inDepth: Force-based Interaction with Objects beyond A Physical Barrier

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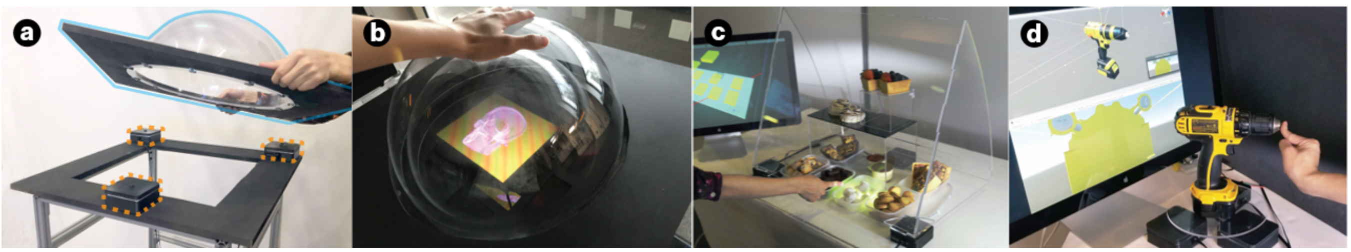

Figure 1: An overview of inDepth. (a) Force sensors are installed underneath a physical barrier to enable force-based interaction with objects beyond the barrier. Example applications include (b) manipulating 3D rendered models on a 3D display, (c) selecting food items in a showcase, and (d) accessing internal geometric contents of gadgets.

ABSTRACT

We propose inDepth, a novel system that enables force-based interaction with objects beyond a physical barrier by using scalable force sensor modules. inDepth transforms a physical barrier (eg. glass showcase or 3D display) to a tangible input interface that enables users to interact with objects out of reach, by applying finger pressure on the barrier's surface. To achieve this interaction, our system tracks the applied force as a directional vector by using three force sensors installed underneath the barrier. Meanwhile, our force-to-depth conversion algorithm translates force intensity into a spatial position along its direction beyond the barrier. Finally, the system executes various operations on objects in that position based on the type of application. In this paper, we introduce inDepth concept and its design space. We also demonstrate example applications, including selecting items in showcases and manipulating 3D rendered models.

CCS CONCEPTS

• **Human-centered computing** → *HCI theory, concepts and models.*

KEYWORDS

user interface: tangible interaction; touch input; force sensing;

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1 INTRODUCTION

In everyday life, we regularly interact with physical objects around us. Researchers in the field of HCI have been resonated with a vision of tangible interaction with objects for diverse purposes [17]. However, in some cases, objects of interest are out of reach, such as food items in showcases or rendered graphics beyond the glass of 3D displays. While physical barriers play an important role in preserving objects, they may also prevent users from directly interacting with objects out of reach.

Prior work has been investigating solutions to enable interaction with objects beyond physical barriers. Some work uses optical tracking of hand gestures in midair to interact with objects at a distance, but that usually suffers from occlusion and narrow field of view [8, 34]. Other work attaches external tools, such as a touch sensitive layer, on the barrier's surface to make it accept input from users [20, 25]. However, such workarounds are usually limited to position and intensity information only. This may be a sufficient solution for relatively smaller objects, such as smartphones, but manipulating larger objects in 3D space depends on 3D directional information, in addition to position and intensity.

To address this problem, we propose inDepth, a novel system that enables directional force-based interaction with objects located in 3D space beyond a physical barrier by using scalable force sensor

