# POLYHINGE: SHAPE CHANGING TUI ON TABLETOP

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**ABSTRACT**

This paper presents PolyHinge, a variable-form Tangible User Interface (TUI) that provides dynamic affordance and semantics and extends its malleability and mutability by enabling active shape-changing outputs. It is superior to traditional rigid TUIs in that it can provide multistate geometric transformations in the physical world. Highly diverse forms of transformations are allowed as PolyHinge is based upon extended structures of hinged dissections and connections. In addition, the concept of dynamic affordance and semantics is further developed within the context of shape-changing interfaces, as a functional and bidirectional interface applicable for both input and output. Meanwhile, a series of applications are developed, demonstrating how users can interact with PolyHinge on a tabletop, and how the dynamic affordance and semantics can aid users.

**KEYWORDS**

Shape changing interfaces; tabletop tangible interfaces; self-actuation; dynamic affordance and semantics

## 1. INTRODUCTION

The way we understand the physical world is inherently shaped by our interactions with and perceptions of interfaces, yet traditional forms of Tangible User Interfaces (TUIs) are not capable of allowing full understanding of digital content. Usually such interfaces allow a user to control digital content through physical manipulation (Hiroshi Ishii and Brygg Ullmer, 1997), but lack physical feedback for the user.

However, with improvements in actuation, haptics, and material qualities, self-actuated TUIs and Organic User Interfaces (OUIs) are increasingly able to provide physical feedback and present content in more diverse ways. As such they are becoming more common as research topics in the field of HCI.

Among research on self-actuated TUIs and OUIs, shape-changing interfaces are an especially challenging topic due to the complexity of performing physical transformations. Many kinds of soft materials are used to create shape changing interfaces, but the forms of transformation are still nonetheless restricted. In addition, the ability to change shape is often more regarded as an output method, rather than a characteristic of a functional and bidirectional interface.

In this paper we present PolyHinge, a series of novel shape-changing TUIs that use hinge connections to perform physical geometric transformations. PolyHinge can work together with multi-touch tabletop screens to allow the user to interact with digital content. In addition, the concept of dynamic affordance and semantics is further developed within the context of shape changing interfaces. We also developed a series of applications allowing PolyHinge interaction on a tabletop, demonstrating how this concept can assist users. Interaction with PolyHinge is very natural and thus is both accessible and attractive to users.

## 2. RELATED WORK

### 2.1 Adding Actuation to Passive TUIs

Previous research extensively explored methods of adding actuations to passive TUIs. With actuated TUIs, users can get feedback on changes in digital information that passive TUIs cannot.

Ivan Poupyrev et al.'s (2007) research discusses many details about TUIs and actuation. Esben Warming Pedersen & Kasper Hornbæk's (2011) Tangible Bots provide movement and haptic feedback for tangible tabletop interfaces by using active, motorized tangibles, as well as putting forward an interaction framework that can be applied to many actuated TUIs.

Recently, shape-changing interfaces have emerged as a popular research topic in the field of actuated TUIs. Notable and relevant examples of recently developed shape changing TUIs include: Height-Adjustable TUIs (Haipeng Mi and Masanori Sugimoto, 2011); Changibles (Anne Roudaut et al, 2014), which are interactive wireless tokens that can reshape themselves and attach together to create animated assemblies; GaussBricks (Rong-Hao Liang et al, 2014), which are magnetic building blocks connected by magnetic joints, enabling motion, force feedback and shape changes; PneUI (Lining Yao et al, 2013), which is a technology enabling the building of shape-changing interfaces through pneumatically-actuated soft composite materials.

The properties enabling physical feedback present in each of these systems served as inspiration to our approach, and we attempt to extend these approaches into our work.

