelled Tangible User Interfaces (TUIs) that incorporates physical add-ons, referred to as *Mechanical Shells*. The *Mechanical Shell* add-ons are intended to be dynamically reconfigured by utilizing the locomotion capability of self-propelled TUIs (e.g. wheeled TUIs, swarm UIs). We developed a proof-of-concept system that demonstrates this novel architecture using two-wheeled robots and a variety of *Mechanical Shell* examples. These *Mechanical Shell* add-ons are passive physical attatchments that extend the primitive interactivities (e.g. shape, motion and light) of the self-propelled robots.

The project proposes the architectural design, interactive functionality of *HERMITS* as well as design primitives for *Mechanical Shells*. The project also introduces the prototype implementation that is based on an off-the-shelf robotic toy with a modified docking mechanism. A range of applications is demonstrated with the prototype

to motivate the collective and dynamically reconfigurable capability of the modular architecture, such as an interactive mobility simulation, an adaptive home/desk environment, and a story-telling narrative. Lastly, we discuss the future research opportunity of *HERMITS* to enrich the interactivity and adaptability of actuated and shape changing TUIs.

5.1 Introduction

Actuated and shape changing tangible interfaces have been one of the main streams in the field of HCI to explore the role of dynamic actuation capabilities for interaction design [116, 19, 110, 114]. Through such work, researchers envision the ultimate goal of reconfigurable physical matter that is coupled with dynamic digital information, where the physical matter transforms into any shape that users wish and instruct (e.g. Radical Atoms [52], Programmable Matter [39, 156]).

Various implementation methods have been proposed to explore the enabling hardware platform that can adapt to a variety of interactions / applications, including pin-based shape displays [77, 33], actuated curve interfaces [96, 95], or swarm user interfaces [74]. While a variety of incremental efforts (e.g. resolution, additional modalities) have been made to improve the display and interaction quality of these platforms, they each have their own limitations on fidelity with regards to the shapes. This contradicts with their goal to be generic platforms that can be used for anything.

To overcome this limitation, we propose, *HERMITS*, a novel architectural design for self-propelled Actuated TUIs to extend their interactions with interchangeable add-on modules which can be dynamically docked/un-docked by the system. We define self-propelled TUIs as a physical interface with locomotion capabilities, that includes a system with one or more robotic devices which are previously explored widely [35, 74, 41]. The name for this project is inspired by hermit crabs, which are known to actively switch their shells throughout their lifetimes.

In this chapter, we define interaction design values of our approach for enriching the reconfigurablity and adaptability of self-propelled TUIs. While the extension of actuated TUIs with passive objects has been previously explored [125, 98, 144], our project intends to explore a similar approach but particularly for self-propelled TUIs. By leveraging their locomotion capabilities, we introduce a novel approach to add dynamic/automated reconfiguration capabilities to actuated and shape changing TUIs.

Specifically, to explore this interaction design modality, we developed a proof-of-concept prototype. This system is based on two-wheeled self-propelled robots with an active docking mechanism, and a variety of *Mechanical Shell* add-ons that are designed to extend and convert the primitive interactivity of the devices. The docking hardware design (based on off-the-shelf robotic toys) as well as a scalable control architecture are introduced. Using the *HERMITS* prototype, we present applications that take advantage of the reconfigurability and adaptability of the interaction architecture. Finally, we discuss open research opportunities of this interaction architecture to contribute to future research into robotic, actuated and shape changing TUIs.

5.1.1 List of Contributions

- Introduction of the interaction architectural concept of *HERMITS* that augment the interactivity of self-propelled TUIs.

- Definition of the design space of *HERMITS*' *Mechanical Shell* add-ons for extending the interactivity.

- Implementation of the system of *HERMITS* based on an off-the-shelf robotic toy with added active docking capability.

- Demonstration of applications to validate the concept.

- Discussion of limitations and future work to define the open research space.

5.2 Related Work

The concept and design of *HERMITS* are built upon previous work on reconfigurable tangible interfaces, extendable interface with physical attatchments, and self-propelled interfaces.

5.2.1 Reconfigurable Tangible Interfaces and Actuation

The functions of modularity and reconfigurability for Tangible User Interfaces (TUIs) have been investigated by HCI researchers [54] for TUIs to gain the capability of constructive assembly of digital model or functional artifacts with tangible and intuitive interaction [56, 42, 70, 81, 10, 112]. Recently, in the research stream of shape changing and actuated tangible interfaces [116, 19, 52, 114], there have been efforts in developing a modular architecture to improve the richness of shape representation and interaction capability of the actuated hardware [115, 93, 47, 149, 102]. Researchers explored the customizable actuated components to let users design actuated artifacts in a variety of configuration.

While these hardware designs are mainly composed of electric and computational components, the idea explored in our project is a passive mechanical attachment for actuated tangible interfaces. Our approach intends to extend the interactivity of existing generic robotic devices with such passive components, which doesn't require complex and costly computational electrical systems.

5.2.2 Extending Generic Interfaces with Passive Attachments

In HCI, there have also been approaches to extend the interactivity of generic devices/interfaces with passive objects and attachments. For example, optic interaction functionalities (display and optic sensing) were extended using optical fibers, 3D printed clear parts, or mirrored objects that act as optical guide [169, 8, 173]. Capacitive touch sensing surfaces, that are common in smartphones and laptop. were extended with passive objects containing conductive traces [65, 117, 177]. Other sensors within general purpose devices were extended to detect tangible input to attachable passive modules with use of microphones [73], accelerometers [171] or force sensitive surfaces [46]. As for commercial products, *Nintendo Labo* [104] smartly enables the tangible and embodied gaming experience by extending generic sensing capability of the gaming console using cardboard crafted attachments.

The use of passive attachments for extending interactivity of actuated tangible interface have also been explored in HCI. For example, pin-based shape display have been employed for assemblying passive magnetic blocks [125, 144], and actuating flexible crafts for storytelling and rapid prototyping [99, 29]. Among them, *TRANS-DOCK* [98] and *KineticBlocks* [125] introduced conversion of mechanical motion of pin-displays with passive mechanisms to enrich its dynamic interaction capabilities. Katakura et al, introduced extension and conversion of 3D printer's motion with mechanical attachments printed with the printer itself [63, 64]. These approaches fill the gap between users and generic actuated hardware to achieve enriched adaptable interactivity by using passive modular attachments.

Greatly inspired by such research, we intend to apply this approach to self-propelled TUIs. Self-propelled TUIs are tangible interfaces with locomotion capabilities. *HERMITS* leverages their capabilities and contributes to the research space through the novel exploration of self-docking functionalities as well as motion transmission designs specific to two-wheeled robotic devices.

5.2.3 Self-Propelled TUI and Swarm UI

TUIs with locomotion capabilities have been explored in-depth to explore a way to advance the classic tangible (graspable) interface paradigm [32, 160, 54] (where all the tangible pucks were passive). For example, tabletop actuated TUI has been explored with technical means of electro-magnet array [110, 141, 143] and self-propelled wheeled robotic system [35, 136] from 2000s. Moving across tabletop surfaces provided novel interaction opportunities with TUIs for bi-directional tangible / haptic interaction as well as the use of additional passive instruments [111].

More recently, with advancements in modular robots and the control of swarms in the field of robotics [123, 121, 124, 176], HCI researchers have expanded upon research into actuated tangible interfaces by introducing the concept of Swarm User Interface (SUI) [74]. These involve interfaces which leverage multiple self-propelled wheeled robots. By using a number of self-propelled actuated modules, researchers have investigated a way to configure the number of actuated pucks for information display [68], gestural interaction [67], haptic feedback [69], and education [109, 43]. SUIs have also been employed for activating passive modules including assembling blocks for rendering haptic proxies [180], and moving furniture and walls for rendering room-scale VR space [140]. To enhance the capability of SUI with reconfigurable interactive functionalities, *HERMITS* augment SUI with passive mechanical transmission attachments, and investigates the a new research space

For adding extra shape changing modality to SUIs, Suzuki et al. have explored with *ShapeBots* [145] and *RoomShift* [140] to add linear actuation modules. While some *Mechanical Shell* prototypes presented in *HERMITS* overlap with the interaction modalities for shape changing SUIs, our novel contribution is the possibility for self-propelled interfaces (including SUIs) to selectively attach and detach to modules, enabling more flexible functionalities. This is not possible with *ShapeBots*, which is constrained to its original mechanical design. To investigate this reconfigurability, we introduce a specific docking joint design for wheeled robots.

5.3 HERMITS

In this section, we outline the overall design of HERMITS as well as the benefits of using *Mechanical Shells* for interaction.

HERMITS is a concept and design for an interactive modular system for self-propelled tangible user interfaces. As shown in Figure 5-3, the components of the system include the (1) self-propelled TUIs (robots), (2) *Mechanical Shells*, (3) an interaction stage, and (4) a computer to control the system. In this chapter, we refer to *robots* as self-propelled TUIs that activate *Mechanical Shells* in *HERMITS*, and we refer to the combination of one or more robots and a shell as a *unit*.

In the system, robots can selectively attach/detach to the *Mechanical Shells* by

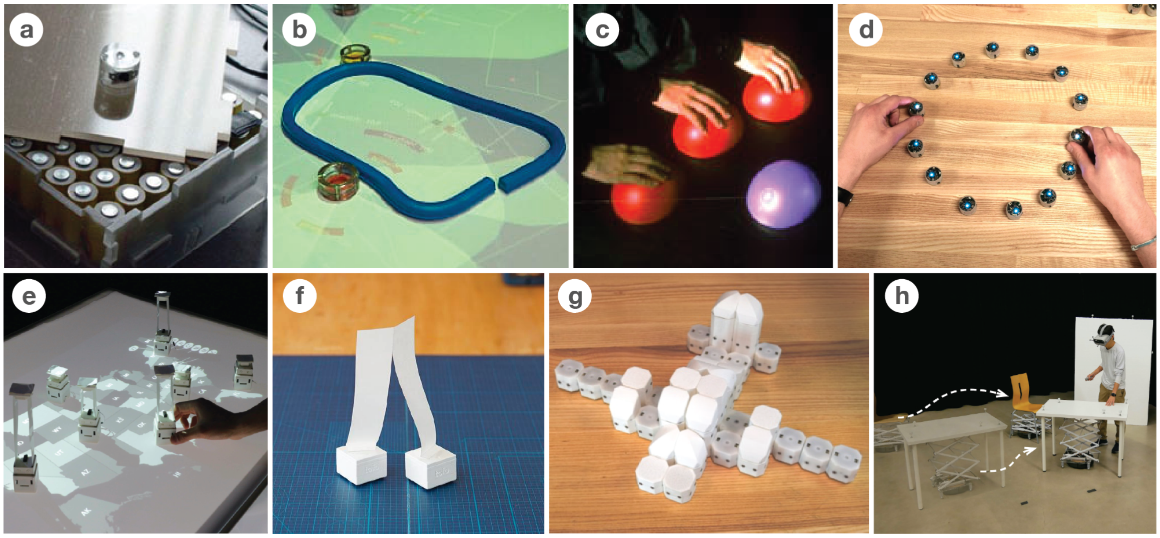


Figure 5-2: Related Work of *HERMITS* (a. Actuated Workbench [110], b. PICO [111], c. Curlybot [35], d. Zooids [74], e. ShapeBots [145], f. toio's Gezunroid [28], g. Robotic Assembly of Haptic Proxy [180], h. RoomShift [140]).

locomoting across the stage. While the robots themselves support generic interactions to users (as in [35, 74, 136]), a variety of *Mechanical Shells* allows the system to provide specific and reconfigurable interactivity to the users dynamically and on-demand.

Regarding the number of robots, some of the *Mechanical Shells* in *HERMITS* can be docked and controlled with only a single robot, while others need to be activated by multiple robots. Hence, it is not necessary that *HERMITS* have to have a swarm of robots. For example, one robot activating a variety of *Mechanical Shells* one after another is an architecture option in the design of *HERMITS*. As a design space, we

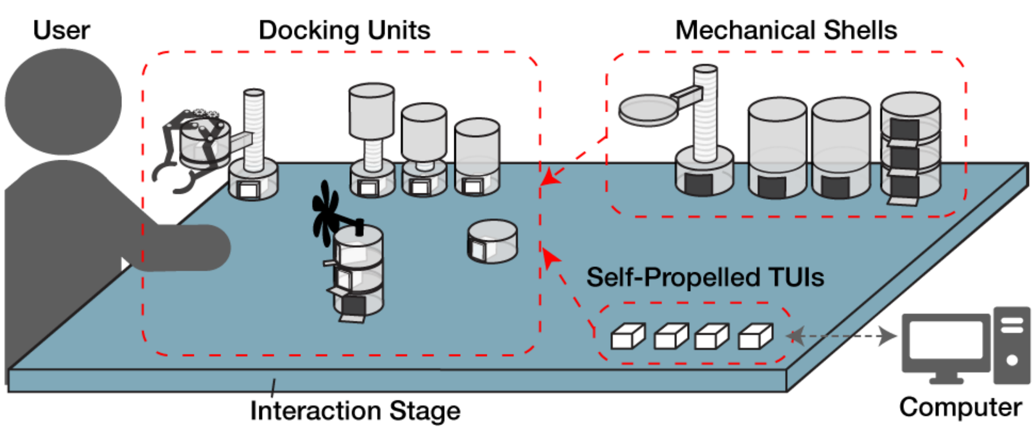


Figure 5-3: Overall design of *HERMITS*.

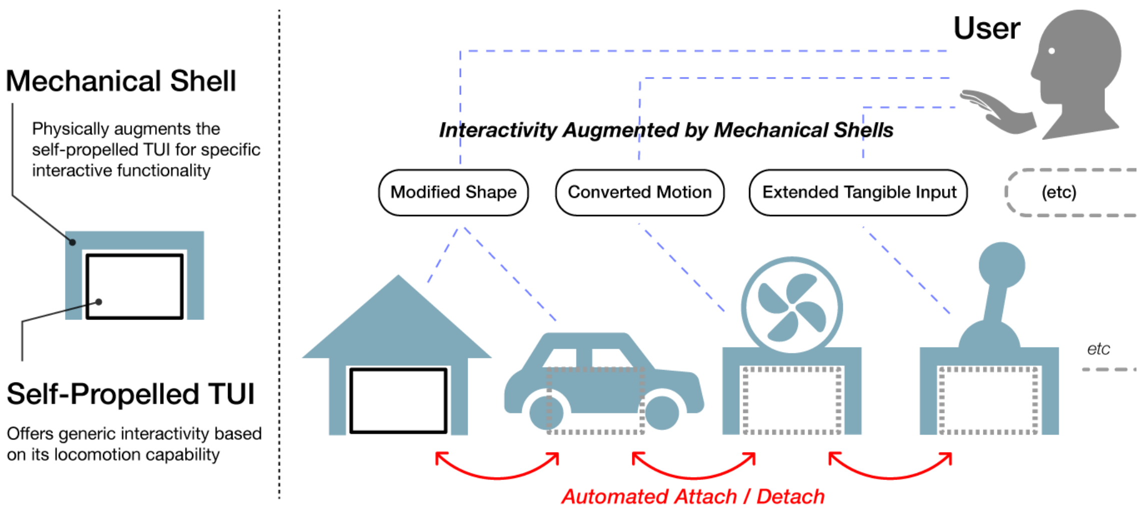


Figure 5-4: The concept of mechanical shell. A mechanical shell can be attached and detached to self-propelled TUI. The shell can thereby transform the interactivity of the device including shape, motion and other tangible I/O.

also consider having a swarm of robots as with SUIs to be an exciting option. This opens the door to interactivity with a collective and pushes the versatility of the system.

The diagram on Figure 5-5 illustrates the primitive relationship between a self-propelled TUI and *Mechanical Shells*. The shell is an attachment that can modify, convert or extend the interactive functionalities of the actuated TUI. For example, *Mechanical Shells* can modify the interactive property of 'shape', convert the locomotive 'motion' via transmission mechanisms, or extend other I/O capabilities by taking advantage of installed sensors and actuators in the device. The *Mechanical Shells* can be designed with combinations of these tangible augmentation capabilities.

Mechanical Shells in *HERMITS* can serve multiple purposes, as shown in Figure 5-5. By reconfiguring its shape and converting mechanical I/O motion, *Mechanical Shells* can enhance the dynamic physical affordances of the system and enrich its interaction space. For example, this enables the system to be used for tangible and haptic controllers (Figure 5-5a) as well as for shape representation (Figure 5-5b). Reconfiguring the shell with expressive and iconic shapes and motion would enhance its communication capability to users which can be great tool for storytelling (Figure

Figure 5-5: Overview of interaction design purposes and benefits of *Mechanical Shells* from instances of *HERMITS* (a. Tangible and Haptic Controllers, b. Data Physicalization / Tangible Representation, c. Storytelling with Expressive Shapes and Motion, and d. Extended Robotic Manipulator and Locomotion)

5-5c). Furthermore, the motion conversion capability allows the self-propelled TUIs to extend their robotic functionalities to affect the physical environment, such as with the manipulator and locomotor units pictured in (Figure 5-5d). These will be highlighted by the application section of this chapter. In summary, the benefit of the mechanical shell concept is not only that they can provide each capability described above, but that they allow for the system to dynamically adapt and be reconfigured to flexibly support interactions.

5.4 Design Space of Mechanical Shells

Many primitive interaction properties of self-propelled TUIs can be extended and converted using *Mechanical Shells* that are designed either for single or multiple robots. Figure 5-6 shows these primitive design properties, which are demonstrated in *Mechanical Shell* examples in this project.

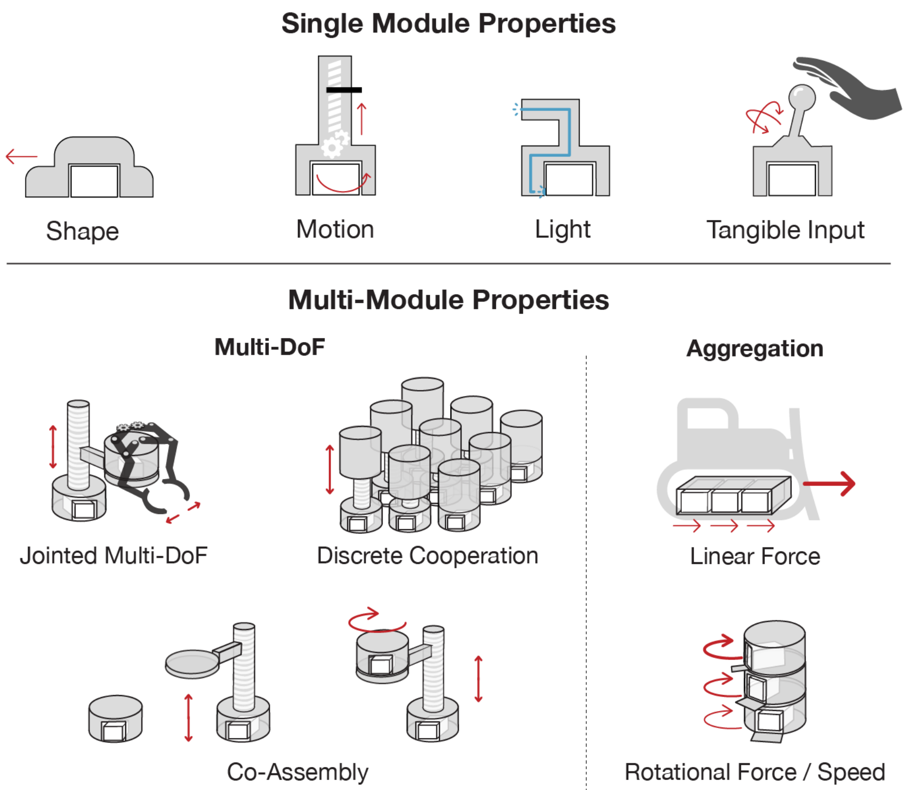


Figure 5-6: Design space for primitive properties of *Mechanical Shells*.