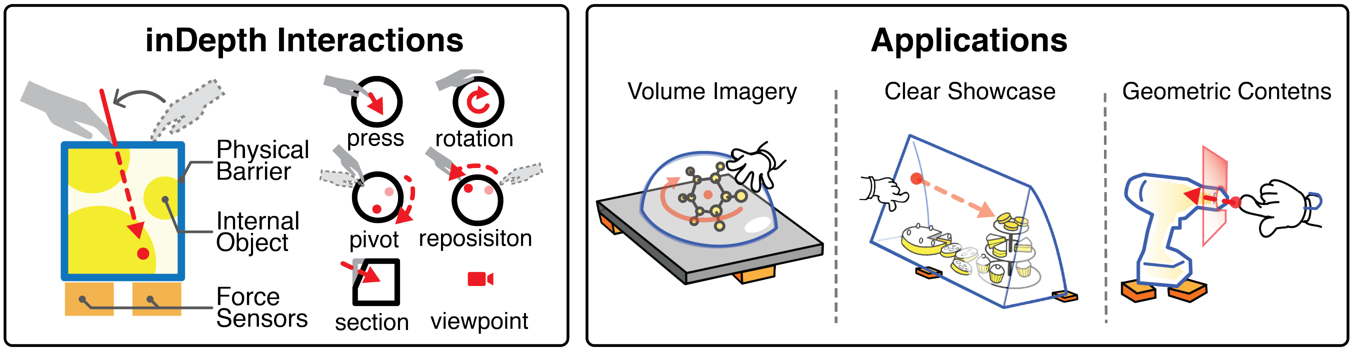

Figure 2: The design space of inDepth. (Left) Users interact with objects beyond a physical barrier by applying finger pressure on the barrier's surface to specify a point in 3D space beyond the barrier. inDepth tracks the applied force vector through three force sensors installed underneath the barrier, then executes various interactions on objects in that position. Possible interactions include: press, rotation, pivot, reposition, section and adjustment of viewpoint. (Right) inDepth can be used in a variety of applications. We tested our proof of concept in three scenarios: Manipulating rendered graphics on a 3D display, selecting food items in a showcase and accessing internal geometric contents of gadgets.

modules. As showed in Figure 1, our system transforms the existing barrier to a tangible input interface that enables users to interact with objects out of reach. With our system, users apply finger pressure on the barrier's surface to specify a point in 3D space beyond the barrier and execute various predefined operations on objects in that position.

In this paper, we first review prior work related to interacting with objects beyond a physical barrier, as well as force-based interaction systems. Additionally, we describe the details about our proposed system; its concept, hardware, algorithm and design space. We also demonstrate the application space in three example domains: manipulating rendered graphics on a 3D display, selecting food items in a showcase, and accessing the internal geometric contents of gadgets through its external surface. We finally conclude by discussing our system, its limitations, and future work.

Our contributions described in this paper include:

- Introducing a novel system that enables force-based interaction with objects beyond a physical barrier by using scalable force sensor modules
- Developing a force-to-depth conversion algorithm to translate force intensity into a spatial position along its direction beyond the physical barrier.
- Demonstrating several example applications in the design space of enhanced force-based interaction

2 RELATED WORK

Our project is related to touch sensing on everyday objects and interaction with objects out of reach.

2.1 Sensing A Human Touch on Everyday Objects

Touch sensing has been studied extensively over the last decade in the HCI community. Many researchers have been exploring the wearable approach to accept such touch input. Their approach contains different form factors, such as finger rings [18, 36], wrist bands [19, 27], glove types [3] and body mounted [10]. While these wearables are advantageous for capturing all the touch inputs thoroughly along with a single user, it requires times and effort when the target users interchange. Besides wearable methods, another approach is to augment the target object by attaching sensors. Towards this non-wearable approach, many different materials and structures have been employed, such as vision [6, 32], capacitive layer [25, 35], acoustic propagation [28], IR reflection [9, 33], electromagnetic [21, 39], force [24, 38], and their influence on user performance and experience has been studied. Among non-wearable sensors, a force sensor makes the most of force vector information which conveys additional information on its direction and intensity. In the HCI community, force sensors has augmented interactions with mobile devices [11, 12], 3D printed objects [15], tables [7, 30], furnitures [16, 26], and everyday objects [37, 38]. In sharing the matured technology of force sensing with these prior works, our project aims at exploring further use of force sensors for interacting with objects at a distance from a user's hand.

2.2 Interacting with Objects Out of Reach

Objects of interest are not always in reach of our hand. Many researchers have been studied interaction with 3D imagery at a depth in a digital display, which imagery is placed beyond the glass boundary and out of reach of our hand, such as 2d display [1, 14] and 3D display [4, 8]. Other researchers utilizes direct touch on a screen to interact with 3D imagery in a digital display by leveraging physical transformation of objects, such as screen membrane [2, 31] or hand-held devices [22]. These works give a useful insight that force intensity can be interpreted as depth input. Beyond interacting with digitally-rendered objects at a depth, interacting with physical objects at a distance has also been investigated typically by overlaying image, such as with handheld devices [13] and with desktop devices [23]. A see-through barrier between a user and objects of interest can become a place for interaction.