## 2.2 Affordance

The term "affordance" originated from the field of Psychology, and is now widely used by HCI researchers. Orit Shaer and Eva Hornecker (2010) frequently discusses cuing interaction with affordances. Norman (1999) presents the idea that affordances reflect the possible relationships among actors and objects. Similarly, Dhaval Vyas et al.'s (2006) research emphasizes that affordance is an interpretative relationship that emerges between users and technology during their interaction within their lived environment. inFORM (Sean Follmer et al, 2013), which introduces dynamic physical affordances and constraints, is also a closely related work.

## 2.3 Hinged Dissection and Connection

Hinged dissection is a geometric problem. What inspired us most is the classic hinged dissection of an equilateral triangle into a square by Dudeney (1902) shown in Figure 1. Furthermore, Timothy G. Abbott et al. (2008) have proved that any finite collection of polygons of equal area has a common hinged dissection. That is, for any such collection of polygons there exists a chain of polygons hinged at vertices that can be folded in the plane continuously without self-intersection to form any polygon in the collection. This result guarantees that PolyHinge devices, with its hinged dissections and connections, have various forms it can transform between which can be used for various applications.

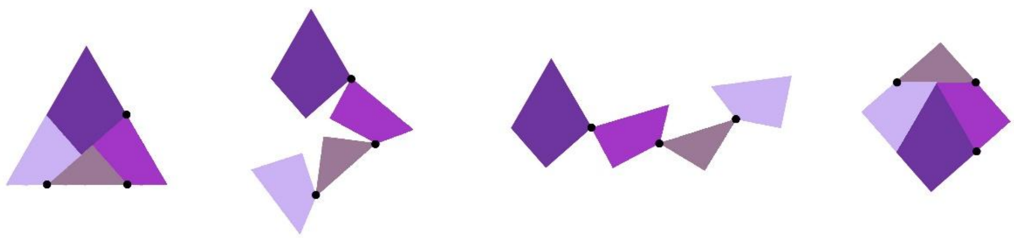

Figure 1. The classic hinged dissection of an equilateral triangle into a square by Dudeney

## 3. DESIGN

Inspired by Dudeney's hinged dissection of an equilateral triangle into a square as well as related research, we chose hinged dissection and connection as the method of changing the TUI's shape. This is a convenient way to change the TUI's geometric shape, and enables dynamic affordance and semantics in tangible interactions. We also made further research in adapting the concept of hinged dissection and connection on a triangle to a square presented by Dudeney onto polyominoes. In comparison with the classic hinged transformation between two shapes, polyominoes provide a way of performing a multi-state hinged transformation. We present an example of tetrominoes (a polyomino of order 4) transforming into 7 distinct shapes in Figure 2.

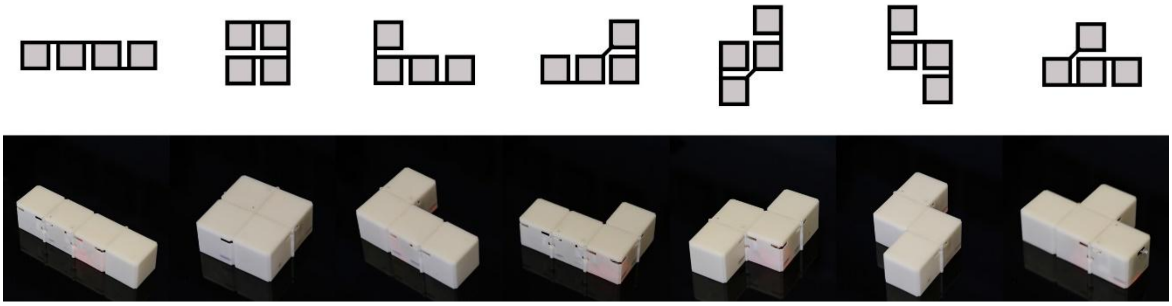

Figure 2. An example of a tetromino transforming into all of its distinct shapes—like Tetris