Single Module Design Properties

The *Mechanical Shells* can extend or convert properties for a single robotic module:

Shape: The most primitive and simple property of a mechanical shell is its shape. With *HERMITS*, each robot is capable of changing its shape dynamically by exchanging the shell it 'wears.' As these shells can be prefabricated, this allows the robots to take on different high-fidelity shapes. This is in contrast to prior work into SUIs, which feature modules that share the same shapes [74].

Motion: The motion that each module can perform can be modified or extended with the use of a mechanical shell with embedded transmission mechanisms. While the robot of a SUI is capable of rotation and translation on a 2D plane, *Mechanical Shells*, for example, can convert lateral movement to vertical movement as in the vertical motion unit presented in (Figure 5-1j).

Additionally, the rotational motion generated by robots can be converted by shells to ramp up their speed or torque by using different gear ratios; the fan shell (Figure 5-1g) ramps up the speed of rotation to generate wind, while the walking shell (Figure 5-5d right) ramps up the torque allowing the unit to push and lift itsself up to traverse uneven surfaces.

Light: *Mechanical Shells* can also augment optical properties. In *HERMITS*, the shells can redirect or forward the light from an LED embedded into the base of each robot to other custom locations via optic guiding materials (e.g. optical fibers), similar to [169, 8, 173]. In this way, the light can be repurposed for different modules, such as for the headlamps of a vehicle module, or the lights on a traffic light module (see Figure 5-1e and f).

Tangible Input: *Mechanical Shells* can also extend the sensing capabilities of the system for interaction purposes. For example, tangible input to a joystick can be interpreted collectively by multiple robots' sensors in order to detect the rotation and direction of the joystick (Figure 5-1a).

Multi-Module Design Properties

As *HERMITS* encompasses the possibility for multiple robots to be used, taking inspiration from SUIs, there are also specific design properties pertaining to a collection of units. *Mechanical Shells* can serve to combine multiple modules that can impact how they coordinate their movements:

Multi-DoF: A single shell can house and leverage several robots' individual actuation capabilities. For example, a robotic gripper shell on Figure 5-1h can be controlled with the use of multiple robots, enabling multiple degrees-of-freedom of motion. This is given the term *Jointed-DoF* (see Figure 5-6). Multiple degrees of freedom is also enabled through the *discrete cooperation* of units. In this manner, units can work together to present collective shapes, similar to [145], but with the added possibility to exchange the shell. *Co-assembly* also involves multiple degrees of freedom. The lift shell (Figure 5-1C) demonstrates this feature by extending the mechanism of the vertical moving shell such that it can lift other robots and help them dock into other *Mechanical Shells*.

Force and Speed Aggregation: A single shell can house multiple robots to attain a greater force than that generated by a single robot; the linear force of a dozer unit for instance features the aggregate force of three robots (Figure 5-5b). Furthermore, greater rotational speeds and forces can be generated when a shell allows multiple robots to be stacked and to rotate on-top of each other in the same direction (Figure 5-1d).

5.5 Implementation of HERMITS

In this section, we introduce the implementation of our proof-of-concept prototype of HERMITS.

5.5.1 Overall System Design based on toio

The overall system of HERMITS is based on the off-the-shelf robotic toy system, *toio*^{TM} [28], developed by *Sony Interactive Entertainment (SIE)* that features two-wheeled robots (only sold in Japan [as of August 2021] with price of approx. 40 USD). We use toio systems as the underlying self-propelled TUIs (referred to as *robots* in HERMITS). While the hardware is sold as a gaming console with dedicated game cartridges, SIE releases its API for maker and researcher communities to design interactions with the robots [26]. Based on their API, we have built a Raspberry Pi-based hierarchical control architecture as shown in Figure 5-7. A computer (either Windows or Mac) takes the central control of the system (based on Processing code), while a number of Raspberry Pi micro-controllers were used for connecting and controlling individual robots through Bluetooth (based on Python code). As for control specs, the Python program on Raspberry Pi operated at 100 fps and Processing programs on the computer operated at 30 fps.

The reason for taking this hierarchical control architecture is due to the limitation of the Bluetooth on a computer to connect to toio robots simultaneously. By using a Raspberry Pi, which is a relatively cheap computer with Bluetooth control and wired Ethernet connection capabilities, the control system can easily scale up to control many toio robots. The number of toio robots we have tested for robust connection per one Raspberry Pi is 5, and overall we have tested controlling up to 70 robots using 14 Raspberry Pis simultaneously. This software platform for the control architecture itself is useful for prototyping SUI interactions using off-the-shelf products as components.

A toio robot has an embedded downward-facing optical sensor (camera) to detect its position on a custom designed toio mat with printed patterns. This is similar to AnotoPen [30] technology. Toio mats feature printed patterns that encode absolute localization information so that a robot can detect its position and orientation when placed on the mat. The resolutions of position and orientation detection offered by the API were 1.42mm and 1 degree, respectively. Each mat has a thickness of 0.1

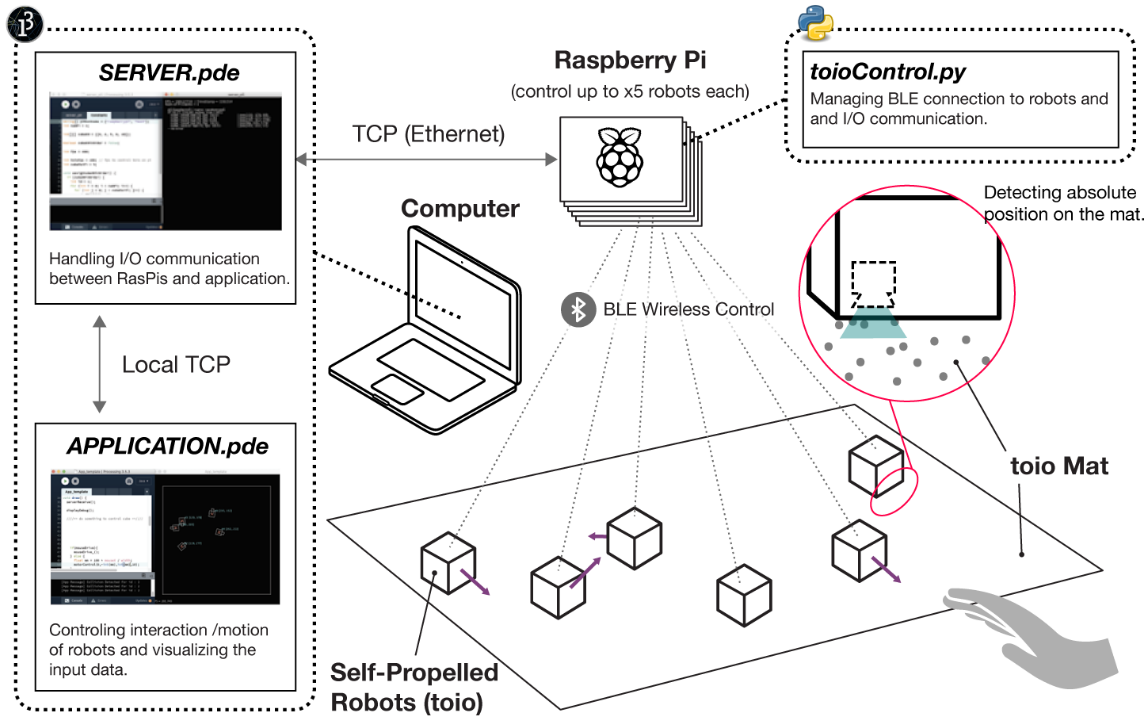


Figure 5-7: System overview and control architecture.

mm. Up to 12 mats can be tiled together to form a maximum area of 1260 x 1188 mm (*toio Mat for Developers* as in [27]). In our implementation, we cut the mats to cover an area of 610 x 920 mm to develop applications that operate within an arm's distance of a user. The remaining parts of the mat are used to augment some shells to enable closed-loop control for automated docking and for the detection of user-input. This will be elaborated upon in a later section of this chapter.

5.5.2 toio modification for HERMITS

We have made three hardware modifications to the toio robots specifically to meet the design requirements of *HERMITS* as shown in Figure 5-8 and 5-9.

The first modification is for the active docking mechanism. In order to achieve the active docking capability needed for the *HERMITS* concept, a technique needed to be developed to connect the robots to passive *Mechanical Shells*. This was done by adding a micro-linear actuator to each toio. To avoid the need to add an additional microcontroller to each robot, we hacked the toios by repurposing their piezo control capabilities. The oscillation pin was soldered to the servo motor, such that generated signals could be used as a PWM signal to control the motor. With this, by using sound control functionality of toio API, the system was able to control the vertical pin up and down (7 mm stroke, 0.15 sec/cm speed, and 0.24 kg-cm torque) [3]. To contain this micro linear actuator, we replaced the original plastic container of the toio with a custom 3D printed case. The modified toios were 32 x 32 x 36 mm in dimension. As shown in Figure 5-8 and 5-9, this vertical pin is positioned at the center of rotation for a toio when two wheels were rotated in opposite directions.

The second modification is the addition of magnets for robust torque transmission to the *Mechanical Shells*. Our earlier prototype of *HERMITS* with original toio configuration revealed that the wheels can easily slip when actuating a mechanical shell, especially for the ones that require a relatively high torque. To increase the friction of the wheels, we added two disc-shaped neodymium magnets (6mm diameter, 1.5mm thickness) to the bottom of each toio with a 3D printed mount and placed a 1mm thick ferromagnetic iron sheet underneath the 0.1mm thick toio mat. This modification was inspired by other SUI hardware for increasing the horizontal force for haptic feedback [69] and for locomotion on a vertical plane [68]. With this, we increased the linear torque from approximately 0.8 N to 3 N. We measured the linear locomotive speed to be approximately 24.7cm/s.

Lastly, we made a modification to the LEDs for optic transmission to our shell prototypes. While the original toio robot had single RGB LED that could be controlled with the API, it faced downwards and was difficult to access by the *Mechanical Shells* for optic transmission. By tearing down the plastic casing, we noticed that we could place a hole on the front side of each toio for the internal LED light to pass through, such that it could be transmitted to shells (Figure 5-8).

5.5.3 Design of Mechanical Shells

Next, we describe the design of *Mechanical Shell* prototypes for *HERMITS*. We fabricated the *Mechanical Shells* mainly with FDM and SLA 3D printers. Additional

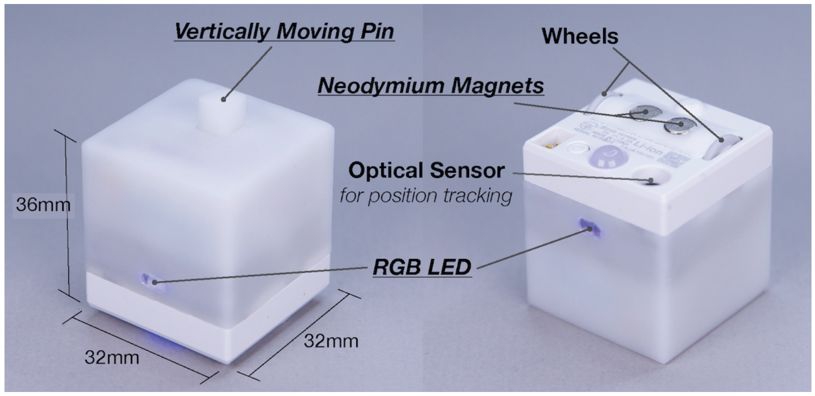


Figure 5-8: The wheeled robots developed for *HERMITS* based on toio, an off-the-shelf robotic toy. (Components with underlines are modified feature from original toio hardware.)

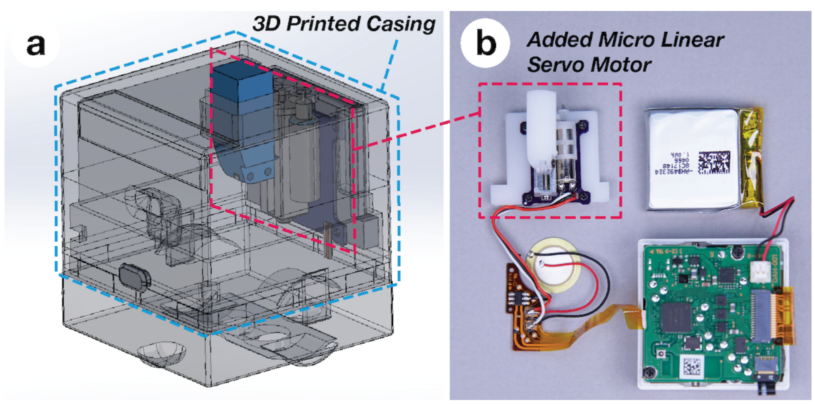
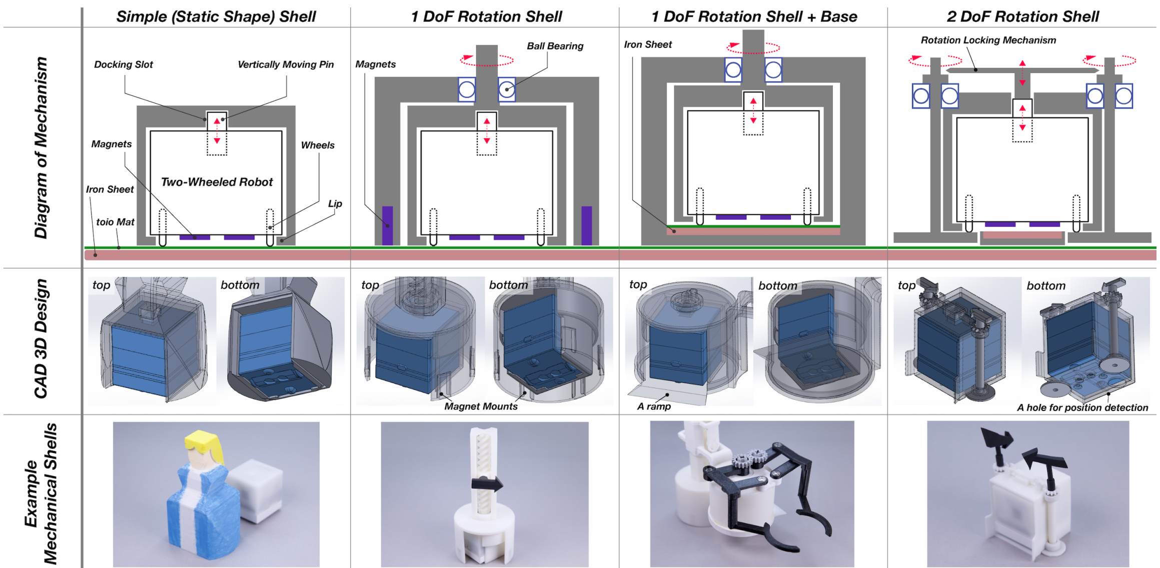


Figure 5-9: a. 3D model of the internal structure of toio with the additional Linear Servo Motor, b. Added Micro Linear Servo Motor soldered on Piezo signal wires.



Characteristics	Simple (Static Shape) Shell	1 DoF Rotation Shell	1 DoF Rotation Shell + Base	2 DoF Rotation Shell
DoF of Motion to Activate	0DoF	1DoF	1DoF	2DoF
Movable on the Plane	YES	YES	NO	NO
Mat Position Detectable	YES	YES	NO	YES
Actuatable when Lifted	—	NO	YES	YES
Capable of Closed Loop Control	—	YES	YES	NO

Figure 5-10: Design and mechanism of four basic types of *Mechanical Shells* implemented for *HERMITS*, and their characteristics.

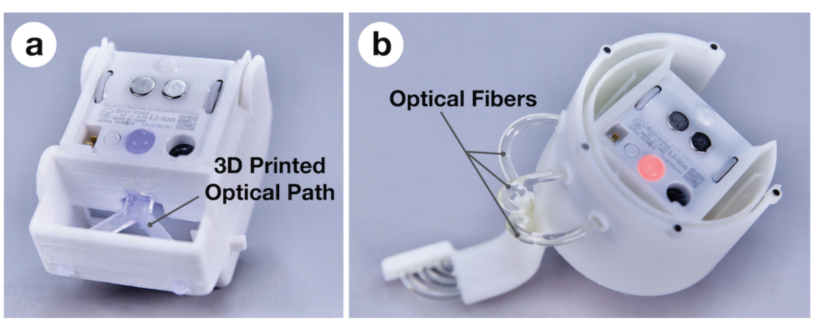


Figure 5-11: Examples of *Mechanical Shells* that extend the illumination of LED (a. 3D printed optical path for vehicle shell, b. three optical fibers for multi-channel output in traffic light shell.

parts including, bearings and magnets were embedded for some of the shell designs as detailed below.

Primitive Types of Mechanical Shell for Motion Transmission

We designed four basic primitive designs of *Mechanical Shells* to extend the motion of two-wheeled robots in different ways. These four primitives serve as the basis for the variety of *Mechanical Shell* prototypes featured in this project. While each primitive was designed for a single robot, these primitives can be combined to achieve more complex *Mechanical Shell* designs that can be controlled by multiple robots.

These basic designs are categorized in how the available activating motion of actuated modules are transmitted. Figure 5-10 describes the mechanism in a simplified section-cut diagram, 3D appearance in the CAD, an example shell prototype, and specific characteristics for each basic shell design.

Simple (Static Shape) Shell: The most primitive deign of the *Mechanical Shells* is the one that modifies only the shapes of the robot. This shell simply contains a docking slot as well as lips on the bottom to hold the toio even if the units are picked up by users. While placed down on a mat, this design allows the robot to touch the platform for locomotion and position detection. This simple shell also became a basis for other modules with moving parts.

1 DoF Rotation Shell: This primitive shell is composed of two solid components (an internal and external part respectively) that are connected through a single ball-bearing. The external part is designed to house the internal one. The internal part has a similar design to the simple shell and can freely rotate within the external housing when the wheels of the robot are activated to spin in opposite directions. With this rotation, this shell can become a motor to activate the mechanism attached on top. Additionally, as the wheels are designed to be touching the platform surface, this shell design allows the unit to move across the surface when the wheels are controlled to move in the same direction.

1 DoF Rotation Shell with Base: This shell design incorporates an additional *base* under the 1 DoF rotation shell design. Unlike the 1 DoF rotation shell, the addition of the base means that the wheels always have a surface to drive against such that the unit can be actuated even when its lifted up. The base of this shell has a ramp such that a toio can smoothly drive into it and dock. The base contains an iron sheet to improve the traction of the wheels and a toio mat to enable the closed-loop control of the robot when it is inside this shell. Because this module can be lifted, it can, for example, be combined with a vertically moving module to act as a robotic gripper with z-axis control (Figure 5-1h). As the bottom base is enclosed in this shell design, the robot docked to this shell won't be able to detect the absolute position encoded on the mat. However, this can be resolved by combining this unit with another.

2 DoF Rotation Shell: Unlike the other shell primitives, the 2 DoF Rotation Shell utilizes the fact that each wheel of a toio can be independently controlled. This shell features two rotating plates that can each be spun by a wheel. These plates are locked to allow the toio to drive into the shell, and are unlocked to enable robotic actuation of the shell. The shell incorporates a special mechanism that can be triggered by the robot's vertically moving pin to control the locking and the unlocking of the plates. When the vertical docking pin is raised, the plates are free to rotate. When it is lowered, the plates are locked such that the robot can drive in or out of the shell. On the bottom of the shell, a hole was positioned so that the optical camera of the robot can continue to identify the position and orientation of the unit on the mat. However, the robot is not able to detect the degree of rotation of the rotating plates that it controls.

