TRANS-DOCK: Expanding the Interactivity of Pin-based Shape Displays by Docking Mechanical Transducers

Anonymous Author1
anonyous
anonyous, anonyous
anonyous@affiliation.org

Anonymous Author2
anonyous
anonyous, anonyous
anonyous@affiliation.org

Anonymous Author3
anonyous
anonyous, anonyous
anonyous@affiliation.org

ABSTRACT

This paper 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 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. Use cases to take advantage of the interchangeability of our approach is discussed. Through this paper 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.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Shape Changing Interfaces, Pin-based Shape Display, Mechanical Transducers

ACM Reference Format:

Anonymous Author1, Anonymous Author2, and Anonymous Author3. 2018. TRANS-DOCK: Expanding the Interactivity of Pin-based Shape Displays by Docking Mechanical Transducers. In *Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY*. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/1122445.1122456

Woodstock '18, June 03–05, 2018, Woodstock, NY

ACM ISBN 978-1-4503-9999-9/18/06…$15.00
https://doi.org/10.1145/1122445.1122456

Figure 1: a. TRANS-DOCK proposes a method to expand what a single shape display can do with passive mechanical transducers, b. Transducers that convert the resolution of shape display for rendering 3D model of a virtual sculpture, c. A transducer for dynamic data physicalization.

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 [6, 13, 45]. While various kinds of actuation techniques and form factors have been introduced to explore their capabilities and applications [24, 35, 59], pin-based shape displays have become one of the most popular approaches [27]. 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[26], material simulation[37], data physicalization[53], animated craft[36], VR[8, 49], AR[28], artistic expression[14], and adaptive furniture[56]. Simultaneously, a range of technical implementations have also been developed, including resolution improvement [61], scaling to room size [18], adding a movable-base [8, 49], detecting or representing variable force [34], and developing a mobile system [3, 16]. 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 passive mechanical transducers that can be docked on a shape display (Figure 1a). Transducers are mechanical systems that interface a users' bodily input and shape output. 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 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 paper includes;

- A general method to expand display and interaction capabilities of pin-based shape displays by docking passive mechanical transducers.
- Design space for the transducers 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 example use cases to motivate the proposed method.

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 [2, 58]. 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 [20, 46, 60]. As for mechanical systems, there are industrial robotic arms with a reconfigurable end effector system that adapts to a range of object handling tasks [47]. PrintMotion proposes a unique approach of converting the motion of 3D Printer with mechanical parts fabricated with the printer itself [19]. 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 [15], aimed to provide haptic sensation to computer graphics by projecting video onto an actuated surface. Based on their vision of *Radical Atoms*[13], 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 [9, 26]. The idea of utilizing shape displays to manipulate the surface of physical objects was further explored using assembled passive blocks[48], animated crafts [36] and dynamic furniture applications [56]. Among them, Schoessler'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 [48]. In comparison, our approach further explores this method by using 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 [33, 44]. *ShapeClip* was proposed for designers, particularly for pin-based shape display systems, to design their own shape displays using custom resolutions, pin-alignments, and number of pins [11]. TRANS-DOCK takes a different approach in that it adds passive transducers to the existing hardware of shape displays with fixed configurations.

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 (see Figure 3).

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 [25]. 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 [3, 61] while others prioritized a large area (larger pin size and spacing) for bodily / room scaled interaction and furniture applications [18, 30, 56].

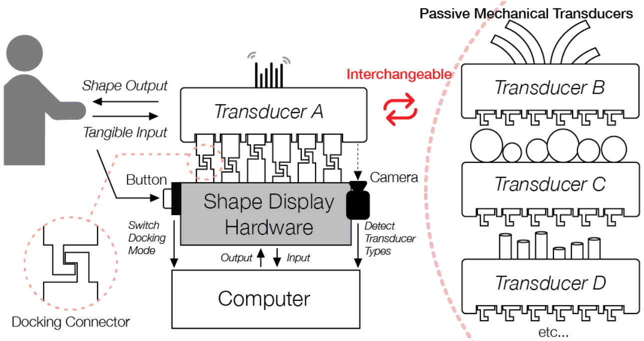

Figure 2: Overview of TRANS-DOCK configuration composed with interchangeable transducers, shape display, computer, camera and button.