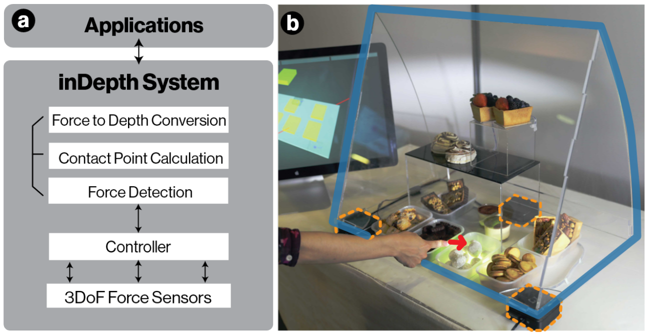

Figure 3: (a) The system architecture of inDepth. 3DoF force sensors track the force applied by the user. For example, (b) installing force sensors underneath a showcase enables users to select items in a store by pressing on the glass.

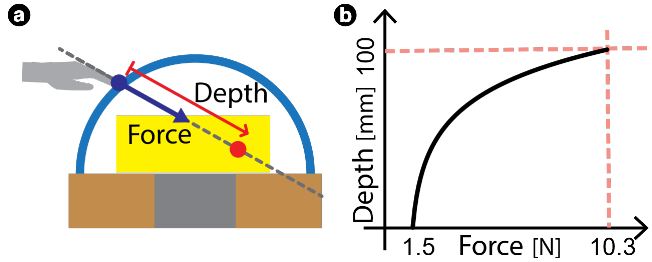

Figure 4: Force-to-depth conversion. (a) inDepth's force-to-depth conversion algorithm translates force intensity into a spatial position along its direction beyond the barrier. The 3D display scenario is shown as an example. (b) Force [N] to depth [mm] conversion graph.

2.3 Position of This Work

In summary, prior work for interacting with objects in digital or physical worlds relies on detecting the position of users' hands by using cameras that suffer from limited field of view, or by using tools that lack directional input from users. inDepth addresses this problem by supporting position, intensity and directional force input to enable interaction with objects located in 3D space beyond physical barriers. inDepth can be used for both digital and physical spaces and has multiple support structures that allow scalability in the future, as we detail in the following section.

3 INDEPTH SYSTEM

inDepth is the system to enable force-based interaction with objects beyond a physical barrier that accepts directional force inputs. Users apply finger pressure on the barrier's surface to specify a point in 3D space beyond the barrier. Users can control the depth of the specified point through by changing the intensity of the force applied on the barrier's surface. As detailed in Figure 2 (Left), our system uses three 3DoF force sensors installed underneath the barrier to track the applied force and execute various operations on objects in that position. inDepth system provides a set of interaction for users, including press, rotation, pivot, reposition, section, and adjustment of viewpoint, as shown in Figure 2 (Left).

We detail the architecture of inDepth in Figure 3 (a). Force sensors installed underneath the barrier track the force applied by the user. A controller receives raw data from the sensors and sends it to a computer to perform back-end processing. On the back-end, force detection, contact point calculation and force-to-depth conversion algorithm enable the system to execute various operations on objects a position beyond the barrier, as specified by the user. For example, as shown in Figure 3 (b), installing force sensors underneath a showcase enables users to select items in a store by pressing on the glass. Lights appear around the selected item as a feedback to the user.

Interactions made possible by inDepth allows the system to be used in a variety of applications. As shown in Figure 2 (Right), we categorized example application scenarios to highlight the application domains: *Volume Imagery*, *Clear Showcases* and *Geometric Contents*.

3.1 Volume Imagery

In this scenario, objects out of reach are the volume imagery on the 3D display, and the physical barrier is the display itself. This is an example of possible interactions in the digital space. Users can specify a point in the 3D space of the rendered graphics by applying force on the surface of the display. Users can then rotate or move the graphics by moving their fingers or changing the intensity of the force they apply on the display's surface.

3.2 Clear Showcases

inDepth can also be used to enable users to interact with items (objects) inside a clear showcase (barrier). This is an example of possible interactions in the physical space. Users can specify a point in the 3D space beyond the showcase by applying force on its surface. The system detects the contact point of the user's finger on the surface of the showcase and translates force intensity into a spatial position along its direction beyond the showcase.