Mechanism Design Approach

Based on these simple primitive mechanical docking design, we have designed and implemented a variety of mechanisms to convert and translate the motion by the robots using *SOLIDWORKS*. Some of them were simply designed and 3D printed (e.g. the vertical motion shell on Figure 5-1j), while some other were composed with *LEGO* gears for quick prototyping and reliable, smooth and robust motion transmission (e.g. the fan shell on Figure 5-1g, and the walking shell on Figure 5-5d).

Optical Transmission

In addition to mechanism design, we integrated optical paths to transmit light from an RGB LED in each robot to different parts of the shells inspired by [169]. Figure 5-11a is an example of 3D printed transparent optical path designed to fit into a vehicle shell to enable head lamps (printed with transparent resin of Form3 SLA printer [34]). While our employed robots only had single RGB LED, using multiple optical paths with combination of motion enabled the shell to exhibit the light in multiple locations. Figure 5-11b presents the underline mechanism of traffic signal shell that incorporates three optical fibers for the robots to selectively illuminate by adjusting the rotation angle.

5.5.4 Tracking Mechanical Shells with AR Markers

While the toio robots were able to identify their own location on the toio mat, for us to explore and develop certain interactive functionalities (for automated docking and detecting controller inputs), we have implemented a way to track the location of *Mechanical Shells* through a computer vision technique. As shown in Figure 5-12a, we have designed AR marker modules to be magnetically attached on some of the *Mechanical Shells*. To track them, we placed a USB camera above the interaction stage facing down. Figure 5-12b shows the actual footage from the USB camera with graphically overlaid tracking information that is assigned to each AR marker associated to each mechanical shell. We chose to use detachable marker modules to quickly explore and demonstrate the concept of *HERMITS*. In the future, more advanced tracking techniques, such as using sensors underneath the interaction stage [163, 82, 117] should be incorporated for a robust, accurate, and compact system.

As shown in this figure, we programmed the software in the way that individual markers are associated with the relative docking position and orientation of the *Mechanical Shells*. With this, the system was able to control the robots movement to be automatically docked to the associated *Mechanical Shells* dynamically. This marker tracking capability also allowed the system to capture controller inputs from

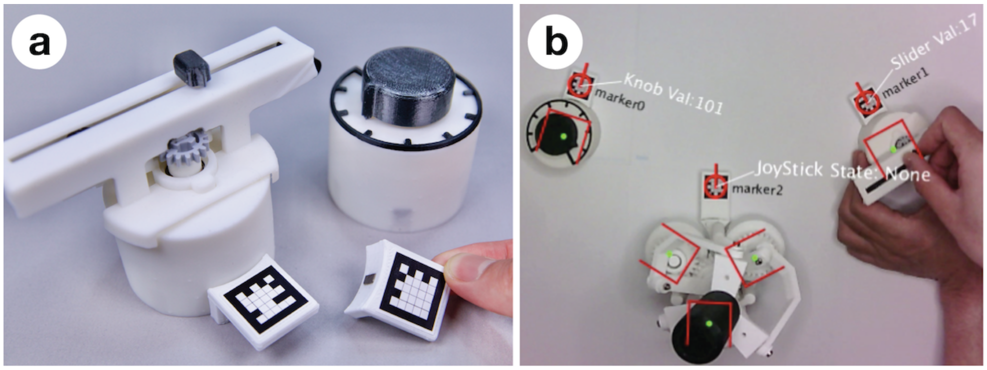


Figure 5-12: Tracking of *Mechanical Shells* (a. Magnetically attachable AR markers for tracking *Mechanical Shells*, b. the actual software view of the tracking.)

the knob, slider and joystick shells by decoding the relative orientation between the robots and the *Mechanical Shells*.

5.5.5 Manual Control with JoyStick-based Controller

In addition to automated docking control, we have developed an Arduino-based controller with three joysticks to manually steer three robots simultaneously. As the prototyping process in this exploration heavily focused on the iteration and fabrication of the different *Mechanical Shell* designs, this allowed us to quickly test and validate our prototypes of *Mechanical Shells* with the controller, without writing code for each shell.

5.5.6 Docking Procedure

As for the docking procedure, each *Mechanical Shell* has pre-defined entry points for each robot to move-in and dock (Figure 5-13a), similar to *RoomShift* [140]. After the robot is in the docking position, the robot actuates the vertically moving pin upwards to make the robust connection to the slot of the shell (Figure 5-13b), then it can switch to the activation/interaction mode (Figure 5-13c). The undocking procedure would be in the opposite process, while the robots have to adjust its orientation to secure the exit path when docked into *Mechanical Shells* with double layered shells (e.g. 1 DoF shell). The tracking of the *Mechanical Shell* as well as the robots are required

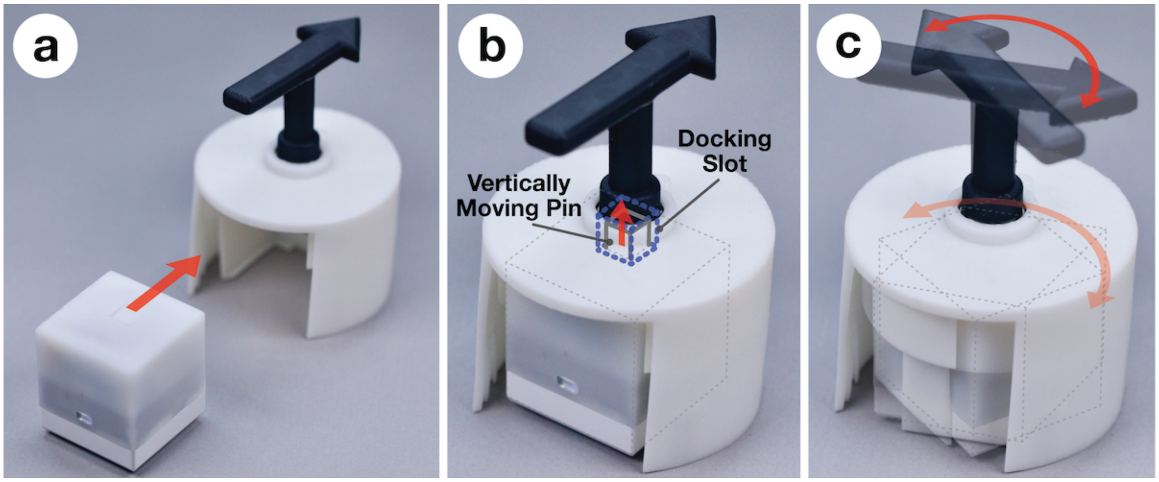


Figure 5-13: Docking process (a. A robot moving in from the entry point of a mechanical shell, b. a robot docking by moving its pin, c. the robot activating the mechanical shell.)

to automatically moderate this procedure.

5.5.7 Opensourcing the Code and CAD

We opensource the following programs and design. We believe this can contribute to the community the following: A. a generic and scalable Swarm UI interaction platform based on off-the-shelf hardware (toio and Raspberry Pi), and B. a toio docking modification design as well as primitive designs for *Mechanical Shells* that other people can use to design their own

- Python software for Raspberry Pi control
- Processing software (Server App + Basic Template App)
- SOLIDWORKS 3D model of the primitive shell designs and modified toio casing

5.6 Applications

In order to demonstrate the strengths of *HERMITS*, we present it's applications to fulfill three different use-cases. We explain how the *HERMITS*' architecture and different types of mechanical shells are leveraged for each.

5.6.1 Interactive Mobility Simulation

TUIs have been utilized to facilitate multi-stakeholder interaction with urban mobility simulations. The tangibility of such tools encourages city governors and citizens to plan and discuss the future city together [2], while the output information remains only as projected graphics. As the technology and service of self-driving cars are drawing increasingly more attention recently, there are demands in tangible actuated tools to emulate the future of mobility. Tangible tools and real physical motion can enable users to gain greater intuition of the dynamic motion of a simulation, and also empowers users to intervene with the system, for instance, by intuitively moving a vehicle from one location to another.

We designed an application for *HERMITS* to support a traffic intersection simulation (see Figure 5-14 left). The actuated TUI enables vehicle motion to be simulated and for the location of different entities (e.g. buildings, traffic lights, as well as different vehicles, such as cars and busses) can be automatically adjusted to match the simulated data and view. They can simultaneously be controlled by users' for real-time tangible intervention with the simulation model. The mechanical shells in this application feature optic transmission of light and automated docking. The light is used to show the break-lamp of cars, as well as to control the color of the traffic signals at the intersection. This feature is critical to allow users to understand the intricate behaviour of the traffic at the intersection. The importance of automated docking to shells is evident in this application, as the types of vehicles in the simulation can be consistently changing and updating. Finally, the interaction stage helps to reveal and conceal different entities as the robots transform their identities by donning different shells. The interaction stage permits modules to switch between on-stage and back-stage locations. This allows for robots and shells that are not needed to be fully of out-of-view from the user (behind the wall on Figure 5-14e), to match the simulated data.

Since urban simulation data often features abstract metrics, *HERMITS* can also

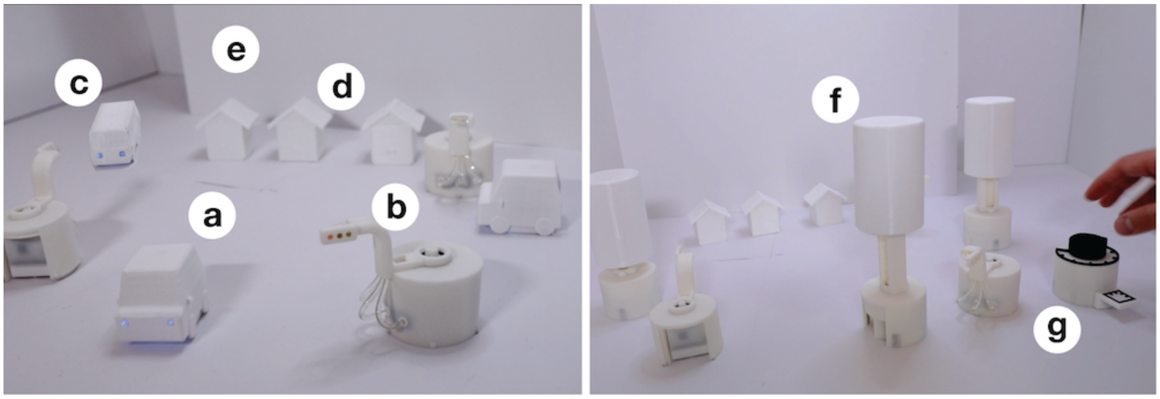


Figure 5-14: Use scenario of tangible interactive mobility simulation (a. car shell, b. traffic signal shell, c. bus shell, d. building shells, e. a wall to hide non-active shells and robots, f. bar chart shells, g. knob shell.)

be used for complementary data physicalization. They can be used for interactive and tangible bar charts [58] for instance to indicate the amount of traffic on each road (see Figure 5-14 right). *HERMITS* can also be leveraged to provide users with tangible controllers in the form of knobs and sliders to control the simulation parameters.

5.6.2 Adaptive Environment/Desktop

While the previous application largely demonstrated the use of *HERMITS* to interact with digital information, we believe that they can also be used for enriching physical environments in our everyday lives with their high level of reconfigurability and adaptability.

Figure 5-15 shows how *HERMITS* can contribute towards actuated physical desktop environments [128, 7]. *HERMITS* can sequentially switch the interaction mode by reconfiguring their mechanical shells. On this desktop, there are several shells including a fan shell for temperature adjustment, the dozer shell to provide strong haptic feedback for 'push' notifications, and two vertical motion shells to adapt the height of a display.

Beyond the desktop environment, we believe that the broad design space for mechanical shells can also be applied to dynamic physical environments in general [133, 164]. In a daily living environment, robotic vacuums are now commonly de-

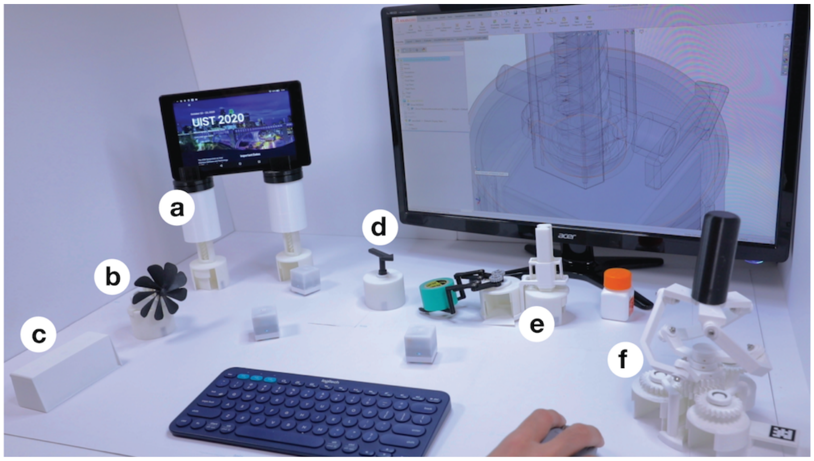


Figure 5-15: Adaptive desktop application. (a. Height adjusting screen shell, b.fan shell for cooling down, c. dozer shell for push notification, d. arrow shell to get users attention to specific direction, e. gripper shell to hand objects to users, and f. Joystick shell for controller to be used in specific software on the computer.)

ployed. As this type of hardware share similar technical components with the wheeled system used in *HERMITS*, the idea of mechanical shells may give such robotic devices a way to handle extensively versatile tasks at home and in the office (e.g. reconfiguring furniture, climbing stairs, and moving obstacles away with grippers).

5.6.3 Storytelling

The strength of *HERMITS* is also highlighted through a storytelling application. Taking inspiration from *Alice in Wonderland*, we use modules to represent the scene where Alice chases after the rabbit that holds an iconic spinning watch (Figure 5-16a). The units are able to play out the chasing motion between the characters across the stage. The mechanical shells bring these characters to life by giving them high-fidelity forms that closely resemble the characters. Similar to the Interactive Mobility Simulation, the stage enables the robots to change their shells out-of-view from the user and return to the visible stage with their correct appearance to match the story (Figure 5-16b). This mimics how actors move on and off-stage to change costumes and play different characters to support the story. With this interchangeability function, Figure 5-16 c and d shows following scenes which represent the Mad Hatter shell

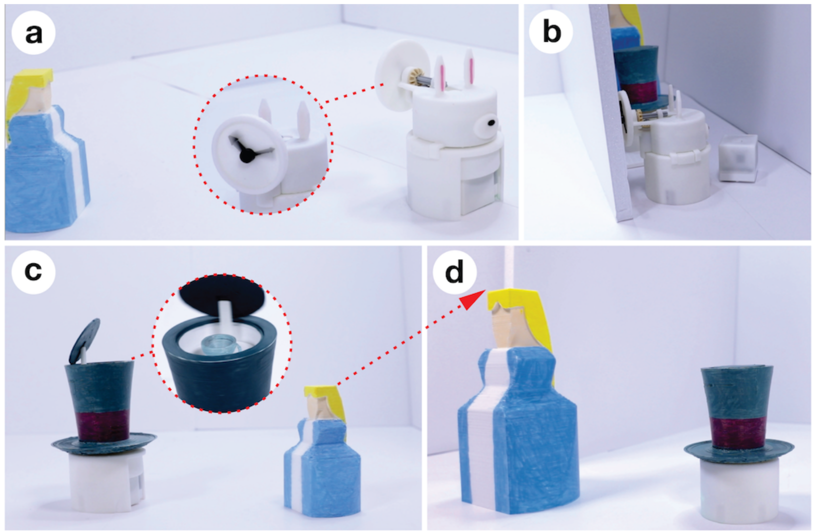


Figure 5-16: Demonstration of storytelling with *Alice in Wonderland* scenario (a. Alice chasing bunny holding spinning watch, b. robots changing the shell in the back-stage, c. Mad Hatter dancing in front of Alice, d. Alice with grown body by switching the shell.)

dancing as a tea-cup weirdly appears from his hat, and Alice's body growing in size by switching to a larger shell. As the characters can be controlled by users as well, this application highlights *HERMITS*' ability to be used as a tangible educational tool for creating animated objects [115, 99, 109, 43].

5.7 Discussion and Future Research Space

In this section, we elaborate on future research opportunities based on the concept of *HERMITS* that extend the interactivity of self-propelled TUIs, and outline the current limitations of our implementation (see Figure 5-17).

5.7.1 Self-Propelled Device

Although we explored the use of wheeled robots as the underlying self-propelled TUI, a variety of other locomotive hardware can be utilized based on the idea of *HERMITS*. Such hardware may include levitating swarm interfaces (e.g. drones) [41, 14], actuated curve interfaces (e.g. serpentine robots) [96, 95], legged robots [132, 24] or wheeled

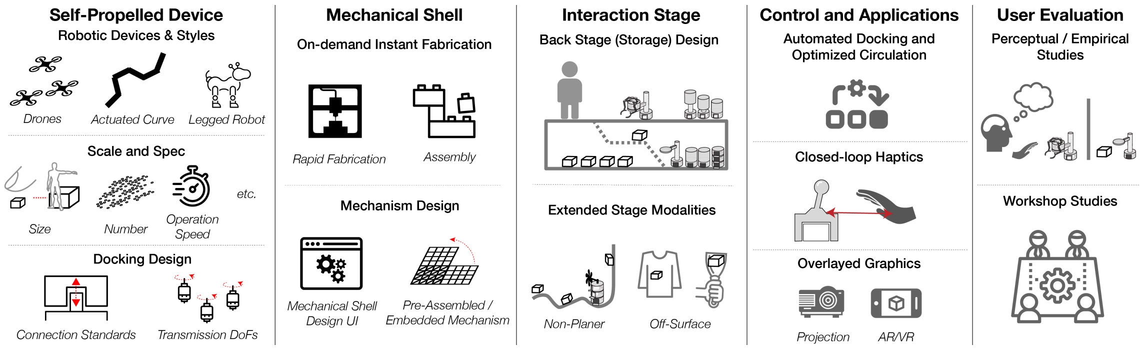


Figure 5-17: Future research opportunities.

pin-displays [131].

Accordingly, a number of properties of the robotic hardware can expand the interaction design possibilities. While *HERMITS* is based on hand-scale devices, we can explore sizes to accommodate a range of scales from nano-scale robots for fingertip interactions [16] to vehicle-sized systems for bodily interactions [161]. Other design parameters may include the number of modules, the operation speed (for general locomotion and docking), etc. Additionally, for project *HERMITS*, there are research opportunities specific to the docking design. These opportunities include defining *connection standards* between different kinds of robots and shells, and exploring more motion transmission mechanisms to cater to different types of hardware.

5.7.2 Mechanical Shells

In *HERMITS*, the shells were prefabricated to meet the demands of the different scenarios, and were stored out of sight when not in use. However, we believe that in the future, instant or rapid fabrication methods [91, 172] as well as methods to rapidly assemble and disassemble [125, 144] structures can be useful additions to the overall system architecture. On a lower-level, further research into the design and fabrication of motion conversion mechanisms [51, 138, 20] is promising. This could improve the design process of shells for end-user applications, and enable them to be more compact and efficient.

5.7.3 Interaction Stage

In *HERMITS*, we demonstrated the idea for an interaction stage with on-stage and back-stage sections to accommodate the need for concealing shells that were not actively in use. Costume changes in theater and fashion shows inspired this design. Extending this metaphor, we can consider the way to store and circulate the shells in the background while users are interacting with the foreground devices. This may help to accelerate transitions. Taking it a step further, it may also be possible to circulate fabrication devices to facilitate on-demand construction and distribution of shells. Additionally, the design of the stage can also be extended to non-uniform or non-planar environments, such as on uneven or vertical surfaces. We can also consider stage design for wearable contexts [22, 62] or for handheld device use-cases [181].