While Leithinger's review was sufficient for standard shape display conditions, there are other types of unique shape display parameters have been explored. Other than basic primitive motions, non-linear motions such as inflation [41] and bending [39, 40] 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 [5, 18]. Non-constrained planes with 2D and 3D movable pin displays were proposed for spatial and mobile interaction [3, 49]. 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 [15, 29]. Variable force control was added to expand the haptic interaction with shape displays [34].

3 TRANS-DOCK

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, and customizability. Figure 2 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.

3.2 Transducers Design Space

Figure 3 presents the design space for TRANS-DOCK transducers. This design space is developed based on a reference to previous shape display hardware and review research (discussed in related work) and intended 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 Configurations* presents the comprehensive list of properties including pin properties, and pin, plane and motion configurations.

3.2.1 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 [55]. 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.

3.2.2 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 [43, 52, 59], which we do not explore in-depth in this paper. For each motion primitives, there are parameters that can be converted;

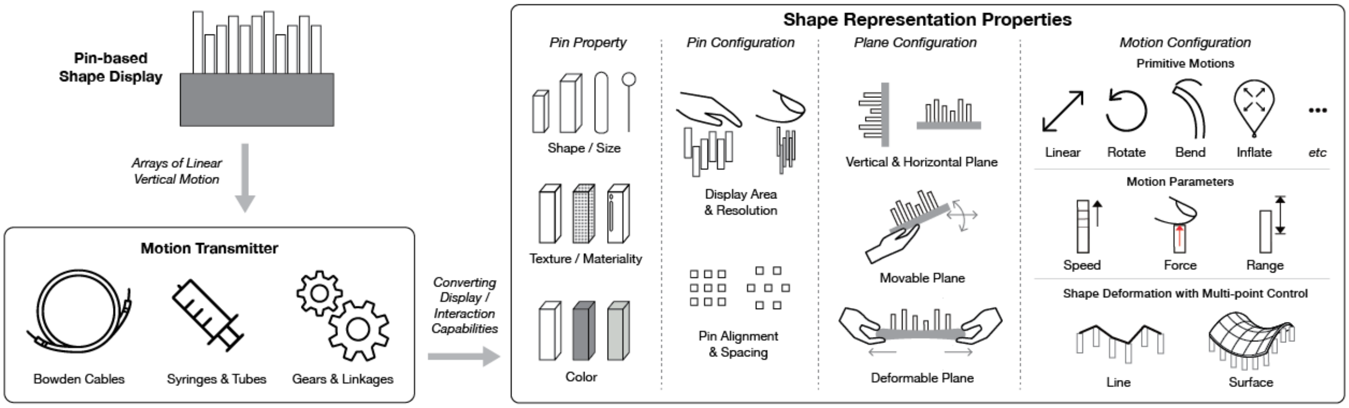

Figure 3: Design Space of Transducers; Linear Motion of Pin-based Shape Display being converted through Several Types of Motion Transmitters to Variety of configurations.

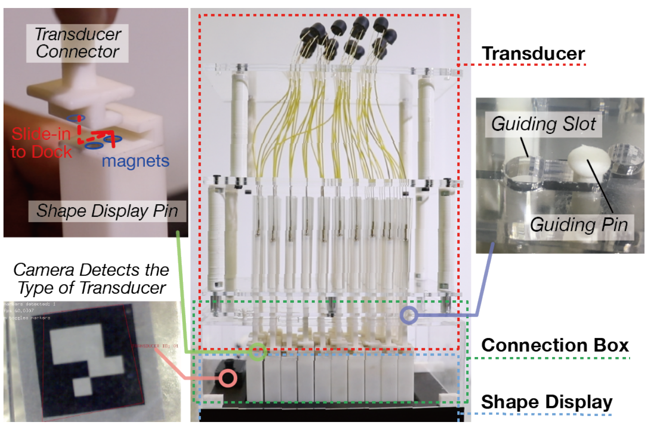

Figure 4: Transducer Structure and connection with the Shape Display (Top Left: Close-up view of Docking Connection for shape display pins, Bottom Left: Detection of Transducer with a Camera, Right: Guiding slot and pin for jointing transducers.)

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.

4 IMPLEMENTATION

In this section, we describe the implementation of our prototype that demonstrates the concept of TRANS-DOCK. As shown in Figure 2, the system is composed of shape display hardware, a computer, camera, button and, most importantly, the transducers. Each component and its connection with each other are described below.