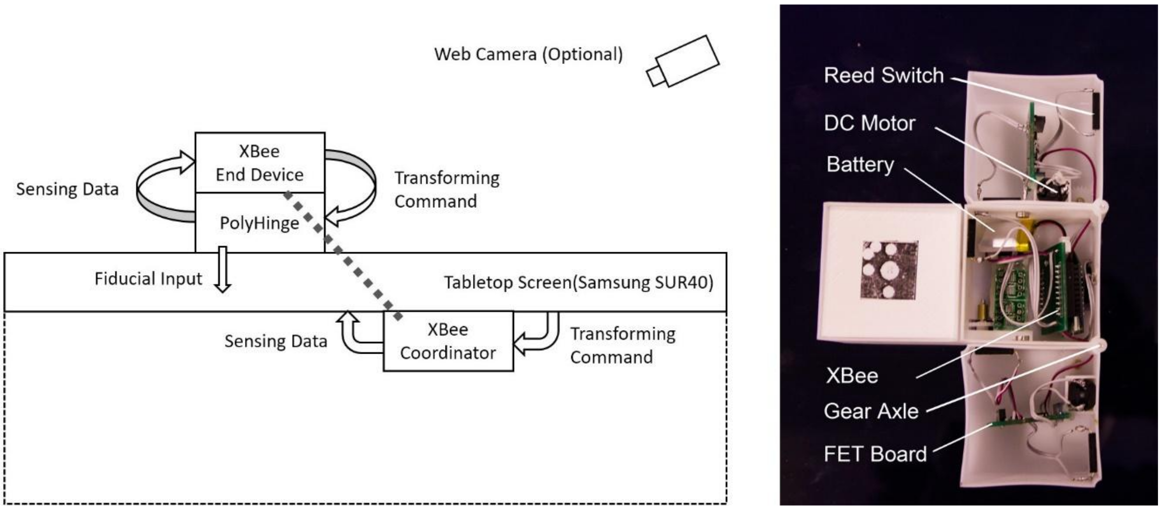


Figure 3. Left: The PolyHinge system architecture. Right: A typical PolyHinge hardware structure

## 3.1 Hardware

A typical PolyHinge hardware structure, shown in Figure 3 (Right), consists of several subunits connected together via hinges. A parent unit contains a DC motor which drives child units using gear axles fixed at hinge corners in order to execute rotations. Surfaces that may come into contact with each other during rotations contain magnet pairs and reed switches so as to detect contact and prevent over-rotation. FET (Field Effect Transistor) boards are used to amplify control signals from the XBee wireless receiver. Wires are routed through the hinged connections, carrying power and signals from one unit to another. The units are 3D printed with SLA, in a proper size that are very comfortable to grasp. In addition, fiducial tags are applied onto the bottom surfaces for optical tracking by the tabletop screen. Furthermore, there are extensible ports on the PCB for sensors to support functions such as tapping.

## 3.2 System

The PolyHinge system architecture is shown in Figure 3 (Left). We employed a multi-touch tabletop screen (Samsung SUR40 with Microsoft PixelSense) as a tracking demonstration platform for PolyHinge. In addition to traditional multi-touch interactions, the screen is capable of recognizing fiducial tags placed on its surface and detect their positions and orientations. An optional web camera can be used to support gesture input. We used XBee technology for bidirectional data communication between a PolyHinge device and the table. The PolyHinge uses an XBee end device while the table is connected to an XBee coordinator. This enables multiple PolyHinge devices to work with the table at the same time.

A typical dataflow is multichannel. The table gathers information from multi-touch input, fiducial input, sensing data from PolyHinge, and the optional web camera in order to recognize a correct input event according to the interaction scenario. Then a transforming command can be transmitted back to the PolyHinge which generates a physical shape output, as well as sound and visual information on the tabletop screen.

# 4. INTERACTION & APPLICATION

Together with a tabletop screen, PolyHinge is a mixed-reality system in which both physical and digital information is presented to the user. In addition to the active shape output, PolyHinge also serves as a multi-channel sensing interface that detects position, orientation, taps, and so on. Therefore, PolyHinge can provide unique interaction styles and applications in addition to ones provided by traditional rigid TUIs.

