Mechanical Shells: Physical Add-ons for Extending and Reconfiguring the Interactivities of Actuated TUIs

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ABSTRACT
In this paper, I introduce a concept of mechanical shells, which are physical add-ons that can adaptively augment, extend, and reconfigure the interactivities of self-actuated tangible user interfaces (TUIs). While a variety of research explores actuated and shape-changing interfaces for providing dynamic physical affordance and tangible displays, the concept of mechanical shell intends to overcome the constraint of existing generic actuated TUI hardware thereby enabling greater versatility and expression. This paper overviews the mechanical shell concept, describes project examples, outlines a research framework, and suggests open space for future research.

Author Keywords
Shape Changing Interface; Actuated Tangible User Interface; Mechanical Shell.

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

INTRODUCTION
Research in actuated and shape changing tangible interfaces have been widely explored in the field of HCI to demonstrate and validate the role of dynamic physical actuation capabilities for interaction design [33, 3, 29, 32, 1]. Through such work, a number of 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 [12], Programmable Matter [8, 43]).

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 [15, 6], actuated curves [23, 22], or swarm user interfaces [14]. While a variety of incremental efforts have been made to improve their display and interaction quality, they each have their own limitations on the fidelity with regards to the shapes and motions. This contradicts with the goal to be generic platforms for high versatility. How can we overcome the limitation of this single hardware capability to be expanded?

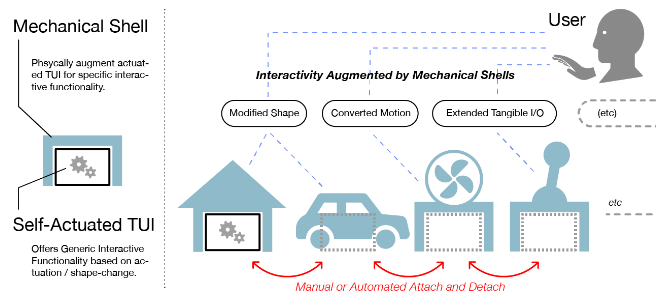

Figure 1. Basic concept of mechanical shells.

In my research, I propose a concept of mechanical shells that are interchangeable physical add-ons designed for extending the interactivity of generic hardware of actuated TUIs. While researchers have previously explored such architecture of augmenting actuated TUIs with passive modules for richer affordances and shape rendering capabilities [35, 39, 5, 13], the mechanical shell I propose in this paper fully takes advantage of transformation / actuation capability by converting and transmitting with embedded mechanisms through docking / motion transmission protocols. My research also intends to provide a landscape view and methodology that is applicable to broad types of actuated TUIs. While, 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), the mechanical shell intends to explore how mechanical physical attachments can empower the interactivity of general purpose actuated TUIs through a broad perspective.

In this paper, I define the concept of mechanical shells as well as architectural inspiration, then introduce the exploration of multiple project instances, TRANS-DOCK [25] and HERMITS [24]. I also introduce the preliminary research framework which seeks to define the methodology based on the idea of mechanical shell. Extended research opportunities are introduced to weave multiple research streams in HCI/UIST community together to indicate an open research space.

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MECHANICAL SHELL FOR ACTUATED TUIS

Concept and Definition

I define mechanical shell[1] as *"an external passive attachment to an existing actuated tangible interface that can be manually or automatically attached and detached."*

The diagram on Figure 1 graphically describes this concept. The shell is an attachment that can modify, convert, or extend the interactive functionalities of actuated tangible interfaces. For example, mechanical shells can modify the interactive property of 'shape', convert the 'motion' with transmission mechanism, or extend other I/O capabilities by taking advantage of installed sensors and actuators in the device of actuated TUIs. The mechanical shells can be designed with combinations of these tangible augmentation capabilities.

As for the role of mechanical shells, they can serve multiple purposes. By reconfiguring its shape and converted mechanical I/O motion, the mechanical shells can enhance the dynamic physical affordance 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 motion would enhance its communication capability to users which can be a great tool for storytelling. Furthermore, the motion conversion capability allows the actuated TUI to gain robotic functionality to affect the physical environment as manipulators and locomotors.

Architectural Inspiration and Terminology

The terminology of mechanical 'shell' stems from the architectural inspiration of 'shell', which is a term for one of the most fundamental concepts of a UI coined in 1960s by Louis Pouzin [19]. 'Shell' was originally developed for users to communicate with OS (Operating System) of computers for commanding instruction and receiving results through pre-defined commands for specific and intuitive interactions. 'Shell' was one of the first concepts of 'interface' which was designed for interfacing between generic computation system and operating users [19].