3.3 Geometric Contents

We can also use inDepth to access internal geometric contents (objects) of a gadget by applying force on its exterior surface (barrier). In this scenario, the internal geometric contents are the objects out of reach and the external surface of the gadget is the physical barrier. Force sensors are installed directly underneath the gadgdet. Assuming we have a 3D model of the gadget in advance, users can manipulate the model by applying force on the external surface of the gadget. Users can change the direction of the force applied by their fingers to change the viewing angle. They can also access internal contents by increasing the intensity of the force applied, which increases the depth of the plane of cross section in the model.

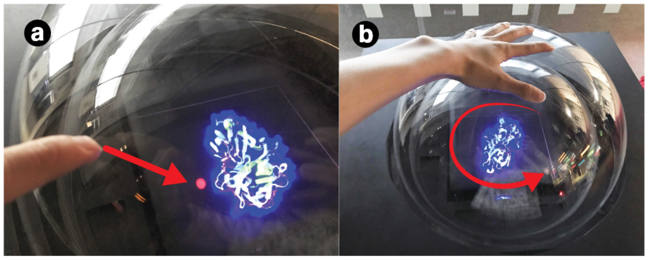

Figure 5: Protein Viewer application scenario on a 3D display. (a) Users can view and focus on specific parts in a protein with their fingers (b) Users can rotate proteins by twisting hands on the surface of the display

4 IMPLEMENTATION

Here we describe the detail of our prototypes we have implemented for conducting a user study and demonstrating example applications. The implementation details are composed of two descriptions: hardware and algorithm.

4.1 Hardware

We used load cells (FNZ100N, Forsentek.inc) with load capacity of 10 kg in our force sensors. We packaged each sensor in a small cuboid with a 90 x 90 x 35 mm form factor. The fabrication protocol is detailed in a related project [38]. All sensors are connected to a controller, which receives raw data from the sensors and sends it to a computer to perform back-end processing.

For volume imagery application scenario, we used Voxon VX1 (Voxon Photonics.inc). The dimensions of the imagery area in this 3D display are 180 x 180 x 80 mm [29]. We implemented an interactive 3D application to test inDepth on this display for volume imagery scenarios. For the clear showcases application scenario, we built an acrylic showcase to demonstrate a bakery shop scenario. This showcase has a large slanted front panel to provide a clear view for users. Finally, for scenarios in which we access internal geometric contents of gadgets, we prepared a 3D model of a motor drill then used it to demonstrate section cuts and manipulate viewpoints using our system.

4.2 Algorithm

In this section, we first describe how to calculate the force vector and the contact point based on data received from force sensors. We then introduce our force-to-depth conversion algorithm to specify a point in 3D space beyond the physical barrier. A force vector is the key element for detecting the contact point $\mathbf{x}$ on the barrier surface and applied force $\mathbf{f}$. We assume the sets of measured force $\mathbf{f}_i$, sensed at i-th force sensor. At least three sensors are needed to all needed information. We assume that the i-th force sensor is placed at point $\mathbf{p}_i$. For simplicity, we assume that all sensors are placed on the same plane. The applied force $\mathbf{f}$ and its torque τ are derived as follows: $\mathbf{f} = \sum_i \mathbf{f}_i, \tau = \sum_i \mathbf{p}_i \times \mathbf{f}_i$

We can also formulate the contact point $\mathbf{x}$ using the components of the measured force vector, as follows:

$$\mathbf{x} = \mathbf{a} + p\mathbf{d} \quad \text{s.t.} \quad \mathbf{a} = \mathbf{f} \times \tau / |\mathbf{f}|^2, \quad \mathbf{d} = \mathbf{f}/|\mathbf{f}|$$

Figure 6: Bakery shop application scenario. Users can select items in a showcase by directly applying finger pressure on the glass. Lights appear around the selected item as a feedback to the user.

Where $\mathbf{a}$ is the anchor point, $\mathbf{d}$ is the normalized vector of the line and p is the parameter of the contact point $\mathbf{x}$. Considering the geometry of the barrier (e.g. hemispheric dome of a 3D display, slanted planar surface of a showcase), the contact point $\mathbf{x}$ will be at the intersection of the force line and the barrier's surface. To convert force to depth, we experimentally designed a logarithmic transformation formula, based on Weber Fechner law [5].

$$depth = d_0 \log (force/f_0)$$

While constants d_0 and f_0 vary depending on the implementation and application, we experimentally selected their value for volume imagery applications. As shown in Figure 4, converting force to depth starts from 1.5 N, while an applied force of 10.3 N is converted to a depth of 100 mm.