5.7.4 Control and Applications

In *HERMITS*, we demonstrate a basic implementation for controlling and coordinating the movement of modules, including the use of AR markers to support automated docking. However, the control system can be refined for greater practicality, speed and robustness. Ultimately, the software system should adapt the number of modules that are present on-stage to match the users' needs, and coordinate the timing of movements (i.e. moving and docking) to facilitate an optimal user experience. Additionally, enabling bi-directional force control for individual shells [88, 94] would open up novel research possibilities in reconfigurable haptic feedback experiences. This requires precise mechanical design for the shells, high-speed control, and an adaptive PID control. With regards to applications, we see the possibility to combine the use of the system with graphical displays or projection mapping. This opens the possibility to use the system for data visualization as well as AR/VR [78, 131, 167, 180].

5.7.5 User Evaluation

Lastly, while this project validates the novel approach to supporting new interactions with a proof-of-concept implementation [49], performing extended validations, such as user study-based evaluations, remains an opportunity. Future studies could include an empirical study to evaluate the affordances of our approach, which could cover how users perceive robots changing theirs shell back-stage and reappearing, or a workshop-based study to ask designers to create their own shells to explore a wider range of applications.

5.8 Conclusion

We proposed *HERMITS*, a novel approach to augment the interactivity of self-propelled TUIs with mechanical shells. We demonstrated this concept with a proof-of-concept implementation based on off-the-shelf wheeled robots. Our applications demonstrated the use of reconfigurability and adaptability in our approach to dynamically provide different interaction opportunities to users. While this project rather focused on the variety of shell designs and the docking implementation, we outlined the future research directions beyond the hardware design, including possibilities to enhance the interaction environment and advance the computational control. We hope this paper inspires the field to open up a new way to fuse actuated computational devices with passive mechanical modules to enrich our digital and physical interactions with greater reconfigurability.

Chapter 6

Stages: Physical Platforms

6.1 Basic Concept

I define Stages as "physical platforms on which the Actuated TUIs can locomote." A Stage consists of a Front Stage, where Actuated TUIs can interact with users explicitly, and a Back Stage, where Actuated TUIs can be obscured from users' attention and reach. Figure 6-1 shows an overall illustration of a Stage, with Actuated TUIs for user interaction. Stages can be combined with *Mechanical Shells* for support the Shells to reconfigure in the back stage and appear on the front stage for user interaction (Figure 6-2).

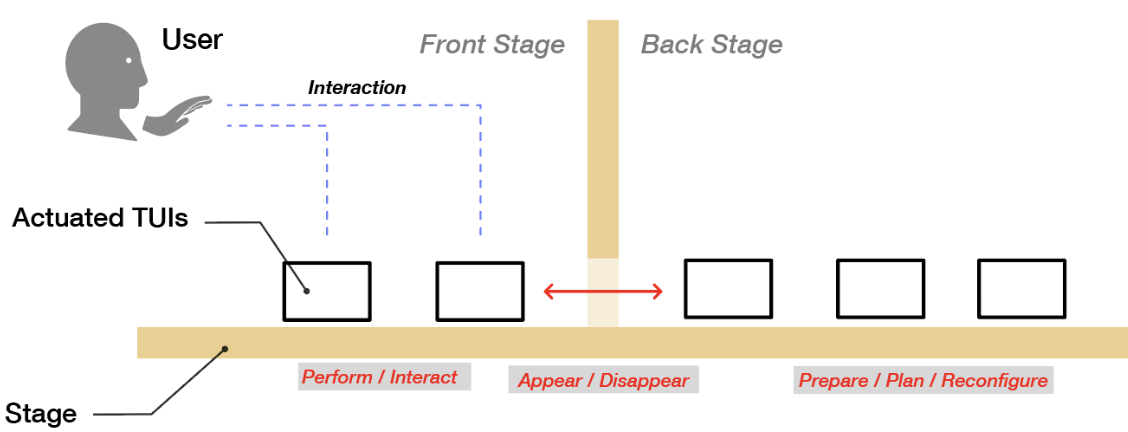


Figure 6-1: Concept of Stage.

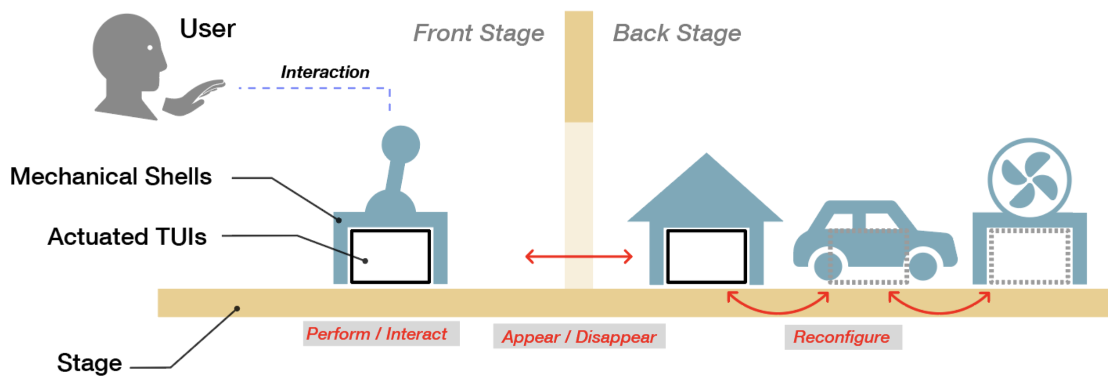


Figure 6-2: Concept of Stage combined with Mechanical Shell.

6.2 Inspiration Source of Stage

The concept and design of Stages were inspired and informed by a variety of sources ranging from theater performance, animation, UI design and biological systems.

6.2.1 Theater, Fashion Shows, and Magic Stages

The concept and configuration of Stages are inspired from a variety of sources, particularly all kinds of stage performances. From the classic theater stages, there have been a shared technique and design process for stages to convey narratives that support actors' actions with different stage designs [154]. For example, trapdoors for actors appearing from the floor, different stage prop configurations, or even stage lights – these contribute towards creating a surrounding environment for actors that support illusions and make a story come to life for audiences. Fashion shows are another source of inspiration where fashion models quickly change their clothing in the back stage and appear in the front stage (Figure 6-3c). This has strongly inspired how both the stages and shells could contribute to the design of novel expressions with A-TUIs. Stage magic is unique in that it is designed to trick audiences into perceiving the existence or non-existence of objects and people. In a similar way, Stages for Actuated TUIs could allow the system to control their perceived existence from a user interaction perspective. Some advanced stage performances, like ShiroA,

Figure 6-3: The inspiration for mechanical Stage from Stage Performances (a. theatrical stage, b. stage design [154], c. Fasion Show, d. ShiroA [129], e. Artistic Swimming[1]).

utilize media technology to develop novel stage expressions. They develop special transition portals that allow actors to enter and exit from the viewers' attention for novel expressions combined with projection mapping [129] (Figure 6-3d). In artistic swimming, we can see how the performers are developing beautiful choreography above the water while preparing for their next move underwater (Figure 6-3e) [1].

6.2.2 Stages in Storytelling and UI Design

Conceptually, Stages have been important for storytelling and UI design to strategically convey information and narratives to people.

In the book "The Illusion of Life" from Disney Animation[153], Staging is listed as one of the twelve basic principles for animation (Figure 6-4a). While the original reference does not refer to physical platforms used in stage performances, it outlines how to compose scenery in a frame in an animation. The guide discusses how animators "should use motion to guide the viewer's eye and draw attention to what's important within the scene. Keep the focus on what's important within the scene, and keep the motion of everything else of non-importance to a minimum." In such way, the concept of Stages for Actuated TUIs plays an important role not only as a physical surrounding system but also for physical interaction design for display, interaction and expression.

In the HCI domain, Tognazzini discusses the applicability of stage magic's technique, principles, and ethics for User Interface design [158]. This paper was published in 1993, before the concept of Tangible Bits was developed. While their paper ap-

[1] Image from https://i.insider.com/57b7747104732f1d008b5023 (NBC)

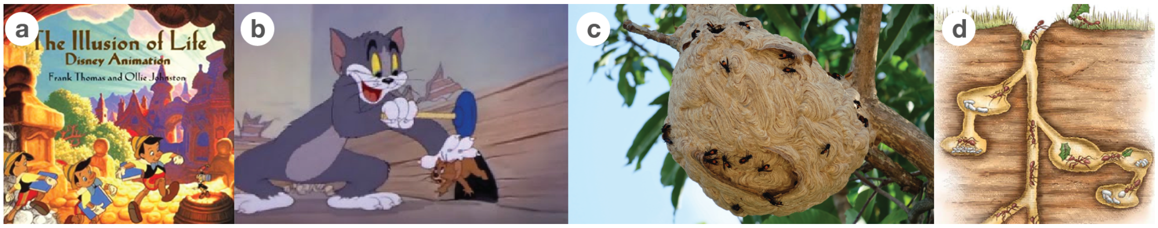


Figure 6-4: The inspiration for Stages from animation and biology (a. "The Illusion of Life" [153], b. "Tom and Jerry", c. bee hive, d. and nest)

plies concepts from stage magic to computer-display-based UI design, extending this technique and philosophy to the design of stages for dynamically moving A-TUI is an exciting open research space. Furthermore, the term Virtual Reality, an important realm in HCI, is said to be first coined by a theater director, Antonin Artaud, in his book in 1938 [6]. Artaud has discussed how the theater stage can act as an illusional world from the perspective of audiences to compose a certain reality. As such, the design and the composition of a stage play a crucial role in conveying and expressing information and reality to users.

6.2.3 Biological Nest and Hives

The way a Stage is composed in my thesis with the duality of front stage and back stage overlaps with nests in biology. Ants or bees store food and equip their nest, and appear in the field from the nest to explore the field and acquire food (Figure 6-4c, d). Mice hide in the wall of a human's house and appear from holes in the wall, such as in the cartoon "Tom and Jerry", another inspiration (Figure 6-4b). Just as it can be surprising for us to see mice coming out of a hole in the real world, the sight of moving objects appearing and being within a person's reach can afford a novel form of physical expression as well as an interaction opportunity.

6.3 Compositions of Stage and Design Space

From the classic research in Tabletop TUIs, tangible pucks have been placed on top of a tabletop surface for projecting graphical information attached to tangible objects.

Stage expands on the role of such tabletop surfaces as a physical platform for A-TUIs. In my exploration, I define Stages to comprise four basic primitive components: Front Stage, Back Stage, Boundaries, and Transition Portals.

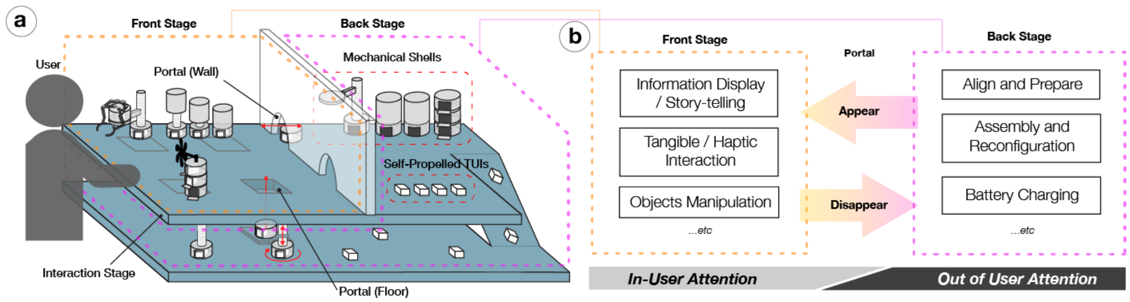


Figure 6-5: Overall Design and Components of Stage.

6.3.1 Front Stage

Front stage is the space for Actuated TUIs to offer foreground interaction with users. A-TUIs can perform explicit interactions with users in the front stage and can be used in the same way they have been used in classic Tabletop TUI systems – including information display, tangible interaction, or object manipulation for users.

6.3.2 Back Stage

Back stage is the space for Actuated TUIs to perform background tasks outside of users' attention. The back stage gives opportunity for interaction designer and Actuated TUI systems to engage in certain processes that are ideally hidden from a user's view. Such background tasks may include assembly and reconfiguration - to reconfigure themselves with, for example, *HERMITS*' *Mechanical Shells* - or battery charging. Furthermore, to appear to the Front Stage effectively through the transition portal, the background task may include alignment and preparation for the entry onto the front stage.

6.3.3 Boundaries (Wall / Floor)

Boundaries are physical barriers in-between the front stage and back stage. The boundaries are either walls (vertical) or floors (horizontal), which block users from seeing and reaching the Actuated TUIs behind. Boundaries would contain a type of transition portal to allow Actuated TUIs to transition in-between front and back stages.

6.3.4 Transition Portal

Transition Portals bridge the front stage and sack stage to allow Actuated TUIs to move in-between. A variety of design of portals are possible according to the types of boundaries (wall/floor), as well as intended expressions. The design of portals is crucial to convey an illusion of appearing and disappearing. Different design of portals as well as expressions utilizing the portals are introduced and demonstrated in the project (Dis)Appearables.

6.4 Interaction Design Roles and Benefits of Stage

In this section, I summarize the roles and benefits of the stage for designing interactions to augment Actuated TUI hardware.

6.4.1 Dynamically Reconfigure Users' Attention and Reach towards A-TUIs

By reconfiguring A-TUIs position on the stage (both front and back), the A-TUIs can be configured so that they are intentionally outside of the reach and view of users, and vice versa. With this, the stage provides novel opportunities for designers of an A-TUI system to control users' attention towards the device for specific interaction design and modes of expression. Such example cases include letting users focus on rather important / foreground display expression, while hiding specific reconfiguration assembly tasks in the back stage. Such back stage tasks may also include battery charging, shell reconfiguration, or even shell 3D printing. Such opportunities can allow for novel interaction design approaches to design dynamic physical affordance - to intentionally invite users to interact with devices - as visibility and being in one's reach are generally crucial for interaction design.

6.4.2 Present Novel Expression and Interactivity for A-TUIs by Transitioning through Portals

With the design of Stage comprising dual spaces of front and back stages connected by portals, the way Actuated TUIs enter and exit from the Front Stages would give novel interaction and expression opportunities for Actuated TUIs. As the portals allow Actuated TUIs to transition in and out of users' attention, such novel expression would include appearing and disappearing from users' perspective. In this way, the (Dis)Appearable project would focus on exploring this research space to demonstrate how Stage could support Self-propelled Actuated TUIs to control the existence on top of the Stage for user interaction. Furthermore, when the Stage is combined with *Mechanical Shells*, to interchange the functionality and appearance of Actuated TUIs, it becomes possible to design advanced expressions such as teleportation and shell transitions.

Chapter 7

(Dis)Appearables

Contributors in this project: Ken Nakagaki, Jordan L Tappa, Yi Zheng, Joanne Leong, Sven Koenig, and Hiroshi Ishii.

Abstract

(Dis)Appearables is an approach for Actuated Tangible User Interfaces to appear and disappear from user experience perspective which is supported by a physical platform, Stage. In our approach, by taking the advantage of the locomotive capability of self-propelled TUIs on Stages that consist of front and back stages, the actuated TUIs can dynamically appear and disappear from users' attention. This generic approach, where actuated TUIs can dynamically transition in and out of users' attention, provides novel interaction design opportunities in the domain of physical and tangible user interfaces for expressive display, and dynamic physical affordances.

We demonstrate this generic concept with a proof-of-concept implementation based on two-wheeled-robots, and a range of stage designs with transition portals. Our stage design pipeline allows users to plan and design front/back stages and the composition of transition portals, and control the motion of the actuated TUIs to navigate them on the stage through portals. With this proof-of-concept prototype, we demonstrate a range of applications including interactive mobility simulation, remote hockey and gaming. Inspired by theatrical stage designs, this is a new take for controlling the existence of matter for user experience design.

7.1 Introduction

"The ultimate display would, of course, be a room within which the computer can control the existence of matter." (Sutherland, 1965) [139]

Researchers have been motivated by the malleability of Graphical User Interfaces (GUIs), where the existence of visual and graphical information/interfaces are instantly and dynamically controlled within 2D flat displays or even in 3D spatial Virtual Reality. As the quote from Sutherland in 'Ultimate Display' indicates, this notion and power of graphical interfaces inspired the researchers to envision ultimate technology that can control the existence of any objects in a space [139]. Similarly, ultimate physical matter that is computationally controlled to conform and transform according to users' input and intention are envisioned as well [52, 156].

Towards such a vision, HCI researchers have explored ways to dynamically reconfigure physical interfaces through research in actuated and shape changing TUIs [110, 19, 116]. Through such research streams, researchers have demonstrated the power of dynamic physical interfaces for interaction design, including dynamic physical affordances [33] and data physicalization [58]. Although a variety of hardware approaches have been explored to embody this idea, one of the limitations towards the 'controlling of the existence of matter' – how physical objects can be controlled to appear and disappear – has not been addressed in-depth. Some research has explored ways for physical interfaces to emerge and be rendered from interaction surfaces [119, 33, 144], but they essentially reveal their underlying mechanisms. How can we design physical interfaces that can completely hide and appear, from the users' perspective, towards 'controlling the existence of matter'?

(Dis)Appearables is a general approach for physical interfaces to appear and disappear from a user's perspective for novel physical display and interaction design based on *Stage*. In this research project, we define the general approach, design space and interaction design benefits of *(Dis)Appearables* based on *Stage*. *Stage* is a physical platform that enables A-TUIs to appear and disappear and facilitate the illusion of controlling the existence of matter. We then demonstrate the approach with an existing Actuated TUI system based on two-wheeled self-propelled robotic devices [97, 28] as a proof-of-concept prototype. Our implementation introduces a design and fabrication pipeline for the Stage that becomes a physical platform for the self-propelled robots. Using the prototyped system, we demonstrate applications ranging from an

urban mobility simulation to remote physical gaming, that take advantages of the '(Dis)Appearing' effect.

The list of contribution includes:

- A research exploration of *(Dis)Appearables*, a general interaction design approach for self-propelled TUIs to actively appear and disappear through a stage consisting of front and back stages.
- Design Space of *(Dis)Appearables* for creating Appearing and Disappearing effects by combining self-propelled TUIs, an interaction stage, projection, and *Mechanical Shells*.
- A proof-of-concept prototype based on an off-the shelf two-wheeled robotic hardware platform with additional implementation on control and stage design.
- Applications to demonstrate the design space of Stages, including transition portals as well as the interaction effects.

7.2 Related Work

7.2.1 Actuated TUIs and Transition of Bits and Atoms

Often inspired by the flexibility and dynamism of GUI, researchers have been investigating physical interfaces that can actuate and shape change through novel mechanical hardware design. Various prior hardware interfaces have had the expression capability of a physical interface appearing and dis-appearing. For example, with vertically actuated pin arrays, 2.5D shape and physical UIs can appear by rising from the surface[33, 77] - Pneumatics technology enabled to render volumetric shapes emerging from flat compressed shapes [174, 151, 152]. With *Dynablock*, Suzuki et al. extended the pin-display architecture to assemble blocks to compose 3D shapes rising from a surface [144].

Emergeables [119], on the other hand, proposed a top-down concept of physical interfaces that can emerge from a surface, for eyes-free interaction on mobile device with emergeable physical controllers with continuous inputs (e.g. envisioning knobs and sliders emerging from smartphone screens). While we were inspired by the concept in this paper of emerging physical interfaces, their general implementation approaches were limited in the types of interfaces and shapes to emerge / render as well as tangible input flexibility.