Heavily 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,the *mechanical shell* similarly fills in the gap between actuated tangible interfaces (capable of generic but limited interactivity) and users' diverse and specialized needs / requirements (Figure 2). Unlike the original shell (including CLI or GUI shell), mechanical shell's role is not served as an interface to OS, but acts as literally/tangibly 'shell' to interface with generic actuated 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."* – A quote from Ken Thompson, the first Unix Shell developer [36].

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 being replaced to provide versatile and adaptive interactive experiences depending on users' preferences and requirements. I'm much inspired 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 actuated TUIs (as in hardware and interactivity constrain).

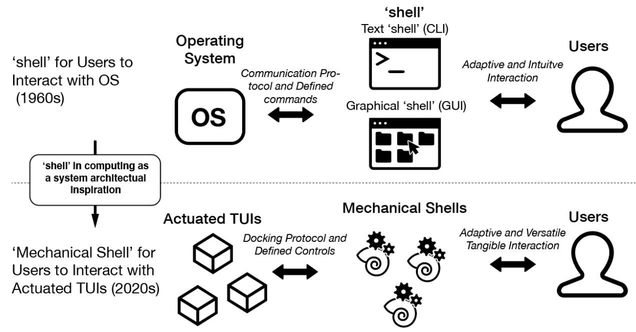

Figure 2. Shell as an architectural inspiration for mechanical shells.

INSTANCE PROJECTS

I have previously investigated in developing novel interactions with shape changing UIs including introducing a novel form factor [23, 20, 22] and representing material properties beyond shapes [27, 21]. In this paper, I focus on how the actuated TUIs' interactivity can be augmented using passive material / mechanisms, which I preliminary explored in [26, 44].

TRANS-DOCK (for Pin-Based Shape Displays)

Project *TRANS-DOCK* [25] is a docking system for pin-based shape displays that enhances their interaction capabilities for both the output and input (Figure 3). While a variety of pin-based shape display hardware has been proposed and developed for a range of applications and interaction modalities individually [15, 6, 37], each shape display hardware was constrained to provide limited types and variations of applications / interaction modes.

TRANS-DOCK intended to overcome this limitation to expand the interactivity of a single shape display hardware to dynamically reconfigure the functionality that adapts to users' needs and preferences using mechanical shell modules (called 'mechanical transducers' in [25]). By simply interchanging the mechanical shell add-ons, composed of passive mechanisms, to be docked on a shape display, users can manually 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. The project introduced a design space consisting of several mechanical elements, as a primitive to develop a variety of mechanical shells with rich interaction capabilities. I have developed a proof-of-concept prototype based on a 10 x 5 pin display with modification of docking mechanism for each pin to make a connection to the mechanical shell. This design allowed the

[1] While I have defined the concept of mechanical shell in [24] specifically for self-propelled TUIs, I intend to explore the broader definition in this paper and my dissertation.

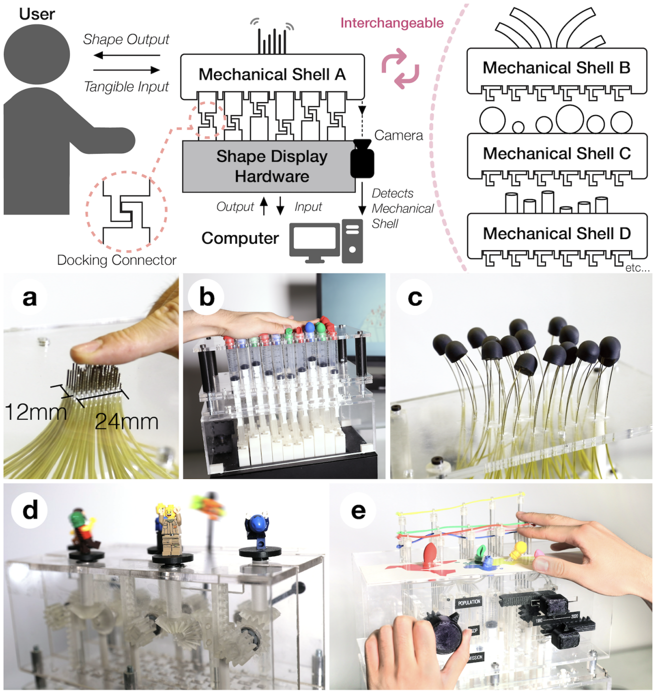

Figure 3. TRANS-DOCK and example applications (a. high resolution shape display, b. inflatable shape display, c. bending pin display, d. animated characters, e. interactive data physical embodiment)