## 4.1 Hinge-Based Interaction

Users can physically manipulate PolyHinge devices beyond ways in which they can interact with traditional TUIs. Hinge-based interaction as an interaction style is simple and natural, as is shown in Figure 4. Users activate a hinge using a physical or a digital select, and then trigger a transformation using a virtual slide gesture on the tabletop screen. In this interaction, users naturally and directly manipulate the PolyHinge device's shape with individual control of each hinge.

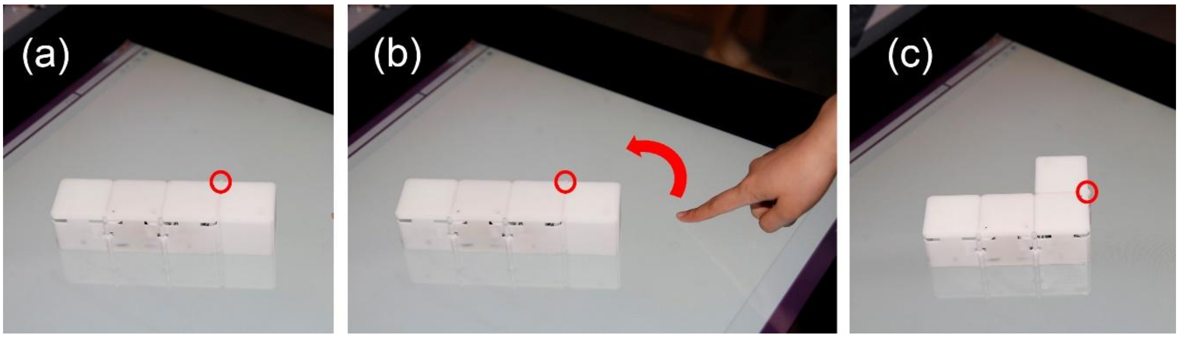


Figure 4. Hinge-based interaction, (a) a hinge is selected and activated; (b)(c) using a slide gesture on the tabletop screen to control the shape change

## 4.2 Shape-Based Interaction

For more complex PolyHinge geometric structures, indirect interactions are more natural. For example, for a PolyHinge device that transforms between a triangle and a square, users can outline a shape by hand and make the PolyHinge transform into the outlined shape (Figure 5). In such shape-based interactions, users control the device's shape with natural methods such as gestures, drawings, and so on.

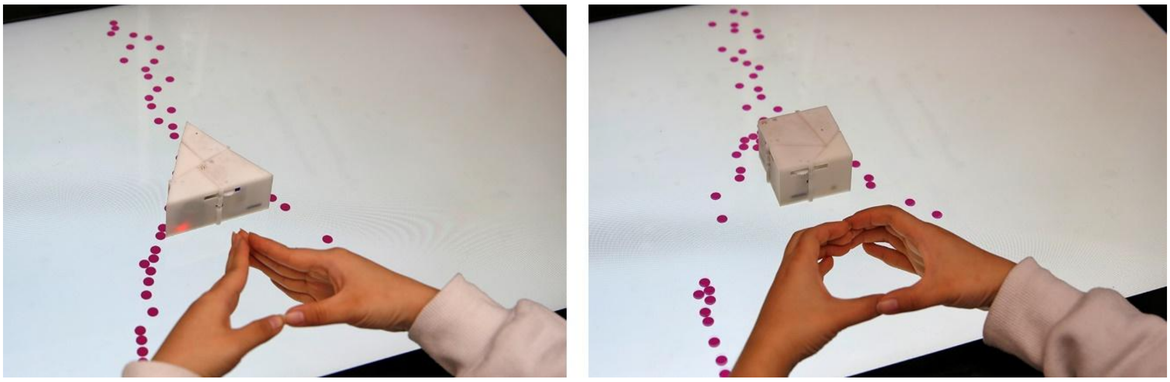

Figure 5. Shape-based interaction: outlining a shape by hands to control the shape of PolyHinge

## 4.3 Context-Based Interaction

In a complex real-world context-based interaction scenario with PolyHinge, users can perform a physical or a digital input and get both digital and physical outputs. There are a myriad of possibilities in designing the specific interaction style for different applications.