In our paper, we introduce a novel approach for physical interfaces to dynamically appear and disappear from interaction surfaces by combination of self-propelled robotic TUIs and physical platforms with duality of front and back stage designs, allowing the hardware to hide from users view and reach. By taking the approach of physical interfaces to hide behind walls or under floors, unlike previous methods listed above, the mechanism of physical interfaces can completely hide from the users perspective which could create a strong illusion of disappearing and appearing from a user experience design perspective.

Additionally, by hiding in the backstage from users' view, the self-propelled TUIs can physically reconfigure with additional modules (e.g. constructive assembly as in [180], or mechanical add-ons as in [97]) behind the walls and appear to users with the reconfigured shapes. While such assembly and reconfiguration process may not be ideal for users to see from interaction design point of view (it can attract unnecessary attention from users or indicate unintended affordances [113]), our approach gives new opportunities for designers and researchers to selectively hide such systematically necessary operation that is not preferable to be witnessed by users. By enabling such reconfiguration to be handled in the back-stage, out of users' sight, our general approach has a wider potential for the kinds of interfaces and shapes to appear comparing to previous approaches mentioned above, which will be partially demonstrated in our applications. With such advantage of reconfiguring the peripheral attachments and the capability of the self-propelled TUIs to freely move across the stage, it also gives much higher flexibility for tangible input controls by users (which is a critical axis in the design space of *Emergeables* for continuous inputs but was limited in their prototypes [119]).

7.2.2 Tabletop Actuated TUIs and Swarm User Interfaces

Tabletop TUIs have been explored based on the idea to give actuation capabilities to passive tangible tokens on horizontal tabletop surfaces, one of the most classic style of TUIs [54, 160]. One of the first prototypes for tabletop A-TUIs were implemented using electro-magnetic arrays to control the position of the tangible pucks interactively [110]. Recent advancements in this technical approach made the hardware drastically thinner with the use of coil-embedded PCBs [143, 141].

Instead of embedding the actuation capability into the tabletop surfaces for controlling passive tokens, there has been another approach proposed for tabletop A-TUIs to employ self-propelled robotic devices. *Curlybot* was one of the first instances of such interfaces that had embedded wheels to locomote across a flat plane while being able to detect users' movements [35]. While the modular and swarm robotics have been technically demonstrated in the robotics field for collectively composing shapes and accomplishing tasks [123, 121, 124, 176], recently in HCI, Le et al. proposed the concept of *Swarm User Interface* (SUI) as a new category of A-TUIs [74], which is a type of interfaces composed with self-propelled elements that can collectively interact with users. This approach has displayed broad interaction opportunities within haptics [69], constructive assemblies [180], gestural interaction [67], additional shape-changing capabilities [145], and furniture actuation [140]. As for extended locomotion capabilities, even levitating self-propelled TUIs have been proposed [41, 14].

In HRI and in an education context, Robert et al. proposed a wheeled robot that appears from a gate in an MR environment as an interactive character expression that appears from the digital space [118]. We were inspired by this simple but strong expression to be applied as a generic approach for self-propelled TUIs and Swarm UIs. Our approach takes into account operating one or more self-propelled robots, which can work collectively on functional stage designs for novel interactions.

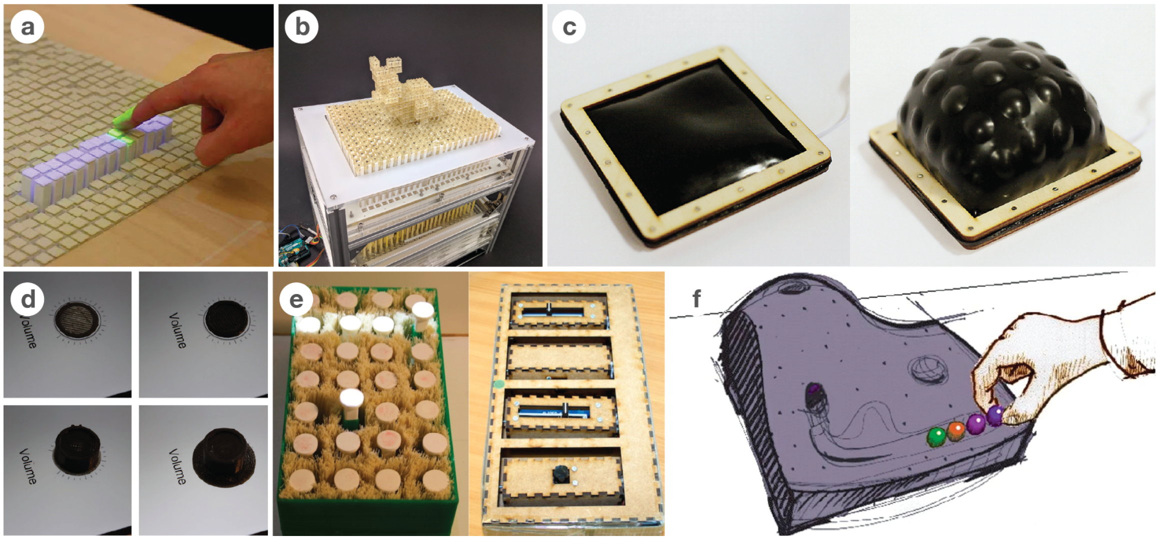


Figure 7-1: Related Work of *(Dis)Appearables* (a. inForm [33], b. DynaBlock [144], c. PneUI [174], d and e. Emergeables [119], f. Marble Answering Machine [21])

7.3 (Dis)Appearables - Concept and Overall Design

We introduce *(Dis)Appearables*, a general approach for self-propelled TUIs to appear and disappear from the user experience perspective based on stage designs consisting of front and back stages. On the stage, the self-propelled TUIs (wheeled-robots) can move and transition in between the front and back stages.

By composing the stage design to have dual spaces - Front Stage (visible and within users' reach for foreground interaction), and Back Stage (non-visible and intangible to the users for background configuration) - the self-propelled TUIs can enter and exit from the user's attention adaptively and automatically. This section provides an overview of the general design and approach of *(Dis)Appearables*, design criteria for appearing and disappearing effects, including portal design space.

7.3.1 Overall Design

The overall design of *(Dis)Appearables* includes the self-propelled TUIs, the stage and the computer. The stage is the supporting physical platform for the overall design,

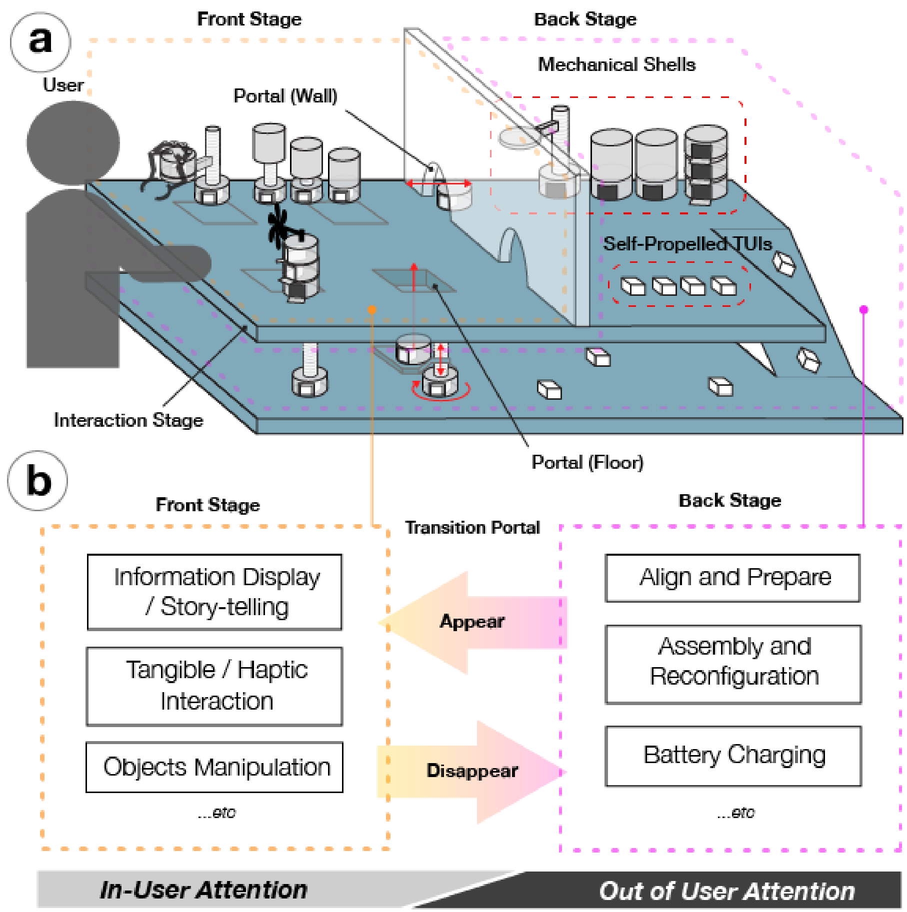


Figure 7-2: Overall Design of (Dis)Appeaerables (a. Physical Construction of the System, b. Interaction Modality that utilizes Front Stage and Back Stage to facilitate the appearing and disappearing effects.)

which allows self-propelled TUIs to dynamically and adaptively appear and disappear from the user's attention. The stage consists of a front stage and back stage, separated by the physical boundary 7-2. The boundary, either wall or floor, contains one or more portals which are doorways for the self-propelled TUIs to transition between front stage and back stage.

There are also peripheral primitives that take advantage of *(Dis)Appearables* such as additional module that works with the self-propelled TUIs (e.g. *Mechanical Shell* or assembly blocks), and display/projection for adding 2D graphics.

7.4 Design Properties of (Dis)Appearing Effects

7.4.1 Portal Design and Examples

Figure 7-3 and 7-4 shows a collection of portal designs implemented in the project *(Dis)Appearables* for both walls and floor. For both wall and floor portals, there are either static portals (containing no moving parts), or dynamic portals (containing actuating parts).

Wall Portals

The simplest wall-portals use the edge of the wall. For this portal, the actuated TUI would simple go around the wall to transition between front and back stages (Figure 7-3a). Other static wall-portals include, tunnels (a hole on wall) or curtains (fabric hung on the wall with a hole). As for the dynamic wall portals, we have implemented multiple types of doors using servomotors. The ones on Figure 7-3 b and c are hinged door, with side-way opening and top-way opening. The one on Figure 7-3 d is a fabric door which can have seamless surface when closed – the portal itself disappear into the wall.

Floor Portals

For the static floor portal, we have implemented a slope portal as shown on Figure 7-3 a. This portal allows actuated TUIs to climb up the slope to appear on the front stage through a hole on the floor. The one on Figure 7-3 b adds a trap door actuated by servo motor to the slope portal, so that when the portal is not in use, it can remain closed for Actuated TUI to locomote over. The last floor portal is a lift as on Figure 7-3 c, which vertically moves the actuated TUI with a scissor mechanism.

Different types of portals can provide different ways for actuated TUIs to appear and disappear on the stage. Designers and researchers could effectively utilize these portal designs according to the intended applications. Some usages of these portals are demonstrated in the application section.

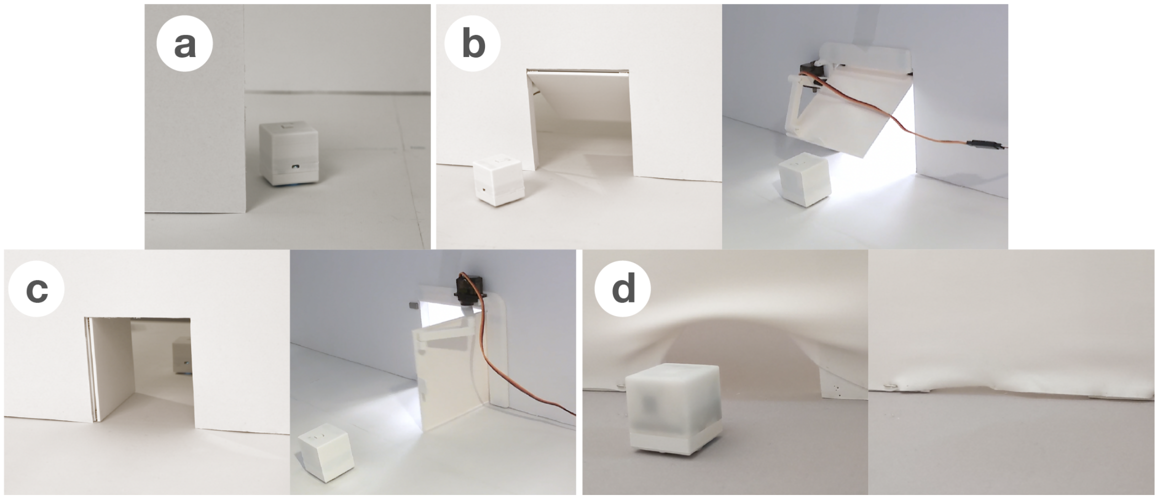


Figure 7-3: Transition Portals on Wall (a. Wall, b and c. Actuated Door, d. Fabric Door).

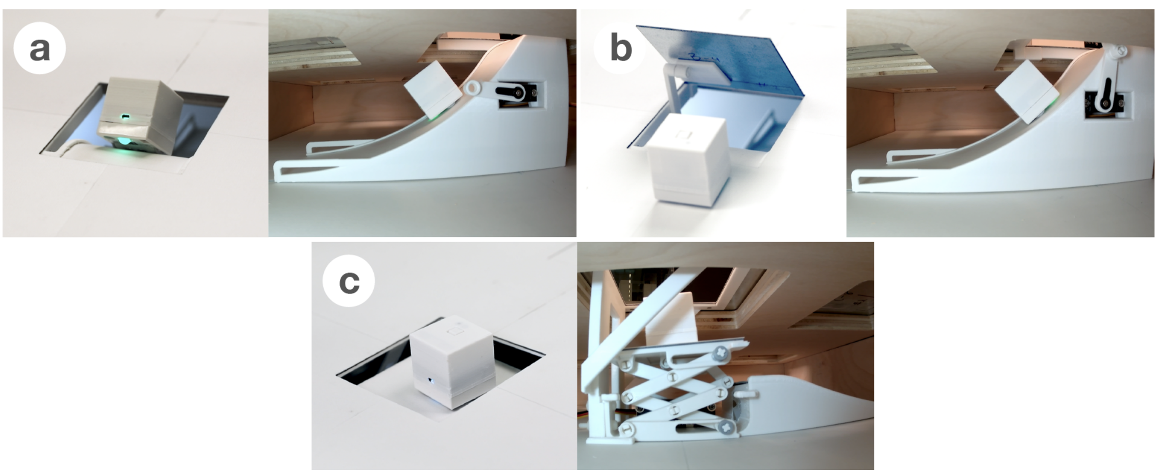


Figure 7-4: Transition Portals on Floor (a. Slope, b. Slope with Trap Door, c. Lift).

7.4.2 Interaction Expression

With the diverse portal design, self-propelled TUIs can transit in-between front and back stage. With this, the portals bring opportunity for the interactive hardware to create novel expressions which are described below (Figure 7-5).

Appear and Disappear

Firstly, simple appearing and disappearing effects can be achieved by transitioning between the front and back stage. These are the basic effects presented and explored

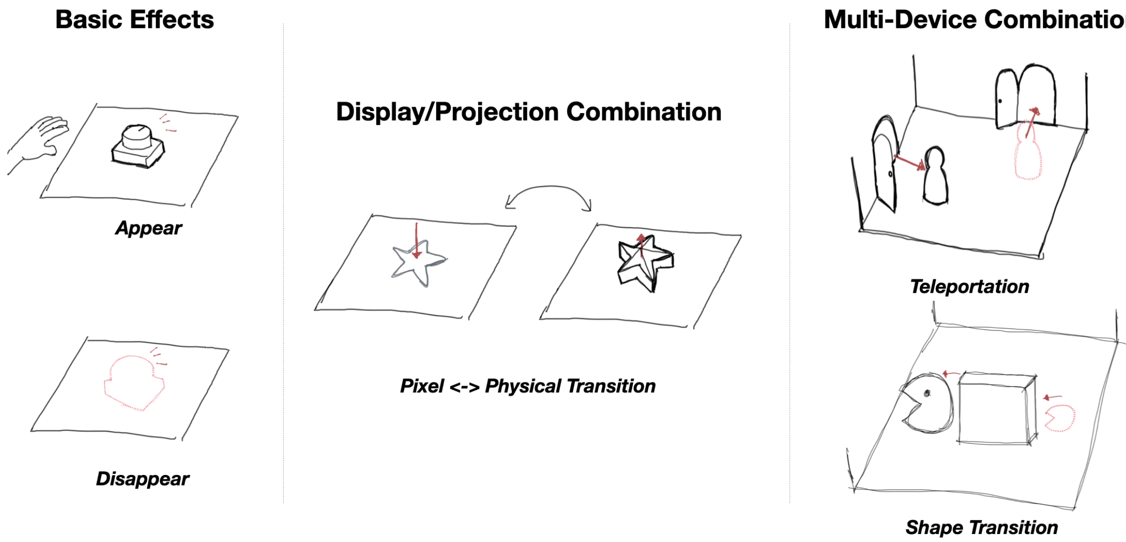


Figure 7-5: Expression and Illusion in *(Dis)Appearables*.

in *(Dis)Appearables*, and are used for other effects as a primitive.

Pixel - Physical Transition

When the basic effect of appearing and disappearing is combined with graphical media (display or projection), the stage allows the Actuated TUI hardware to transit between pixel to physical, or visa versa. While such expression has been previously explored in stage performances [129], shape changing UIs [33, 119], or Human Robot Interaction [118],

Teleportation

When appearing and disappearing effects are combined with multiple actuated TUIs, other illusional effects can be created. One example is an expression of Teleportation – enabled by disappearing one device from one place, while appearing another device in another place. By syncing the timing, it can convey the expression of the physical objects teleporting to other place.

Shape Transition

By utilizing multiple devices, but with different shell shapes, it can create an expression of Shape Transition. By letting the two devices disappear and appear in co-located portal, it can convey an expression that a single device or character has changed its shape or size of its body.

7.5 Implementation

To explore the concept and design space of *(Dis)Appearables*, we have implemented a system based on two-wheeled robots used in HERMITS [97]. This implementation was focused on developing a design and fabrication pipeline for Stages with control tools to navigate the robots on the designed stage. We describe the four phase design and control pipeline. This pipeline follows, 1) Design of Stage, 2) Fabrication of the Stage, 3) Control of A-TUI on the Stage and 4) Execution.

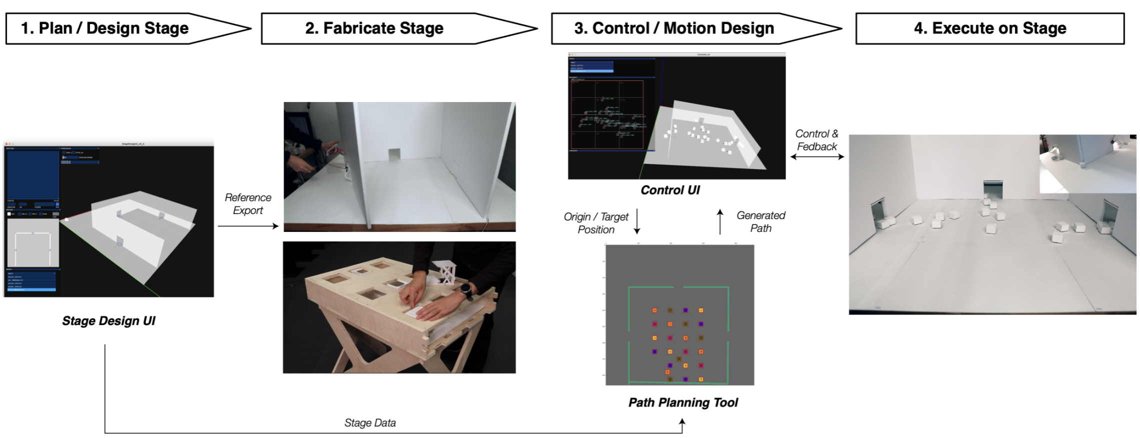


Figure 7-6: Stage Design Pipeline.