4.1 Pre-developed Shape Display Hardware

For the pin-based shape display, we used a hardware named *inFORCE* [34] 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* produced by Faulhaber were installed. The actuator enabled a vertical motion distance of 100mm, continuous force of 3.6N, peak Force 10.7N, 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 spec are reported in [34]. 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.

4.2 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, 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 1a and 4 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 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, the docking joint was designed in a way where all of the pins had to be set to 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.

4.3 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 the purpose of clarify in this paper, 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 [9]. 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 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.

4.4.1 Comparison of Motion Transmitters' Characteristics . Figure 5 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 [10], high efficiency pneumatic joints [57], etc), 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.

4.4.2 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 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 6. Generally, the mechanical relationship needs to satisfy the following formula:

$$F_{SD} > F_s^{max} + F_{ex} + (F_{touch}) \tag{1}$$

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 exF 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 an higher efficiency technique [50].

4.4.3 Display Area v.s. 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 7 shows an example of such a relationship for the inFORCE shape display with the actual Transducers we have developed.

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

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	Linear (The Direction of Linear Motion can be Changed); Bend	[Push] Poor [Pull] Good	Good	Good	Fair
Gears & Linkages	Linear; Rotate	Good	Poor	Poor	Fair
Syringes & Tubes	Linear; Inflate	Fair	Fair	Good	Poor

Figure 5: 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)

Figure 6: 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).

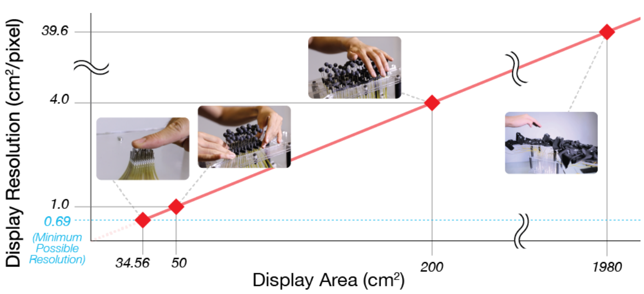

Figure 7: Graph of Display Area v.s. Resolution with inFORCE shape display as an example. As the number of pin is constrained, the transducers are generally constrained on the redline. Four prototype transducers (shown in Figure 8 and 9) are mapped on the red line as a reference.

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.

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 8a). 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 8b). Utilizing the 3D printed auxetic structure [42], 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 1c present such application usage.

Figure 8c 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 [41]. Balloons 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 [38].

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 8f). The behavior of bending motion adds interesting opportunities for interaction with shape displays including conveying impression of living creature (like tentacles or tails) [40, 54], recreating overhanging structure which are difficult to do with pin-based shape display, or grabbing and holding objects or hands [51].

The **Movable Plane Transducer** demonstrates the *movable plane* configuration, which provides a hand-held shape changing surface (Figure 8g). 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 [16] and spatial tangible / haptic interfaces [1, 3].

5.2 Application-Specific Transducers

Beyond generic shape display-like transducers, we've also prototyped Application-specific ones to demonstrate its versatile nature. Figure 9 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. [36].

Figure 9b shows the **Data Physicalization Transducer** which is designed to convey complex data in the world over several decades by dynamically rendering physical charts [31, 53]. With this

Figure 8: TRANS-DOCK Prototype Transducers (a: High Resolution Transducer, b: Resolution Changeable Transducer, c: Rendering 3D model on (b), d: Mechanical Gear Transducer, e: Balloon Array Transducer, f: Bending Pin Transducer, g: Movable Plane Transducer, h: Data Physicalization Transducer)

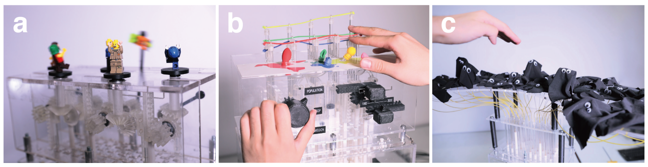

Figure 9: Examples of Application-Specific Transducers for Story-telling / Dancing Figures (a), Data Physicalization(b), and Whack-a-Mole(c).