TUIs have persistent mappings (Shaer, O. and Hornecker, E, 2010) and thus the metaphor of a TUI has temporal and cognitive continuity. By making use of affordance and semantics in a TUI's appearance, its meaning or function as well as how to interact with it can be conveyed to the user. Affordance and semantics is an effective way to aid users in tangible interaction. This is similar to the use of metaphors in GUIs though TUIs are less malleable and less mutable than a purely digitally computer-controlled representation (Shaer, O. and Hornecker, E, 2010). In contrast with the static affordance and semantics of traditional TUIs, PolyHinge has a dynamic continuity and presents dynamic affordance and semantics as a characteristic of functional and bidirectional interface. This makes dynamic function and meaning accessible for physical TUIs, and expands the usage of TUIs in user cuing and many others ways.

PolyHinge can provide dynamic affordance for a user's input. This can be seen in a Tangible Tetris game that uses a transforming tetromino as a handheld device shown in Figure 6. Similar to traditional Tetris, the transforming tetromino will change its shape randomly each time after the user places it. In this case, dynamic affordance is used to cue users on how to interact with the TUI devices. The shape-changing property can indicate different interactions under the TUI's individual metaphor, and provide more possibilities for various scenarios.

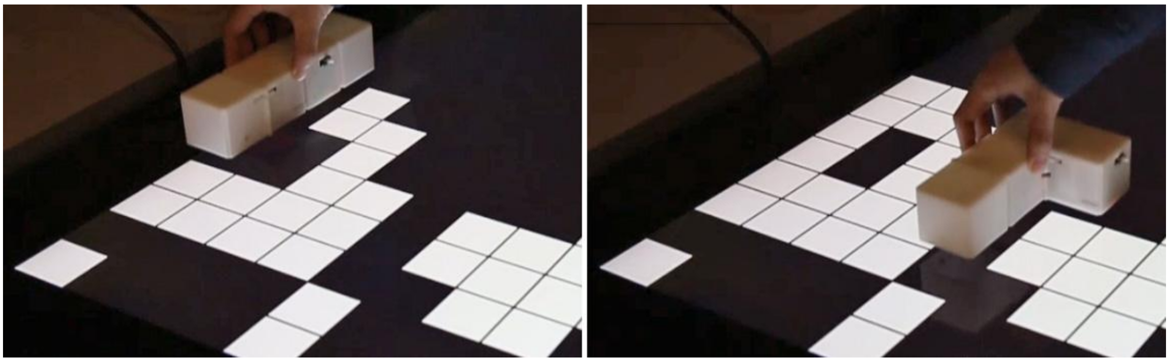

Figure 6. Dynamic affordance in a Tangible Tetris game

PolyHinge can also provide dynamic semantics for multi-state metaphors. For instance, a PolyHinge transforming from an equilateral triangle to a square can be used as a physical play/stop button of a digital media player (in Figure 7). With the user's previous experience, the state indicated by the button can be easily recognized, and they can still move it around to control different movies like traditional TUIs. In this scenario, dynamic semantics is used to cue users on the state or result of an interaction.