7.5.1 Plan and Design of the Stage with Design UI

Firstly, to allow researchers and interaction designers to plan and design the stage as a platform for self-propelled TUIs, we have developed a design software tool for Stages using Processing (Figure 7-7). In this GUI-based software, users can freely design the size of the stage in rectangular shape, the existence of an underground floor beneath the main stage, positioning of walls, positioning of portals on the wall and on the floor. For the parameters of the portals, it is possible to adjust the size and types of portals (e.g. slope, lift for floor portal) in detail.

With this software, designers can plan the stage design and preview what the stage would look like with the 3D visualization model in the tool. The design file is exported to be used for the fabrication of the materials used for *Stage*, as well as the control UI for the robotic hardware to recognize their position on the stage to plan the motion path accordingly.

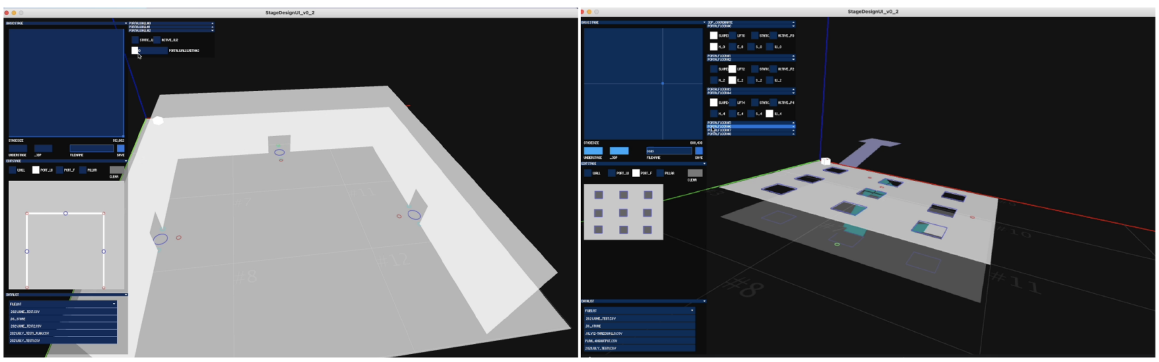


Figure 7-7: Design UI of Stage.

7.5.2 Fabrication of the Stage

For the fabrication of the Stage, the stage's basis has the similar composition as the one in HERMITS, where it has a multi-layer design of ferromagnetic thin metal sheet and toio mat, placed on a rigid surface (e.g. wooden table).

For the holes of floor portals, the metal sheet was cut using a waterjet. To compose a multi-story stage, we have also utilized a CNC router (ShopBot), to cut out wooden boards to compose as seen on figure 7-8b. The lower stage also has the multi-layer composition. For the wall, styrene board was cut and placed on the stage with extra holes for portals.

To enable dynamic portals, we have implemented a servomotor-activated mechanism. As shown in Figure 7-4 and 7-3, these such servomotor-activated portals include doors, fabric doors, trapdoors and lifts. The portals on the floor, slopes and lifts were 3D printed with additional layers of toio mats and metal sheets to allow robots to travel (Figure 7-9). These slopes and lifts have toio mats with fixed IDs, so that the control tool would be able to localize where robots are on the stage. As shown in Figure 7-9, we have designed these portal modules to be reconfigurable so they can be reused in different stage designs.

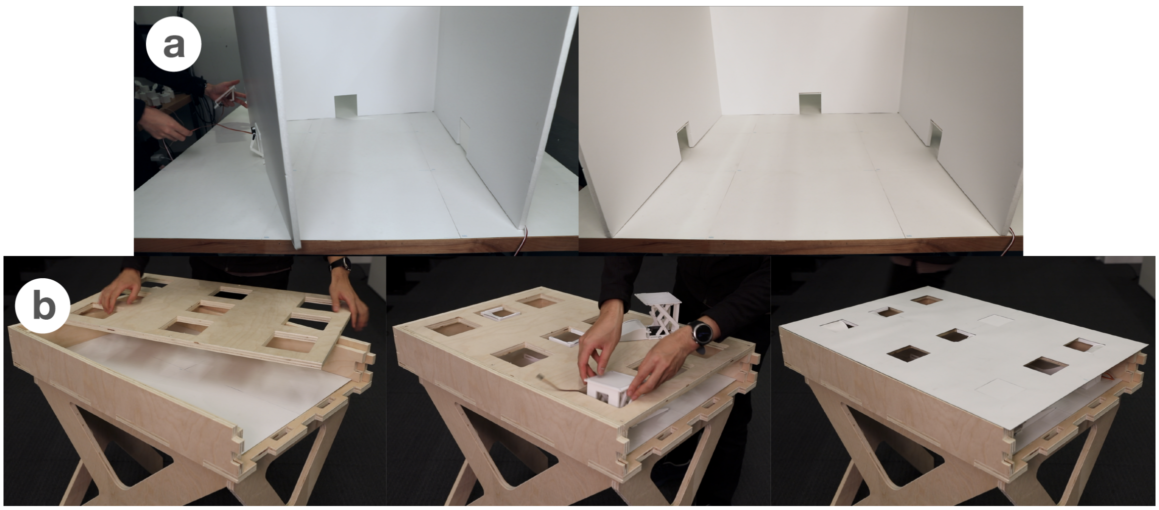


Figure 7-8: Fabrication of Stage.

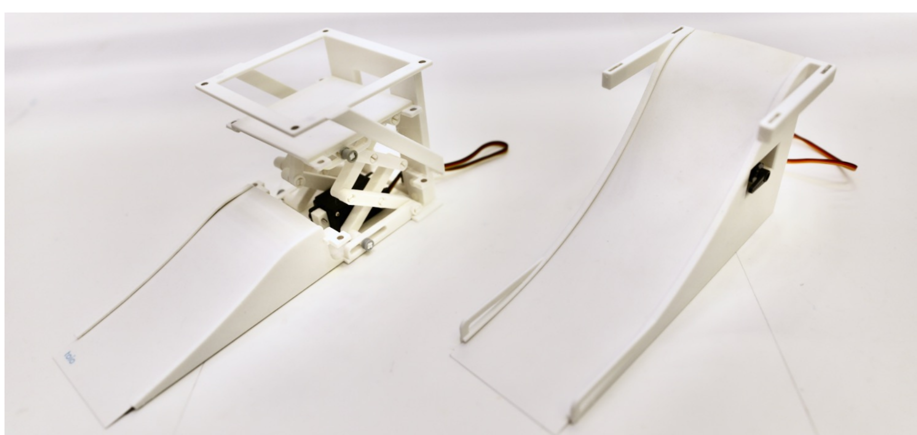


Figure 7-9: Modules of Floor Portals (Left: Lift, Right: Slope).

7.5.3 Control System based on HERMITS

Once the stage is fully fabricated, the actual robotic modules can be placed on the stages and their motion can be controlled. To control the robots on the stage, we have developed two software tools, a Control UI and a Path Planning Tool. The Control UI is an updated tool from the HERMITS' tool to handle the I/O data with robotic hardware via Raspberry Pi BlueTooth Modules. For the update, we have added 3D visualizations which renders the detected robot positions in real-time on top of the model of Stage based on the exported stage design file (Figure 7-10). With this control tool, users can control the behavior of robots using joysticks, keyboards and other primitive control interfaces.

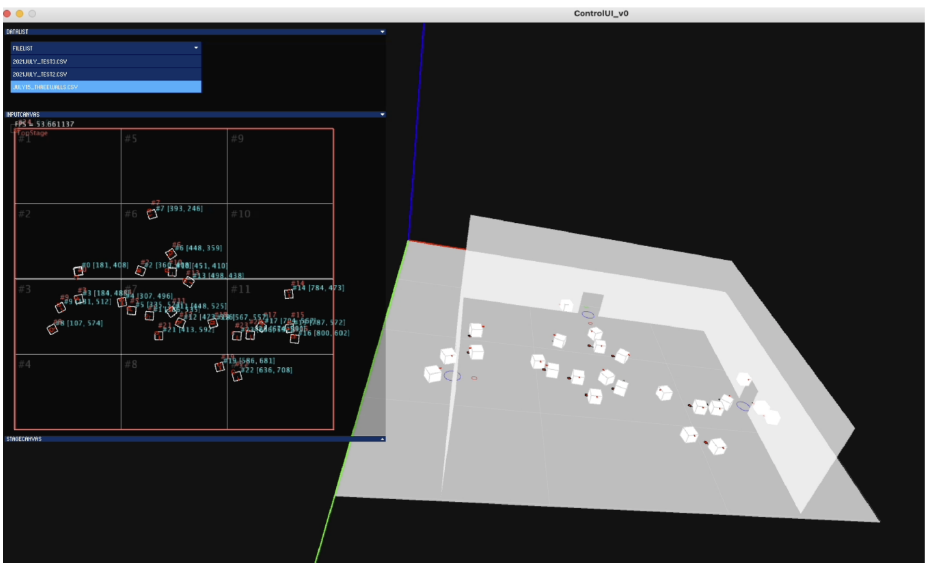


Figure 7-10: Real-time Control Tool with 3D Visualization.

7.5.4 Multi-Agent Path Planning Tool

Furthermore, we have designed the control UI to communicate with a multi-agent path planning tool for the system to automatically generate paths for multiple robots to navigate on the stage from origin points to destination points.

To manipulate multiple robots on a Stage, the path planning tool was developed based on a basic version of Conflict-Based Search (CBS) [127], which is a popular

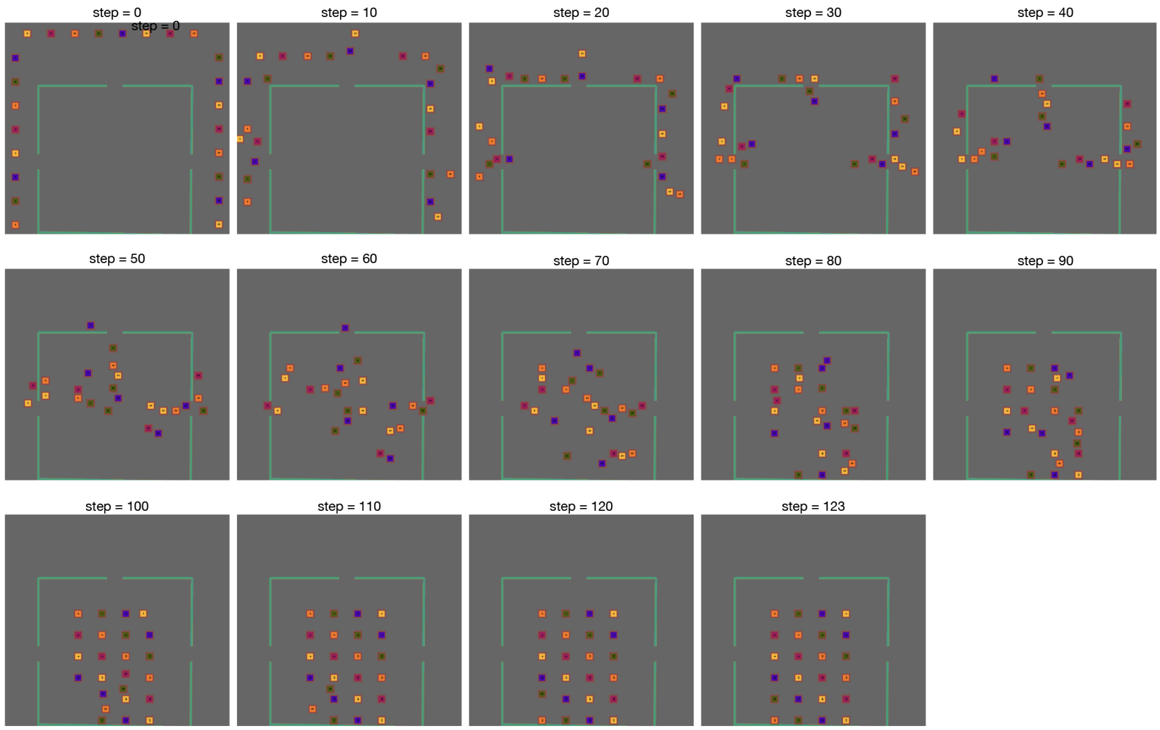


Figure 7-11: Result of Path Planning. Total of 123 steps to navigate 24 robots on the stage (1260 x 1188 mm size).

optimal algorithm from Multi-agent Pathfinding (MAPF) literature. A survey by Stern et al. [134] gives a review of variants of MAPF problems and the algorithms developed for solving each variant. MAPF techniques have been popularly used in action planning for warehouse robots [86].

The path planner tool first reads a stage file that is generated by the control UI and creates a grid map. The tool creates a set of blocked cells on the grid map to represent the stage walls. It also reads the start and goal configurations (e.g., locations) of robots from a control file that is generated by the control UI. Based on the grid map and the robot configurations, the tool runs the CBS algorithm to find a set of collision-free paths for the robots. Each path contains a sequence of actions (move up, down, left, right, wait) that a robot needs to take at each time step. A set of paths is collision-free if robots do not collide with other robots or obstacles while moving on the map. A simple body collision checking is implemented. A circle shape safe zone, which uses the diagonal length of the robot as the circle's diameter, is defined for each robot. Two robots collide when their safe zones intersect. This

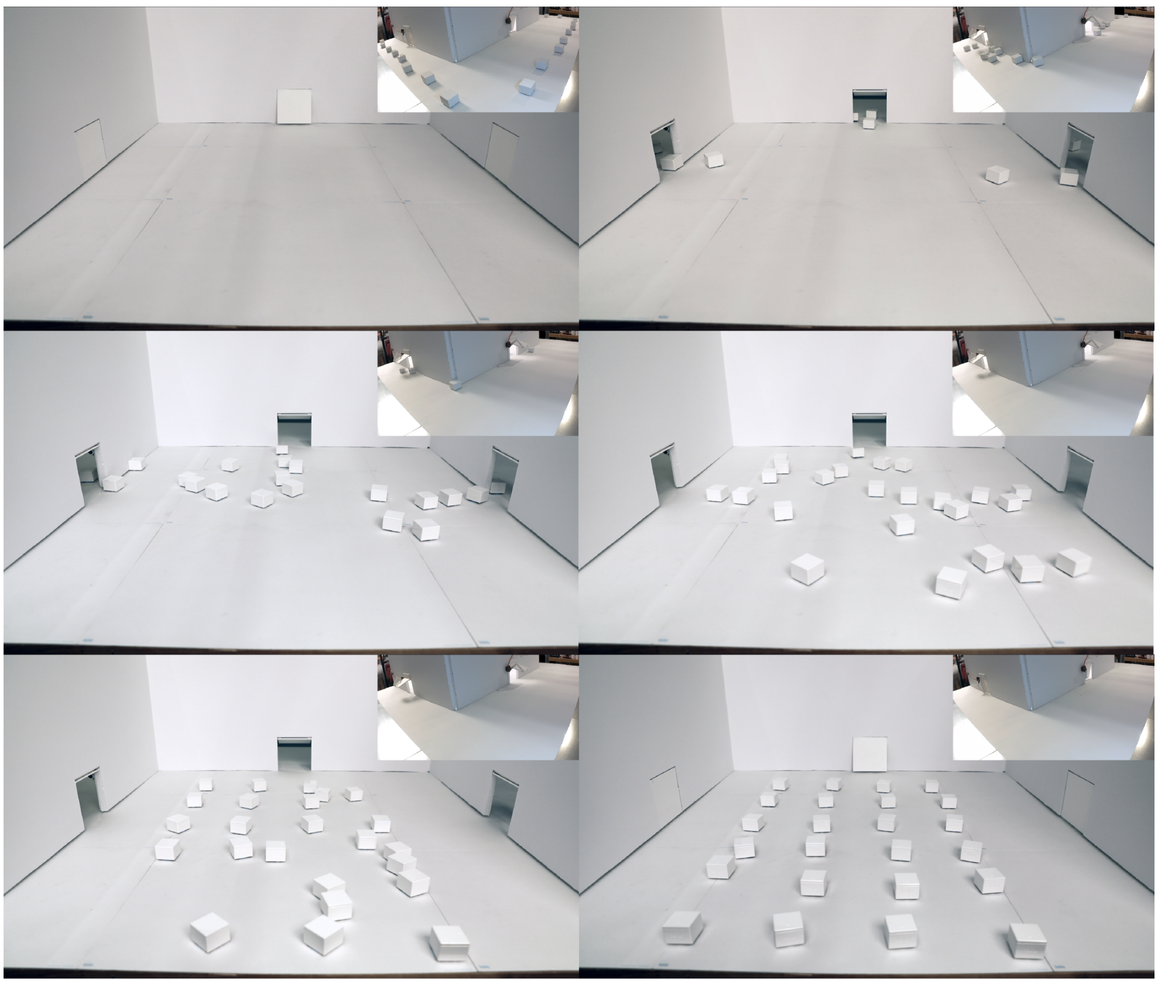


Figure 7-12: Result of Path Planning with 24 toio devices.

circle design aims to avoid the potential collisions during rotations of robots. After finding a set of collision-free paths, the tool adds rotation actions as a post-processing step and creates an action plan that the robots can execute.

Figure 7-11 shows, the generated path from origin to destination points for 24 robots on a stage, sized 1260 mm x 1188 mm, with three walls and three wall-portals.

Currently, the basic version of the control software does not take the reconfigurability of shells into account, as it would add to the complexity. However, it may be implemented in the future. For example, we could employ an advanced control algorithm from warehouse robot control tools, which is designed to carry boxes from one place to another.

7.5.5 3D Printing Shell on-demand in Back Stage

Additionally, to demonstrate how the dual stage design of *(Dis)Appearables* potentially allow shells to be 3D printed on-demand in the back stage, we have prototyped a method to 3D Print shells directly on a 3D Printer bed, and control the toio robots to take the shells away from the 3D Print bed. Figure 7-13 shows the example workflow, where shells are printed on the 3D print bed, then the self-propelled robots move onto the platform using a slope to take away the shells. Then, the robots can bring the shell to the users in the front stage for foreground interaction.

While HERMITS had only pre-fabricated shells, such on-demand 3D Printing Shell systems would be able to generate shells with different shapes, functionality and expressibility by adapting to users' demands and application requirements in real-time. In the future, an ideal version of this system coupled with a Stage design may look like 3D Printers rapidly generating shells according to users' interaction happening in the foreground to adaptively provide different tangible shells for interaction. To enable such interactions, instant 3D printing technology [144, 172] may be integrated into the Stage design. Shells with more complicated mechanism designs, could be printed directly by 3D printers suing modern techniques [63].