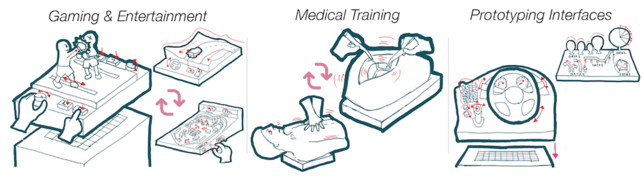

Figure 10: Examples of Potential Use Cases. (Boxing, racing and pinball transducers for Gaming and Entertainment, surgery and CPR simulator for Medical Training, and automobile interface and data display for Prototyping Interfaces.

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, demonstrate, 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 9c). 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.

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

6.1 Entertainment and Learning

Under the context of entertainment and gaming (Figure 9c 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 [21]. As shown in Figure 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 [17]. 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 can be used for presenting the shape of historical objects / sculptures (Figure 1b), and different types of Data Physicalization Transducers (Figure 9b) 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 [4, 23]. 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.

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 [45].

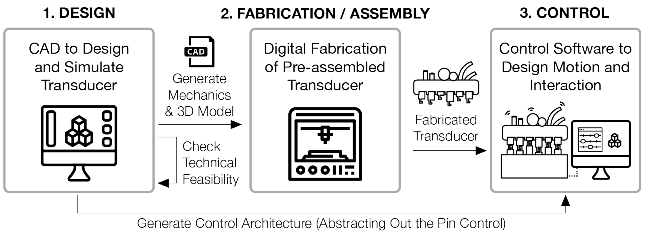

Figure 11: Future Design, Fabrication and Control Pipeline for TRANS-DOCK.

7 FUTURE WORK

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 11); **1 .Design** (to develop special CAD software for easy customization and mechanics optimization), **2. Fabrication** (to develop implementation methods to automatically assemble or fabricate the transducers), and **3. Control** (to enable users to design desired motion and interaction). We can learn from previous research on computational fabrication to develop such pipeline [7, 12, 22, 32]. 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 background may make for their own practical and artistic use cases.

7.2 Technical Improvements

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

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 the pin-base shape display becomes 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.

ACKNOWLEDGMENTS

[Anonymous for Review]

REFERENCES

[1] Mahoro Anabuki and Hiroshi Ishii. 2007. AR-Jig: a handheld tangible user interface for modification of 3D digital form via 2D physical curve. In *Proceedings of the 2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality*. IEEE Computer Society, 1–10.
[2] Patrick Baudisch, Torsten Becker, and Frederik Rudeck. 2010. Lumino: tangible blocks for tabletop computers based on glass fiber bundles. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1165–1174.
[3] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 717–728.
[4] D Antony Chacon, Eduardo Velloso, Thuong Hoang, and Katrin Wolf. 2019. SpinalLog: Visuo-Haptic Feedback in Musculoskeletal Manipulation Training. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 5–14.
[5] Arielle Bryn Chapin. 2017. Interactive Wall: Dynamic Structure in Living Spaces. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 739–743.
[6] Marcelo Coelho and Jamie Zigelbaum. 2011. Shape-changing interfaces. *Personal and Ubiquitous Computing* 15, 2 (2011), 161–173.
[7] Stelian Coros, Bernhard Thomaszewski, Gioacchino Noris, Shinjiro Sueda, Moira Forberg, Robert W Sumner, Wojciech Matusik, and Bernd Bickel. 2013. Computational design of mechanical characters. *ACM Transactions on Graphics (TOG)* 32, 4 (2013), 83.
[8] Daniel Fitzgerald and Hiroshi Ishii. 2018. Mediate: A Spatial Tangible Interface for Mixed Reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, LBW625.
[9] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation.. In *Uist*, Vol. 13. 417–426.
[10] Kapil Gupta and Neelesh Kumar Jain. 2014. Analysis and optimization of micro-geometry of miniature spur gears manufactured by wire electric discharge machining. *Precision Engineering* 38, 4 (2014), 728–737.
[11] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: towards rapid prototyping with shape-changing displays for designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 19–28.
[12] Sugihara Hiroshi. [n. d.]. *READY TO CRAWL*. https://www.youtube.com/watch?v=G0-lJKOgTuo - accessed April-5-2019.
[13] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. *interactions* 19, 1 (2012), 38–51.
[14] Hiroshi Ishii, Daniel Leithinger, Sean Follmer, Amit Zoran, Philipp Schoessler, and Jared Counts. 2015. Transform: Embodiment of radical atoms at milano design week. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 687–694.
[15] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*. ACM, 469–476.
[16] Sungjune Jang, Lawrence H Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. 2016. Haptic edge display for mobile tactile interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 3706–3716.
[17] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and challenges for data physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 3227–3236.
[18] Jonpasang. [n. d.]. *Hyper-Matrix*. http://jonpasang.com/?portfolio=hypermatrix - accessed April-5-2019.
[19] Shohei Katakura and Keita Watanabe. 2018. PrintMotion: Actuating Printed Objects Using Actuators Equipped in a 3D Printer. In *The 31st Annual ACM*

Symposium on User Interface Software and Technology Adjunct Proceedings. ACM, 137–139.