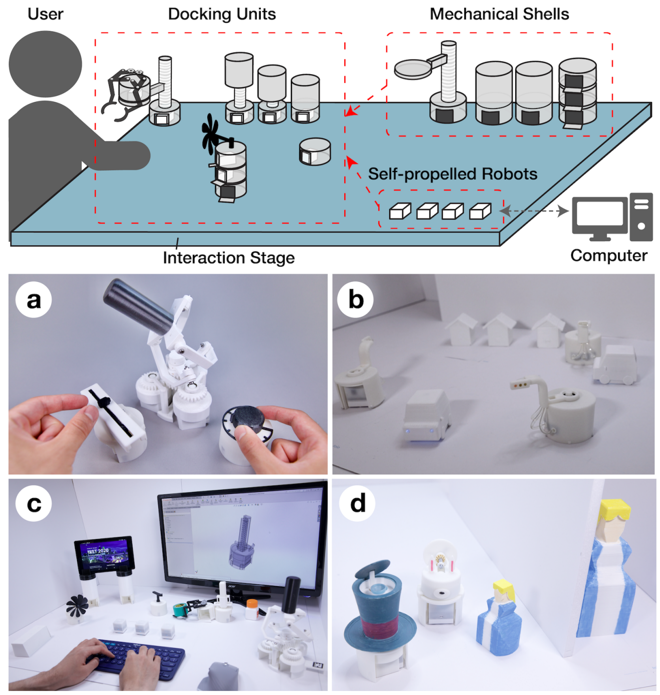

Figure 4. HERMITS and example applications (a. mechanical shells for haptic controllers, b. urban mobility simulation, c. adaptive desktop, d. tangible animated storytelling.)

mechanical shells to fully utilize the vertically moving pins to be extended and converted for rich interactivity.

TRANS-DOCK features the concept of the mechanical shell with manually docking and multiple actuated pins to activate multiple DoF architected mechanical shells. The demonstrated applications include reconfigurable shape display rendering capabilities, animated characters, and data representation with tangible controllers. With the range of applications, the project validated how a single hardware platform can achieve a broad set of interaction modalities with relatively simple docking mechanisms (Figure 3a-e).

HERMITS (for Self-Propelled TUIs)

Project HERMITS[24] is an interactive modular system for self-propelled TUIs extended with mechanical shells (Figure 4). While a variety of self-propelled TUIs has been developed in the HCI field for exploring the locomotion functionalities in TUI for interaction design [7, 38, 30, 14], this research introduces a method to extend their locomotive functionality to be converted for enriched interactivity using a range of mechanical shells with embedded mechanisms.

The design space of HERMITS defines multiple primitive designs of mechanical shells to extend and reconfigure the interactivity of self-propelled robots, including shape, motion, light, etc. The introduced mechanical shell designs can be docked by single robots but also multiple robots following the concept of Swarm UI for collective reconfiguration and actuation [14, 40]. I have developed the proof-of-concept prototype based on a technical platform using off-the-shelf robotic toys to demonstrate the reconfigurable interactivity.

HERMITS features the concept of the mechanical shell with the automated docking functionality by leveraging the locomotion capabilities of the self-propelled devices. It also features the discretely controllable units for collectively activating mechanical shells. Applications of HERMITS demonstrate its reconfigurability for digital and physical space applications including extended robotic functionality, tangible mobility simulation, reconfigurable adaptive desktop, and interactive story-telling (Figure 4a-d).

DISCUSSION AND RESEARCH SPACE

The approach presented in this paper has a range of limitations as well as opportunities. Major limitations include the complexities of the overall system caused by multiple modules, as well as the reconfiguration time of switching mechanical shells to quickly adapt to users' requirements. In this section, I discuss the wide research space and opportunities that stem from the idea of mechanical shells.

Research Framework

Figure 5 shows the preliminary research framework which defines the research space of the overall interaction architecture with the mechanical shell. This framework can be a strategic guideline for researchers and designers to develop their own mechanical shell system. Overall, the left gray box represents an interactive hardware of actuated 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 actuated TUIs to be extended to achieve specific interaction purposes.