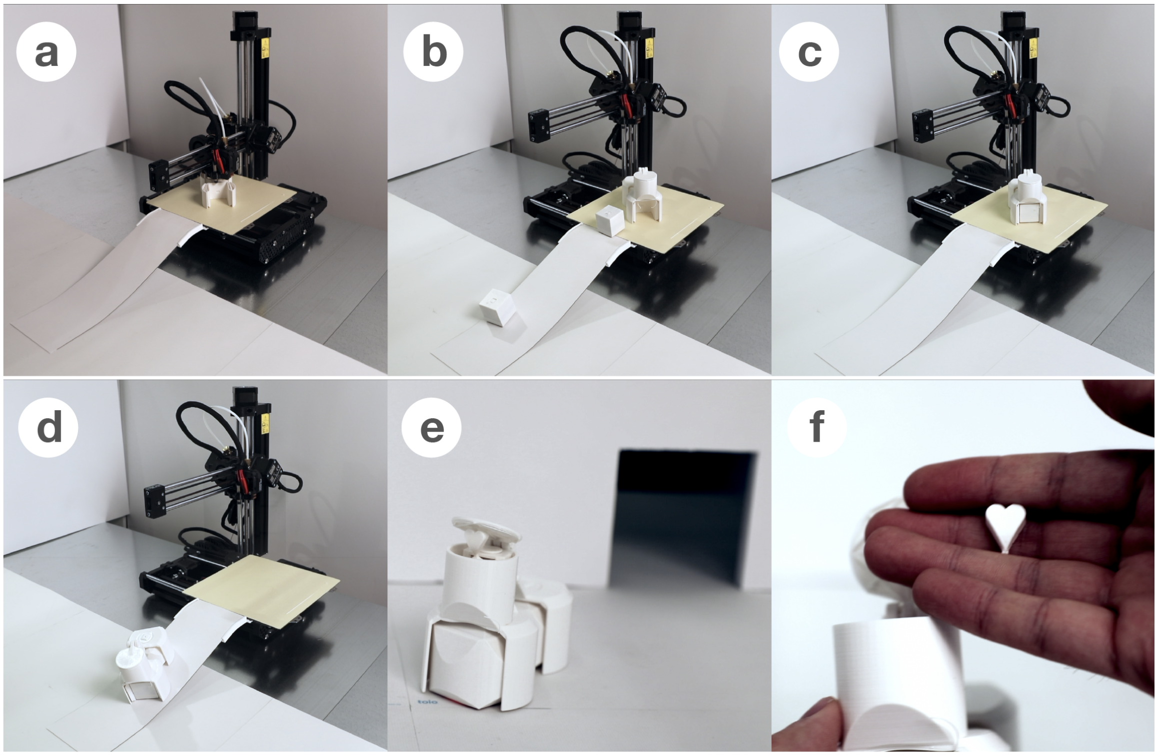


Figure 7-13: 3D Printing *Mechanical Shells* in the back stage (a), robots picking up the shell from the print bed directly using the slope (b, c, d), and the unit appearing on the front stage to provide foreground interaction (e). This example shows an application

7.6 Applications

7.6.1 Interactive Urban Mobility Simulation

The interactive mobility simulation is an advanced application from the one in HERMITS. It demonstrates the use of *(Dis)Appearables* for interaction with digital data. For the stage, the two walls placed on the stage hide the Actuated TUIs from the users' view, while the urban mobility simulation is projected on the front stage. Supplemental simulation information is also projected on these walls for the users. As the users demand, the Actuated TUIs would appear from the backstage to snap to the pixelated vehicle data point, so that users can directly grab the vehicle snapped to the data point. Multiple interactions can be supported by touching a specific vehicle, such as controlling a first-person perspective that can be projected on one of the walls. This would enable the user to simultaneously view a micro and macro view of the urban mobility simulation.

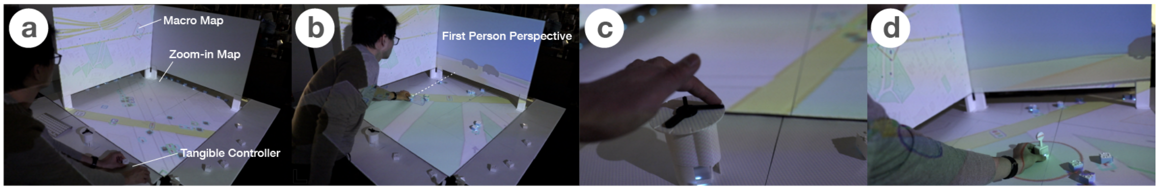


Figure 7-14: Urban Mobility Applications.

7.6.2 Remote Hockey Application

The Remote Hockey application demonstrates the teleportation and physical-digital transition effects of *(Dis)Appearables*. As shown in the Figure 7-15, the hockey pucks, which are self-propelled robots wearing shells, can transition in between one person's field to another person's field remotely. Following a hit by a person with a paddle, the puck can disappear from one person's field via a wide portal on the wall with a curtain where the real-time image of the other person is projected (Figure 7-15 a ,b). The puck, then, can teleport to the another person's side of the field that is visible from the first person through the projected real-time image (Figure 7-15 c). Even if they are physically separated, they can have such a feeling of remote space with continuity through the virtually connected hockey field and teleporting pucks, which conveys the force and speed of the opponents' hit.

Furthermore, by interchanging the shells in the back stage, other special effects to make the game more dynamic and challenging can be achieved, such as splitting a puck into multiple pucks (Figure 7-15 d, e) The paddle can also be composed with the *Mechanical Shell* with embedded robot, to dynamically shift the size of the paddle according to the game dynamics (Figure 7-15 f and 7-16).

7.6.3 Gaming

The Pac-man application demonstrates multiple effects of *(Dis)Appearables*, local teleportation and Shell transition. As shown in the Figure 7-17, just like the classic Pac-man, the characters can teleport from one end of the stage to the another to

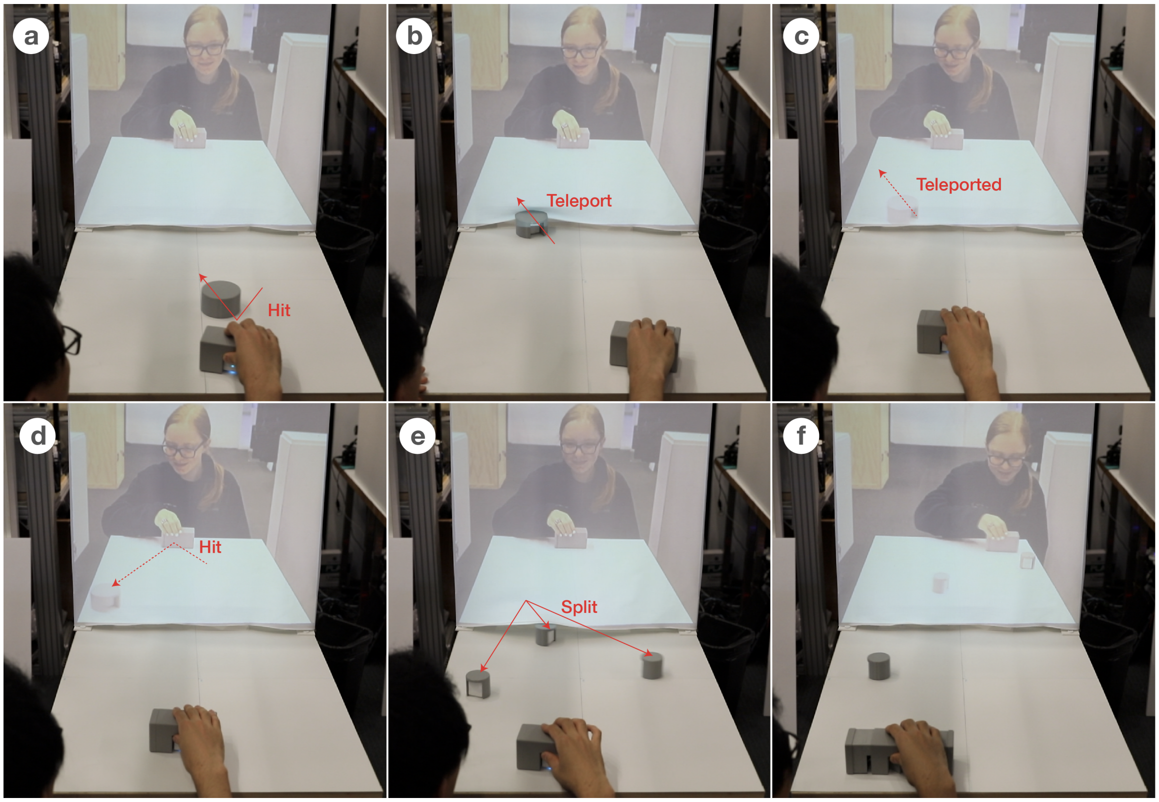


Figure 7-15: Remote Hockey Application.

represent the continuous connection of the field (Figure 7-17 a). While the Pac-man would be running away from ghost characters, the character can also transition to a larger body behind a wall, to chase and beat the ghosts (Figure 7-17 b). As for interaction, this could be a physical representation of the original gaming controlled by other interfaces, or direct tangible gaming with rich shape representations that are, for example, studied to train and support motor skills for the elderly [44].

Another gaming application is a card game. Many card games have employed the concept of 'summoning', to make monsters or characters appear on the field using their cards. While researchers have developed combining augmented reality to create such summoning expression from cards with pixelated overlays [11], the technique of *(Dis)Appearables* would enable the cards to summon physical props. As shown in Figure 7-18, as the cards are placed on the floor portal by players (a,b), the Actuated TUI with an accompanying shell can appear from the floor surface, under the card, as if the physical characters emerged from the card (c). The prototype, shown in the

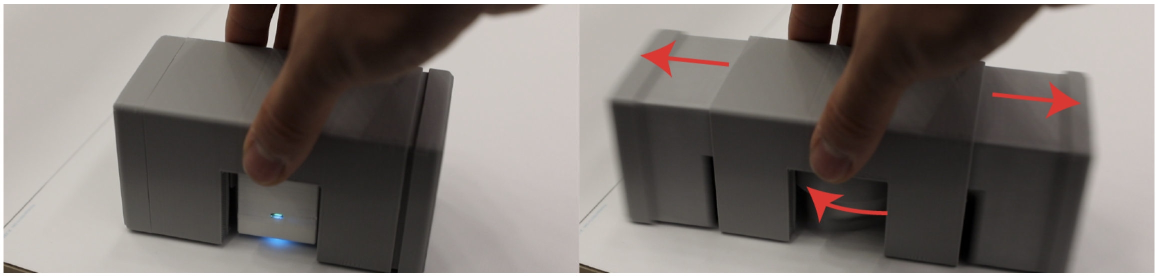


Figure 7-16: Hockey Paddle that can transform the size with embedded mechanism.

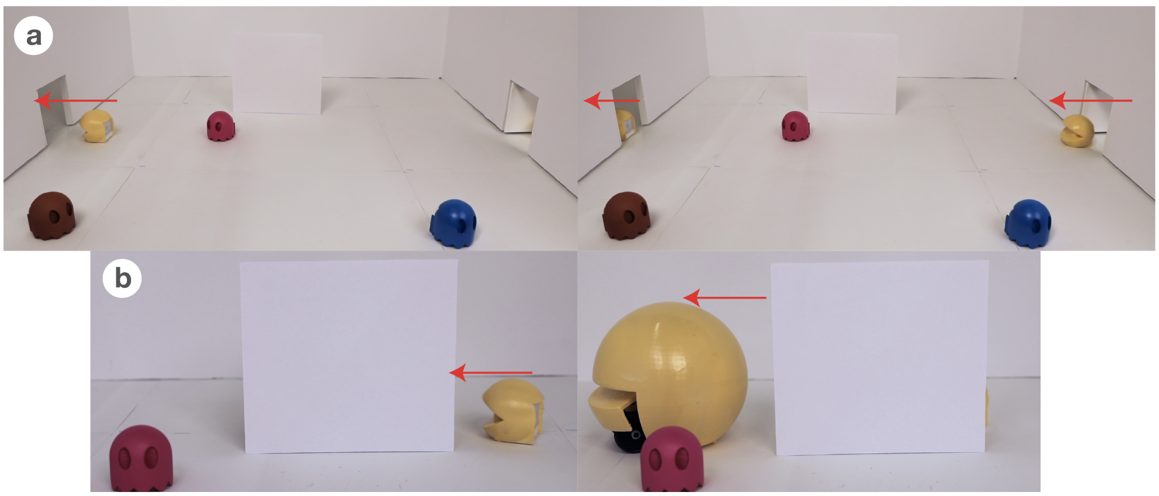


Figure 7-17: Pac-man Application. (a. Pac-man teleporting from one end to appear on the other end, b. Pac-man transitioning the size of the body with wall portal.)

Figure 7-18 d, is designed to have a secondary transformation to expand from the box shape to a dragon. While portal sizes in *(Dis)Appearables* restrict certain sizes and shapes of shells from moving between the Front and Back Stage, such expansion transformation capabilities for shells could help to bypass such limitations.

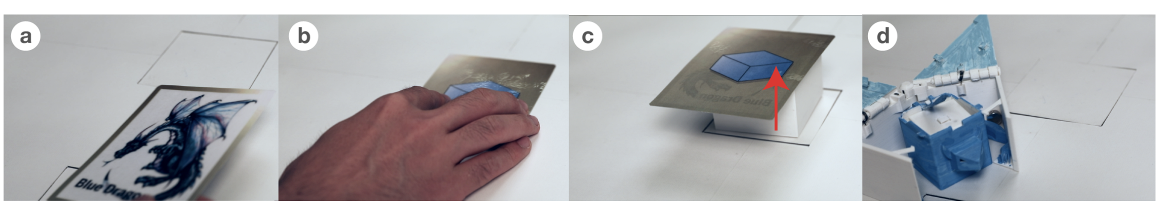


Figure 7-18: Card Game Applications – Summoning A Dragon Shell from the Card placed on the floor portal.

7.7 Discussion, Limitation and Future Work

In this section, we discuss the limitations of *(Dis)Appearables*, to share opportunities for future work on this approach.

7.7.1 Stages for other Self-Propelled UIs

Firstly, the project (Dis)Appearable with Stages using wheeled table-top devices are one of the exploration and demonstration, and the idea of stages can be applied to other interactive hardware. For example, designing stage for levitating TUIs (e.g. drones) would have much more spatial locomotion capability to achieve rather complex appearing and disappearing effects. In such way, there is an exciting opportunity to apply the method for actuated curve interfaces [96, 95], room scaled robot vacuums, or even full-sized vehicles.

7.7.2 Activating Stage with Robots

While the dynamic transition portals were actuated with servomotors in our prototype, the stage itself could be activated by the Actuated TUI robots themselves to rather drive the system with unified hardware. We have created a preliminary prototype to develop lift and door mechanisms activated by the toio-based robot hardware, but there were challenges in making the mechanism compact as well as torque limitations. These issues could be resolved with introducing novel shell design techniques with compact and torque optimized mechanism designs. Control software to operate additional docking would be needed for such a tool as well.

7.7.3 Multi-modal Stage Design Opportunity and Stage Gimmick

While we have focused on the basic stage design primarily in the front and back stage designs, there are more design opportunities inspired by theatrical stage design techniques. For example, lighting is an important component to effectively guide users' attention to specific objects/characters during a stage performance, and such techniques could be applied to Actuated TUI design with advanced light control using projectors, etc. Similarly, other theater techniques and methods including wire actions, smoke, or sound effects could be incorporated into future Stage designs.

7.7.4 User Study

To explore and validate the effects developed in *(Dis)Appearables*, evaluations through user studies would be crucial. Such studies could elucidate which portal designs are best suited for specific types of application and storytelling expressions. One of the key questions here is to validate if it is possible for users' to believe physical objects appearing and disappearing. How would users perceive and understand when physical objects appear and disappear, which would never happen in physical world? How would such effects affect the affordance design of TUIs? Addressing these questions through user studies would greatly contribute to the future design with A-TUI and Stages.

7.8 Conclusion

In summary, project *(Dis)Appearables* explored the concept of Stages with self-propelled Actuated TUIs. We have presented a design space for transition portals to enable versatile ways for the robotic interface to enter and exit from users' attention, and introduced different types of physical expressions to be created through this basic capability. We have developed an implementation pipeline for Stages that includes hardware fabrication as well as design and control software. Multiple applications were presented to demonstrate the broad reconfigurable capabilities of the system. Through *(Dis)Appearables*, we demonstrate an approach for augmenting Actuated TUI hardware with a Stage to serve as a conceptual and physical platform for a variety of robotic and actuated user interfaces. In doing this, we design a novel approach to expand the expressivity of future physical and tangible user interface designs.

Chapter 8

Discussion, Challenge and Future Work

In this thesis, I have introduced the general hardware augmentation methods of Shells and stages to expand and reconfigure the interactivity and expressibility of Actuated Tangible User Interfaces. While I have demonstrated the methods with several research project instances to explore the opportunity and technical implementation methods, there are a rich space of limitation and future research opportunities.

8.1 Shells' Design and Generative Tools

In my research projects, I have implemented the *Mechanical Shells* based on rather bottom up methods of manually designing using primitive motion transmission mechanism (as in *TRANS-DOCK*) as well as basic CAD models (as in *HERMITS*). While this method can be followed by other researcher and engineer experienced in CAD tools, building a design tool of *Mechanical Shell* that is easy to be used by non-engineer users to expand the possibility of *Mechanical Shell* designs.

One way of making the *Mechanical Shells*' design process accessible is by introducing constructive assembly kits for *Mechanical Shells* like LEGO. In such a constructive toolkit for *Mechanical Shells*, users may be able to combine multiple different mechanical modules to iteratively design different *Mechanical Shells*. For example, early exploration in the design of *TRANS-DOCK* featured LEGO-like customizable configurations in which users were able to reconfigure the tubing to manually construct shape display-like arrangements on a plane together with LEGOs (Figure 8-1 Left). Similarly, for the *HERMITS* project, some *Mechanical Shells* were a combination of primitive motion mechanisms – like the one on Figure 8-1 right which combined a gripper Shell + vertical motion Shell to construct a movable gripper Shell. In such way, designing primitive mechanical assembly modules of *Mechanical Shells* as building blocks for customizing one would be a great direction to even allow children to create their own Shell designs.

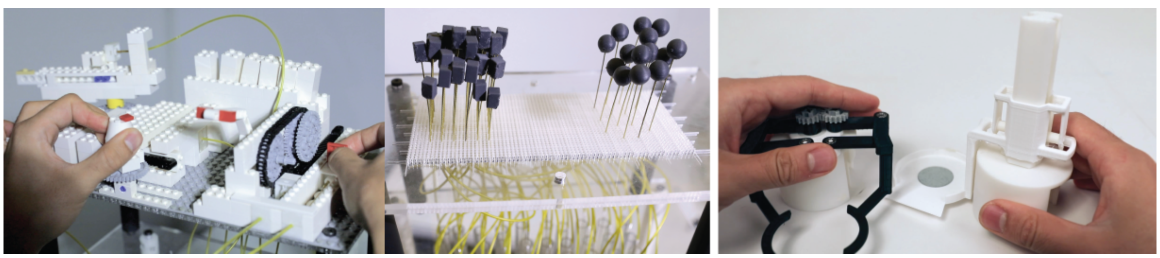


Figure 8-1: Prototypes of *Mechanical Shells* with Constructive Assembly in *TRANS-DOCK* and *HERMITS*.

Additionally, recent advancements in computational and generative design will largely contribute to the design of *Mechanical Shells*. Future Shell design tools could be integrated with a motion design tool that automatically generates a mechanism when a user gives an arbitrary path of motion, as developed in prior research of computational design of mechanical characters [20]. In such way, as discussed in the future work of *TRANS-DOCK*, such a design tool enables the *Mechanical Shells* to be designed for goal oriented models, where the software optimizes the internal mechanisms, and generates control tools accordingly (Figure 8-2). Moreover, recent research on fabricating and designing mechanical structures and properties could contribute to the design of *Mechanical Shells* with embedded interactivity [51, 48, 90].