ISBN: 978-989-8533-64-7 © 2017

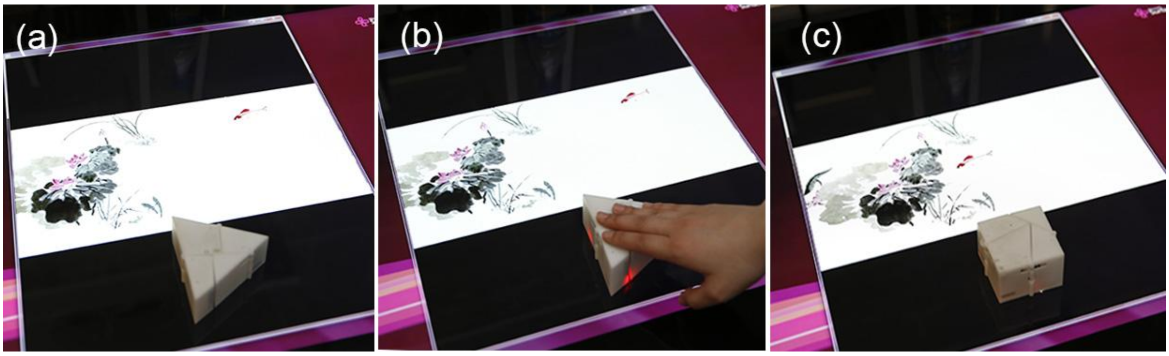


Figure 7. Dynamic semantics, (a) a physical play/stop button of a digital media player, (b) user tapping the button, (c) the movie playing and the button transforming to indicate its changed state and function.

## 5. USER STUDY

In our user study, we arranged 23 participants to play the Tangible Tetris game. After the game we distributed a questionnaire and conducted interviews to collect their impressions and thoughts.

According to the results of the questionnaire, the majority of the participants (N=18, 78.3%) thought the Tangible Tetris game was "really interesting", while a few (N=3, 13.0%) thought it was "a little uncomfortable" to play. In addition, the survey found that some (N=11, 47.8%) preferred the virtual Tetris, some (N=8, 34.8%) preferred the physical and a few were neutral (N=4, 17.4%). However, all except one of the participants (N=22, 95.7%) found the shape-changing TUI itself to be appealing. They felt that the shape-changing TUI is "effective", "accurate", and "attractive". In addition, many participants showed a strong curiosity to the transformation procedure and a great interest in the physical interaction. These results indicate that PolyHinge has a positive contribution to tangible interactions.

## 6. LIMITATIONS & FUTURE WORK

A decomino (a polyomino of order 10) has 9189 possible shapes (Redelmeijer D. H., 1981). However, when extending the structure from tetrominoes to higher order polyominoes, it does not seem to be possible to join 5 or more squares by hinges to form all possible shapes (Demaine, E. D. et al, 2005). This problem can be solved by dividing the polyomino subunits into smaller triangular pieces. Higher order polyominoes with such structures could be made into a physical pixel interface in which every subunit can perform a rotation and thus forming various pixel patterns as a whole.

Meanwhile, we are going to explore possibilities in swarm interactions, in which the PolyHinge devices act as modular tabletop robots, work collaboratively, and attach together using magnets. With the possibility of connecting multiple PolyHinges, more diverse and dynamic patterns can be formed. Such an interface is similar to modular robots, but with more exciting characteristics and greater possibilities in presentation and interaction.

## 7. CONCLUSION

In this paper we presented PolyHinge, a shape-changing TUI which enables active shape-changing output with dynamic affordance and semantics, thus inheriting the representative characteristics of a TUI while also extending its malleability and mutability. As PolyHinge is based on extended structures of hinged dissection and connection, its forms of transformation and interaction are highly diverse. The natural interaction styles allowed by PolyHinge are accessible and attractive to users.

## ACKNOWLEDGEMENT

We thank Ms Qingyuan SHI, Ms. Jiawei LI, Mr. Fengyuan ZHU, and Mr. Qi LU for their support. Thanks for James Ronner and Mr Shaoen MA for proofreading English. This work is supported by National Natural Science Foundation of China under Grant No. 61402250, 61232013, and National Key Research & Development Plan of China under Grant No. 2016YFB1001402.

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