[20] Kunihiro Kato and Homei Miyashita. 2014. Extension sticker: a method for transferring external touch input using a striped pattern sticker. In *Proceedings of the adjunct publication of the 27th annual ACM symposium on User interface software and technology*. ACM, 59–60.

[21] Kidsthrill. [n. d.]. *12 Mini Magnetic Board Games*. https://www.kidsthrill.com/product-page/kidsthrill-12-mini-magnetic-travel-fun-on-the-way-best//-board-games-for-kids-ad/ - accessed April-5-2019.

[22] Robert Kovacs, Alexandra Ion, Pedro Lopes, Tim Oesterreich, Johannes Filter, Philipp Otto, Tobias Arndt, Nico Ring, Melvin Witte, Anton Synytsia, et al. 2018. TrussFormer: 3D Printing Large Kinetic Structures. In *The 31st Annual ACM Symposium on User Interface Software and Technology*. ACM, 113–125.

[23] Kevin Kunkler. 2006. The role of medical simulation: an overview. *The International Journal of Medical Robotics and Computer Assisted Surgery* 2, 3 (2006), 203–210.

[24] Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. 2016. Zooids: Building blocks for swarm user interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 97–109.

[25] Daniel Leithinger. 2015. *Grasping information and collaborating through shape displays*. Ph.D. Dissertation. Massachusetts Institute of Technology.

[26] Daniel Leithinger, Sean Follmer, Alex Olwal, and Hiroshi Ishii. 2014. Physical telepresence: shape capture and display for embodied, computer-mediated remote collaboration. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. ACM, 461–470.

[27] Daniel Leithinger, Sean Follmer, Alex Olwal, and Hiroshi Ishii. 2015. Shape displays: Spatial interaction with dynamic physical form. *IEEE computer graphics and applications* 35, 5 (2015), 5–11.

[28] Daniel Leithinger, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. Sublimate: state-changing virtual and physical rendering to augment interaction with shape displays. In *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM, 1441–1450.

[29] Daniel Leithinger and Hiroshi Ishii. 2010. Relief: a scalable actuated shape display. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*. ACM, 221–222.

[30] Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and gestural interaction with relief: a 2.5 D shape display. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*. ACM, 541–548.

[31] Siân E Lindley, Anja Thieme, Alex S Taylor, Vasilis Vlachokyriakos, Tim Regan, and David Sweeney. 2017. Surfacing Small Worlds through Data-In-Place. *Computer Supported Cooperative Work (CSCW)* 26, 1-2 (2017), 135–163.

[32] Robert MacCurdy, Robert Katzschmann, Youbin Kim, and Daniela Rus. 2016. Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 3878–3885.

[33] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A Paradiso, and Hiroshi Ishii. 2016. Chainform: A linear integrated modular hardware system for shape changing interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 87–96.

[34] Ken Nakagaki, Daniel Fitzgerald, Zhiyao John Ma, Luke Vink, Daniel Levine, and Hiroshi Ishii. 2019. inFORCE: Bi-directionalForce'Shape Display for Haptic Interaction. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 615–623.

[35] Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. Lineform: Actuated curve interfaces for display, interaction, and constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 333–339.

[36] Ken Nakagaki, Udayan Umapathi, Daniel Leithinger, and Hiroshi Ishii. 2017. AnimaStage: Hands-on Animated Craft on Pin-based Shape Displays. In *Proceedings of the 2017 Conference on Designing Interactive Systems*. ACM, 1093–1097.

[37] Ken Nakagaki, Luke Vink, Jared Counts, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2016. Materiable: Rendering dynamic material properties in response to direct physical touch with shape changing interfaces. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 2764–2772.