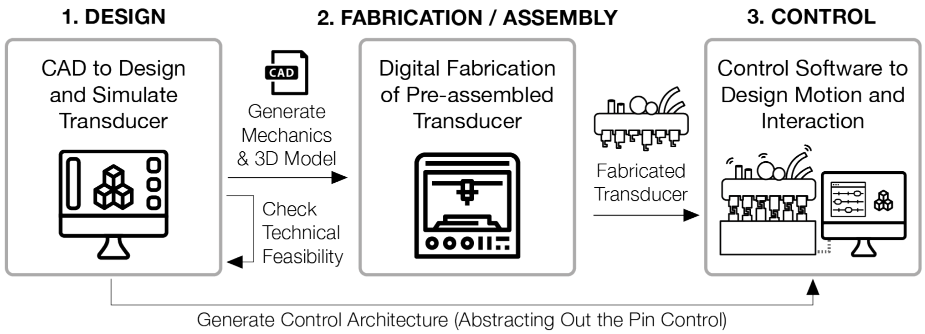


Figure 8-2: Future Design, Fabrication and Control Pipeline presented in *TRANS-DOCK* paper.

8.2 Expanding Mechanical Shells' Capability

There are a variety of opportunities to expand *Mechanical Shells*' capability with different mechanical design techniques, beyond what we have presented in *TRANS-DOCK* and *HERMITS*. For example, by utilizing spring mechanisms, the actuated TUIs can store kinetic energy in the *Mechanical Shells* (similar to spring-loaded toys or clocks), which could, for example, create constant movements even as Actuated TUIs are undocked, or to create sudden radical movements that result in response to touch. Combining such ideas with the capability of *Mechanical Shell* 3D printing, we could utilize prior research in 3D printing mechanical structures for versatile design of *Mechanical Shell* to be 3D printed on-demand [48].

While I have primarily explored the conversion and expansion of mechanical properties of motion and shapes in our *Mechanical Shell* demonstration, future design of *Mechanical Shells* could inherit other properties to be extended and converted, similar to the way we have done with optical fibers to transmit optical properties of Actuated TUIs in *HERMITS*. For example, by utilizing conductive materials and traces, electrical properties could be extended, similar to how many types of electronic parts and modules work (e.g. shields for Arduino). In such way, a variety of interactive parts such as motors, LEDs and sensors could be embedded in the *Mechanical Shells* themselves to offload the size and complexity of robotic Actuated TUI hardware, but to maximize possible I/O through *Mechanical Shell* designs.

One could also envision the concept of 'cognitive shells', where units could electrically dock with one another to add more computational capability, or even 'energy shells' where they could dock with a larger or more freshly charged battery to enable heftier tasks, then abandoning it later to revert to a smaller and lighter state.

8.3 Motion Control and Real-time Interaction

On the stage, there are a wide space of opportunity for controlling and directing the Actuated TUIs motion, with Shells. In project *HERMITS*, I have introduced the prototypes demonstrated with manually controlled Actuated TUIs using joystick controller, while, in the project *(Dis)Appearables*, I have introduced multi-agent path planning tool on the stage for pre-processed automated control. Using this as a basis, I believe there are two major opportunities / approaches to improve motion controls; an intuitive way to tangibly and gesturally design and orchestrate the motion, and real-time interaction with in-situ control.

Firstly, the methods to direct and orchestrate the motion from designer perspective can be improved. While the current path planning tool is operated on GUI tool by setting origin and destination coordinates of the robots, there could be a way for a designer, like a director of a stage play, to design and iterate motion. For example, incorporating tangibility can be a more intuitive way to design motion, as explored in Curlybot [35] or Topobo [115]. Physically grasping the robots on the stage, and moving them across the stage could be a way to direct the robots to make the path. With that, the automated path planning tool could intervene to help define the detailed path to avoid collisions between multiple robots. As the control of multiple robots can be a difficult task for users with their two hands, prior studies in gestural and spatial interaction with Swarm User Interfaces [67] could be applied as well. Additionally, as the gaming application in the *(Dis)Appearables* demonstrated to summon specific Shells using cards, such way of using other physical objects to instruct the robots motion can be another option, which is a method addressed in prior research of Human Robot Interaction [179].

Secondly, rather than designing a pre-processed motion, we would also like to address the control problem of how to introduce in-situ control for enabling real-time interaction for users. How would the robotic system understand user intentions and generate a path to bring appropriate/needed Shells on-demand? How would the system regenerate the path when users interrupt their motion on the stage? In relation to 3D printing Shell, how would the system optimize Shell's design data to generate according to users interaction in the front stage? By addressing these questions with advanced control tool, it should be possible to design a system that is fully responsive, adaptive and interactive. This not only require motion control system, but also sensing and optimizing system to understand user intention.

8.4 Optimizing System Configuration, and System Identification

While the augmentation methods of Shells and Stages introduced in my thesis largely expand the interactivity and reconfigurability of an interface system, they add significant complexity to the system. Unlike modular software architecture, the physical modules of Shells and stage take a lot of resources, both in physical space and cost; this may require an system optimization tool for helping designers and researchers handle such complexity. Such a tool could allow designers of the interactive system to plan the entire hardware configuration based on their required and desired interactivity as well as their resource constraints (Figure 8-3).

Also, in control theory and dynamic systems, System Identification is a standard practice - e.g. when a spacecraft docks with another module or a crane picks up a heavy load, the mass properties of the system under control can change considerably. System Identification techniques allow the values of the changed properties to be refined or determined based on how the new system behaves to stimuli, and the control gains and parameters correspondingly updated to maintain stability and maximize performance [150]. Based on such prior technique and practice, future control system of A-TUIs could reconfigure their Shells to adapt to the tasks and functionality the system has to achieve. To develop such a control system, allowing the system to identify the physical properties of the tasks and A-TUIs' capabilities (e.g. torque, speed, weight), so that the Shells could fill-in the gap in-between the resource (A-TUIs' capabilities) and goal (tasks) via mechanical conversion.

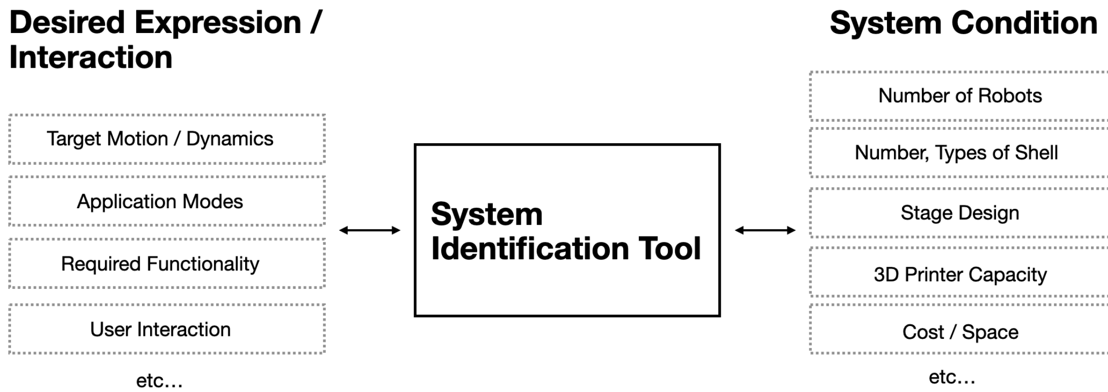


Figure 8-3: Potential system optimization tool for help decide the hardware configuration of Actuated TUIs with Shells and Stages.

8.5 User Evaluation and Study for Shells and Stages

While the COVID-19 situation made it difficult to conduct user studies with the implemented systems in this thesis, there are a variety of evaluation opportunities to be conducted to assess the effects and value of Shells and Stages.

Example questions to be addressed in such evaluation could be; how would users recognize the technological system that is operated by a single device in the background, while seeing a variety of Shells appearing/disappearing in the foreground? How well could users believe the illusional effect of Actuated TUIs appearing / disappearing / teleporting / transitioning? What motion properties (e.g. speed, light, sound etc) would affect how believable these effects were perceived?

Furthermore, the manner in which users may build interactive and actuated system on the implemented platform in this thesis is another opportunity. There could be a brainstorming workshop and case study to access what users may come up with using our system to validate the versatility of the system. Such application areas may benefit from not only conducting the study with the general public, but also with specialized users including medical physicians, museum facilitators, stage directors etc. To conduct such case studies or workshops, the design tool discussed above would be a great platform for them to iteratively design *Mechanical Shells* or Stages.

8.6 Ultimate A-TUI design for Shells and Stages

The concepts of Shells and Stages introduced in this thesis are widely applicable for different types of Actuated and Robotic TUI hardware. This contribution generates a new question – what would be the ultimate A-TUI design with the hardware augmentation capability of Shells and Stages?

One way of addressing this question is to have numerous degrees of freedom for motion I/O capability in a dense hardware package of Actuated TUI. In such way, complex I/O could be achieved to maximize the capability of Shells with embedded mechanisms. Figure 8-4 shows an example of such ideal Actuated TUI devices, based on the design of *HERMITS*, which shows small motors are packed into a small footprint to embed 25 degrees of freedom of motion as output in a single device.

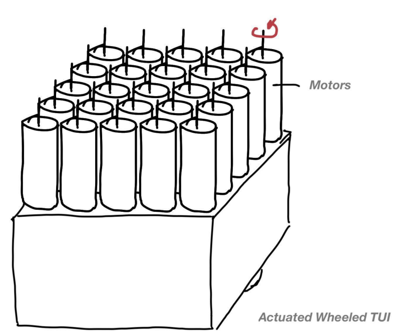


Figure 8-4: An example of ideal Actuated TUI suits for extendability with *Mechanical Shells* with multi-DoF.

8.7 Broader Applicability of Shells and Stages

Lastly, I introduce a broad set of opportunities I have enabled by introducing the hardware augmentation methods of Shells and Stages. Figure 8-5 introduces potential of future development of Shells and Stages in illustrations based on existing general A-TUI hardware and other robotic devices. For example, based on one of my prior works in Actuated Curve Interfaces [96, 93], the actuated line could be woven into different types of *Mechanical Shells* to be activated using the multi-DoF of the device. With Stage, the device could be made more expressive, by appearing through a tiny portal that best utilizes the form factor of line, similar to how snake robots locomote through holes [83].

For levitating A-TUIs or drones[14, 41], the interface machines could freely fly in the 3D space to dock to *Mechanical Shells* in a room or space, for levitating spatial applications. By taking advantage of a quadcopter's motors, a single device could fully utilize the four degree of freedom of the propellers for *Mechanical Shells*. As for stage, the drone device could reside into a nest-like back stage (inspired by bee hives), then appear to the physical space on demand for user interaction.

Other than Actuated TUI research, the idea of Shells and Stages can be applied to augment general robotic systems and architecture. For warehouse robots or vacuum cleaning robots, the idea of Shells may be able to provide new functionality to general robots to adaptively handle different tasks in the warehouse or our living spaces. The idea of Stage with on-demand 3D Printable Shells created backstage would further contribute to such adaptation capability of those robots. By scaling up the perspective, future vehicles could be extended with the approach in my thesis. With Shells, this can allow the vehicle to be re-purposed to approach different tasks. This could be very practical when the idea of shared mobility is introduced in cities, when the self-driving vehicle, which may be used in the morning for commute, is available and free during the day. In such way, the entire city or parking space could be considered a Stage to bring new opportunities and roles for shared mobility, to be stored and reconfigured backstage.

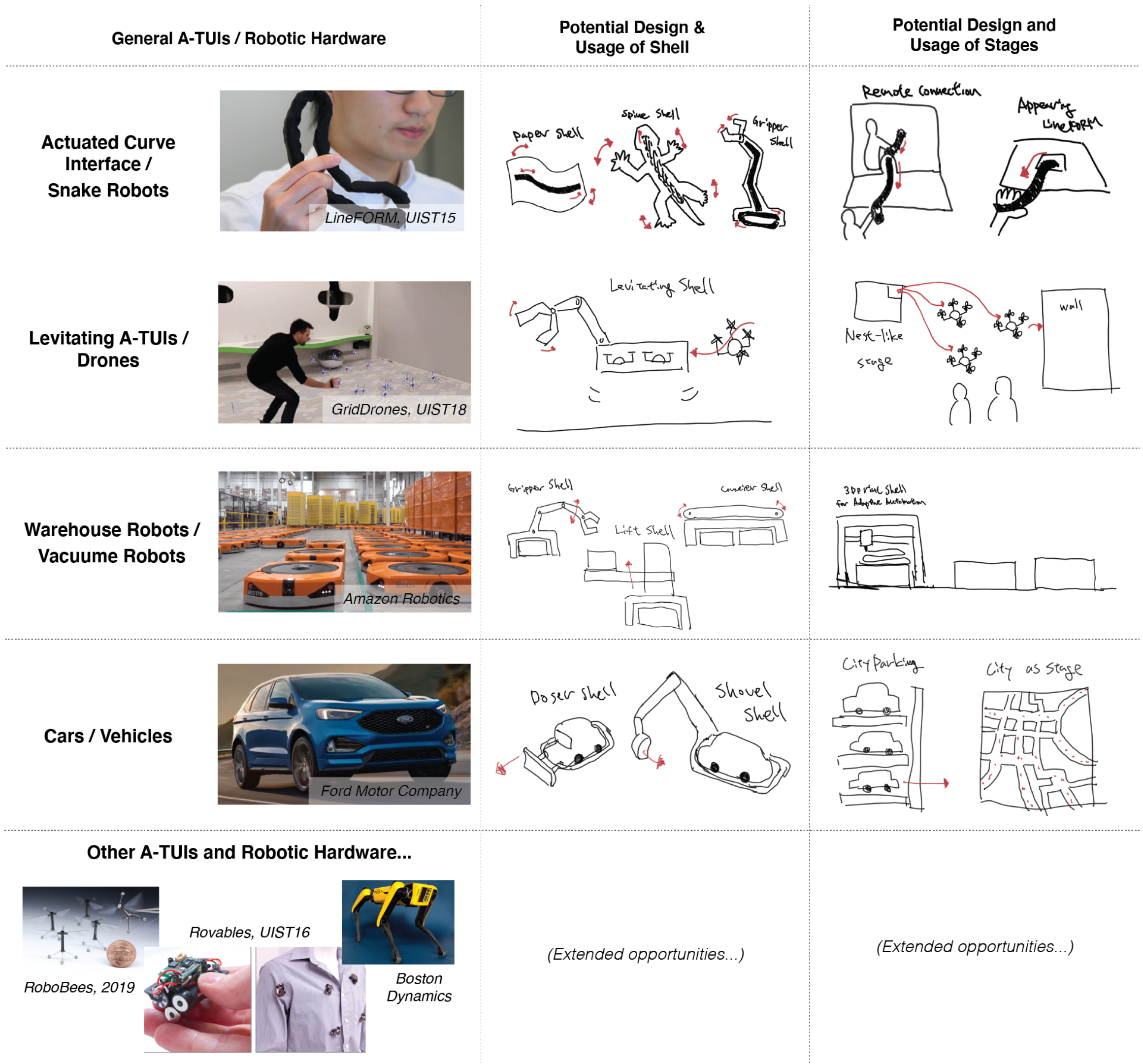


Figure 8-5: Broadset of Applicability and Potential of Shells and Stages not only for Existing Actuated TUIs, but also for Other Robotic Hardware.

While the ideas presented here do have many technical and social challenges, they indicate how the idea of Shells and Stages could open up a massive amount of applications and opportunity in the research of HCI and beyond to bring dynamic actuation into our physical environment and everyday life with greater reconfigurability. These ideas can be further extended for a variety of actuated and robotic devices which are emerging more and more in both academia and commercial products [170, 22, 24]. The perspective introduced in my thesis allows researchers, designers, and engineers, to bring our physical environment coupled with digital information in the next level, by combining of active machines, passive machines and the surrounding environment.

Chapter 9

Conclusion

In my thesis, I have investigated and developed novel approaches – Shells and Stages – to dynamically reconfigure the interaction capability of A-TUIs. Shells are interchangeable mechanical add-ons to expand on and reconfigure the interactivity of Actuated TUIs with embedded mechanisms. Stages act as platforms for Actuated TUIs to locomote on top of their surrounding environment.

To demonstrate these approaches, I have developed research projects based on existing A-TUI hardware. *TRANS-DOCK* demonstrated the Shell method by augmenting and expanding on the capability of pin-based shape displays. *HERMITS* also displayed how to use this approach for self-propelled swarm TUIs to expand on and reconfigure their interactivity via an automated docking capability. Project *(Dis)Appearables* utilized the same hardware as *HERMITS* with the addition of the Stage method that allows the Actuated TUI to appear and disappear from users' perspective. Through these research projects, I have demonstrated the expanded interactivity with the proposed methods using a variety of applications for tangible interaction, including dynamic digital data, dynamic physical affordance, tangible remote communication, storytelling and gaming. By reconfiguring and maximizing the interactivity of A-TUI hardware, my approach enables interactive hardware to flexibly adapt their building blocks across applications using fully expressive and functional mechanical movements.

By introducing these methods and generalizable framework, I have laid the foundation for a variety of research instances that advance inter-device / inter-material interaction to create a future where our physical environment is coupled with dynamic digital information. As more robotic and actuated devices are deployed in our homes and cities, I believe this thesis acts as a first step to many other exciting research avenues to create a more dynamic, interactive and reconfigurable everyday environment.

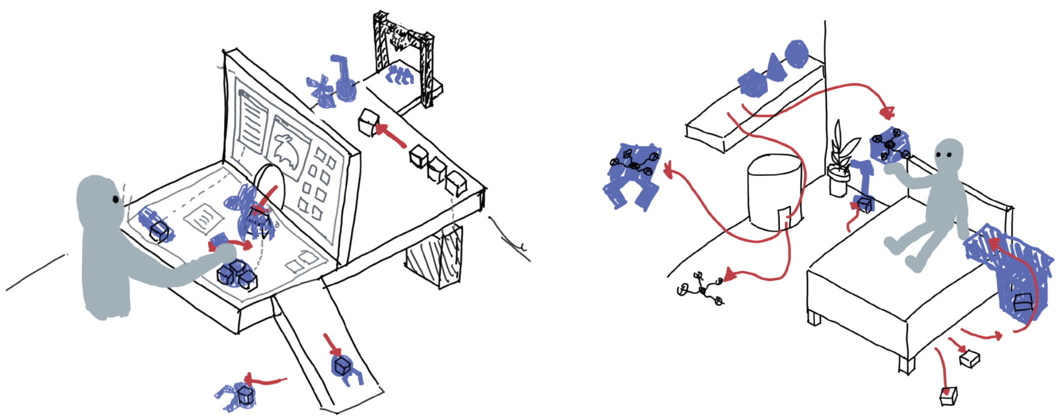


Figure 9-1: Potential Future Physical Environment (A Desktop and A Room as examples) with Actuated TUIs, Shells and Stages.

While this thesis began from the image of a seashore's ecosystem, where a variety of species co-exist and interplay in their environment, my thesis envisions the future of inter-device and inter-material interaction ecosystem in our physical environment with Actuated Tangible UIs. Unlike modern computer interfaces that rely on flat screens, our physical world is filled with rich shapes, materiality and objects that invite us to tangibly and physically interact. As more computational and actuation technology and devices are being integrated into such physical space, my thesis introduces a grand vision of how our future physical environment may be enhanced using general robotic hardware that can be reconfigured with passive modular mechanisms (shell) in their surrounding environment (stage) (Figure 9-1). This idea can be applicable across scale -– from a tabletop, a room, a building, or even to a city — to configure the interactivity of active and dynamic machines for user interaction so that the capability and resource of these powerful computational devices are maximized. This approach acts as a key step to materialize a future physical world composed of adaptable, flexible and reconfigurable hardware that interacts seamlessly with its environment. This dynamic interplay between machine-material-environment signals the next stage in HCI research, particularly how user interactions with computers will be endlessly dynamic and adaptive for tangible expression and embodied experiences.

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