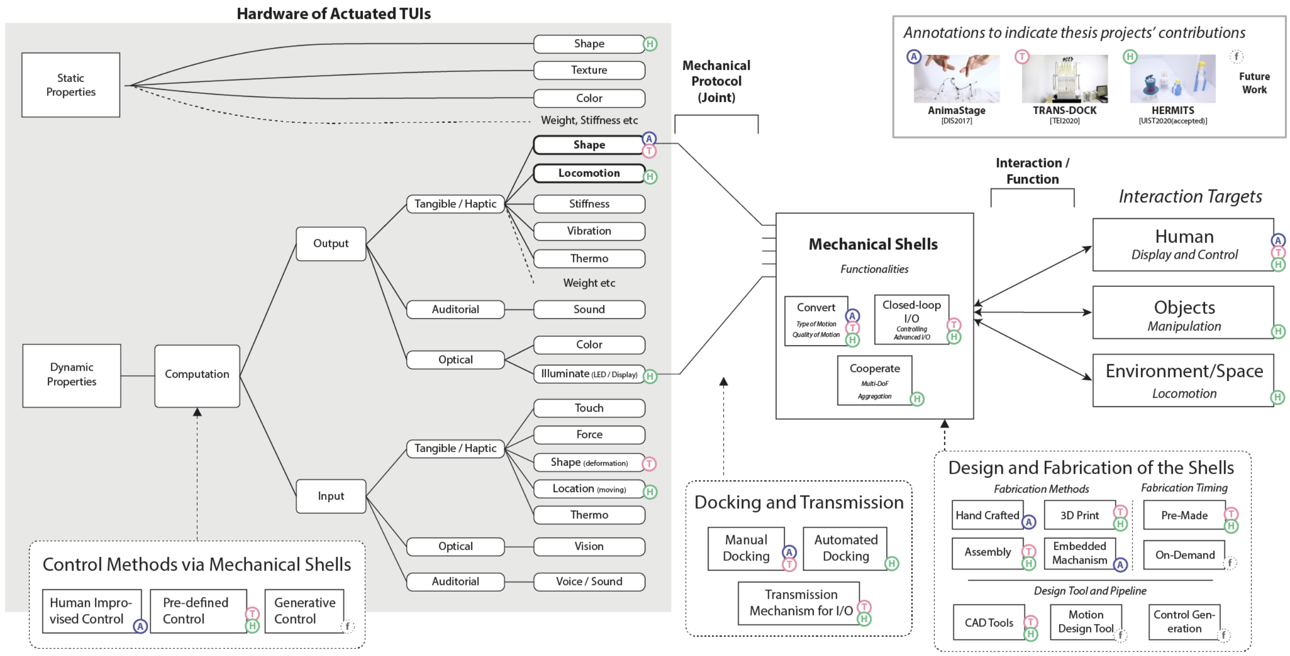

Figure 5. A framework that highlights the research opportunities of mechanical shell.

This framework is also composed of multiple design elements for developing the interactive architecture, including mechanical shell's functionalities, design and fabrication methods, interaction targets, as well as control methods. In my previous projects [26, 25, 24], I have partially investigated different aspects of this framework, while there are other opportunities which I wish to explore in my next projects.

Vision and Extended Research Opportunities

Figure 6 illustrates a visionary interaction setup that digital and physical interactions being empowered based on the concept of mechanical shells (extension of HERMITS' configuration). As shown here, I foresee the concept of the mechanical shell to generate a variety of research opportunities and values in the streams of technical and design research in the HCI community. For example, instant and rapid fabrication research [39, 45] can contribute to generating mechanical shells on-demand rather than being constrained only with pre-made shells. Fabrication techniques of embedded mechanism [10, 13, 4] should benefit this process as well. User-experience oriented research opportunities exist as well, for example, to consider novel affordance and perception design [31, 6, 17, 28] with mechanical shells possibly combined with graphical overlaid information [16, 37], with extended closed-loop haptic feedback [21, 18], or with front/backstage designs for (dis)appearing effects [34, 6]. Each system component can also be explored including actuated TUI devices to be replaced with other types of robotic hardware with unique actuation capabilities [9, 2, 23, 37]. In such a way, I intend to open up and define the research opportunities for the community to tackle and discuss together based on the novel research paradigm of mechanical shell.

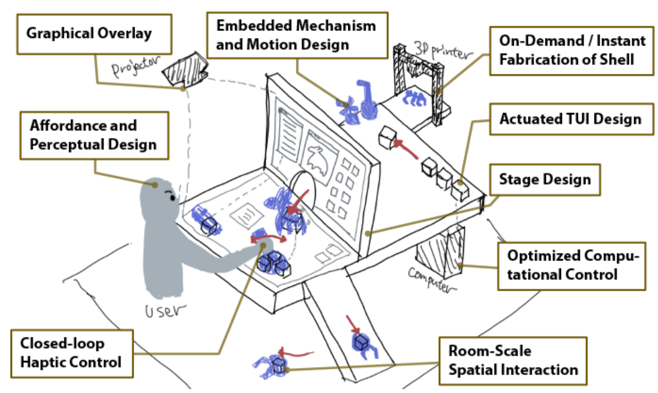

Figure 6. A future interaction setup with research opportunities.

CONCLUSION

In this paper, I introduced the concept of the mechanical shell that is a passive physical attachment for augmenting general-purpose actuated TUIs. With this novel architectural concept, I intend to explore the hybrid architectural approach that combines self-actuated devices (e.g. Shape Displays [6, 15], Swarm UIs [14]) and passively actuated mechanism / materials (e.g. meta-materials [10, 11], 3d printed mechanism [4, 13], programmable materials [42, 41, 46]). While these two realms have been explored separately in UIST/HCI community, I intend to open up a new paradigm to combine these two research realms for a greater reconfigurable and adaptable interaction in TUI, haptic interface, and human robot interaction research.

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