[38] Kosuke Nakajima, Yuichi Itoh, Yusuke Hayashi, Kazuaki Ikeda, Kazuyuki Fujita, and Takao Onoye. 2013. Emoballoon. In *Advances in Computer Entertainment*. Springer, 182–197.

[39] Akira Nakayasu. 2016. Luminescent tentacles: a scalable SMA motion display. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 33–34.

[40] Takuya Nojima, Yoshiharu Ooide, and Hiroki Kawaguchi. 2013. Hairlytop interface: An interactive surface display comprised of hair-like soft actuators. In *World Haptics Conference (WHC), 2013*. IEEE, 431–435.

[41] Fuka Nojiri and Yasuaki Kakehi. 2014. BelliesWave: color and shape changing pixels using bilayer rubber membranes. In *ACM SIGGRAPH 2014 Posters*. ACM, 17.

[42] Jifei Ou, Zhao Ma, Jannik Peters, Sen Dai, Nikolaos Vlavianos, and Hiroshi Ishii. 2018. KinetiX-designing auxetic-inspired deformable material structures. *Computers & Graphics* (2018).

[43] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph-heat-sealing inflatable shape-change materials for interaction design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 121–132.

[44] Hayes Solos Raffle, Amanda J Parkes, and Hiroshi Ishii. 2004. Topobo: a constructive assembly system with kinetic memory. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM, 647–654.

[45] Majken K Rasmussen, Esben W Pedersen, Marianne G Petersen, and Kasper Hornbæk. 2012. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 735–744.

[46] Jun Rekimoto. 2002. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM, 113–120.

[47] Rething Robotics. [n. d.]. *ClickSmartâĎć Plate*. https://www.rethinkrobotics.com/accessories/ - accessed April-5-2019.

[48] Philipp Schoessler, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2015. Kinetic blocks: Actuated constructive assembly for interaction and display. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 341–349.

[49] Alexa F Siu, Eric J Gonzalez, Shenli Yuan, Jason B Ginsberg, and Sean Follmer. 2018. shapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 291.

[50] BERND STOEBER and JIM SCHUMACHER. [n. d.]. *Gear efficiency âĂŤ key to lower drive cost*. https://www.machinedesign.com/mechanical-drives/gear-efficiency-key-lower-drive-cost - accessed April-5-2019.

[51] Koichi Suzumori. 1996. Elastic materials producing compliant robots. *Robotics and Autonomous systems* 18, 1-2 (1996), 135–140.

[52] Koichi Suzumori, Satoshi Endo, Takefumi Kanda, Naomi Kato, and Hiroyoshi Suzuki. 2007. A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. In *Robotics and Automation, 2007 IEEE International Conference on*. IEEE, 4975–4980.

[53] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring interactions with physically dynamic bar charts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 3237–3246.

[54] Jonas Togler, Fabian Hemmert, and Reto Wettach. 2009. Living interfaces: the thrifty faucet. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. ACM, 43–44.

[55] Jan F Veneman, Ralf Ekkelenkamp, Rik Kruidhof, Frans CT van der Helm, and Herman van der Kooij. 2006. A series elastic-and bowden-cable-based actuation system for use as torque actuator in exoskeleton-type robots. *The international journal of robotics research* 25, 3 (2006), 261–281.

[56] Luke Vink, Viirj Kan, Ken Nakagaki, Daniel Leithinger, Sean Follmer, Philipp Schoessler, Amit Zoran, and Hiroshi Ishii. 2015. Transform as adaptive and dynamic furniture. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 183–183.

[57] John P Whitney, Tianyao Chen, John Mars, and Jessica K Hodgins. 2016. A hybrid hydrostatic transmission and human-safe haptic telepresence robot. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 690–695.

[58] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. 2012. Printed optics: 3D printing of embedded optical elements for interactive devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. ACM, 589–598.

[59] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 13–22.

[60] Neng-Hao Yu, Sung-Sheng Tsai, I-C Hsiao, Dian-Je Tsai, Meng-Han Lee, Mike Y Chen, Yi-Ping Hung, et al. 2011. Clip-on gadgets: expanding multi-touch interaction area with unpowered tactile controls. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*. ACM, 367–372.

[61] Kai Zhang and Sean Follmer. 2018. Electrostatic Adhesive Brakes for High Spatial Resolution Refreshable 2.5 D Tactile Shape Displays. In *Haptics Symposium (HAPTICS), 2018 IEEE*. IEEE, 319–326.