5 APPLICATION SCENARIOS

In this section, we demonstrate the wide range of applicability by exemplifying several different use cases, from application domains as detailed in Figure 2 (right). The use cases of protein viewer and section cut are for application domain of *Volume Imagery*. Also, the use cases of bakery shop and interactive orrery are to demonstrate the *Clear Showcase* domain. Furthermore, the use case of an electric drill is for *Geometric Contents*. Every use case contains a set of interactions we have clarified in the design space.

5.1 Protein Viewer

In order to view a digital scientific model in a 3D image viewer, such as a protein structure, it is required for the software to capture the user's input, including selecting, scaling, rotating and so on, towards smooth interaction with the contents. To demonstrate the capability of basic interactions, we displayed a protein model of pepsin, and implemented the functions of selection by applying force, and rotation through twisting, as shown in Figure 5.

5.2 Ordering in a Bakery Shop

In a bakery shop with a variety of cookies, donuts and cakes within a glass showcase, the user can initiate the quick pointing by applying force on the showcase. Augmenting the enclosed showcases with our force sensors, the system could help to identify which product the user is placing the order. As shown in Figure 6, we demonstrate this scenario with small accessories in an acrylic transparent case on an illuminating surface to indicate which product

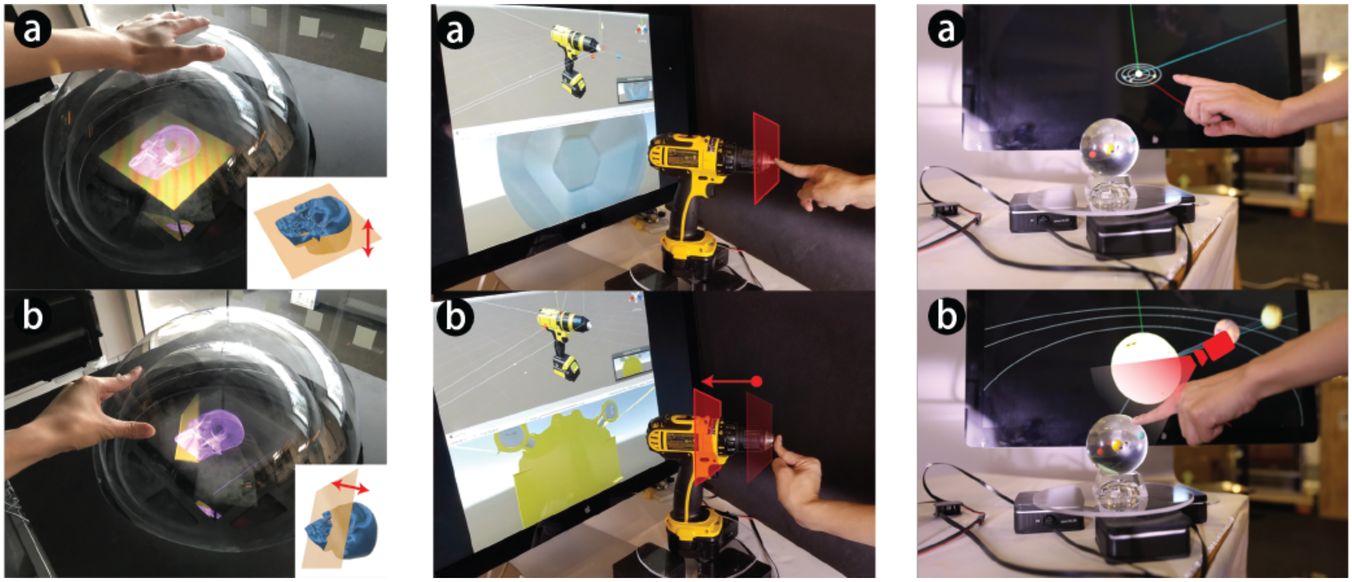

Figure 7: Example Applications of inDepth (Left) *Anatomical Section Cutting*: **Controlling cross sections application scenario. (Center)** *Sensing Inside an Electric Drill*: **Accessing internal geometric contents application scenario. (Right)** *Into the Orrery Universe*: **Understand the solar system by applying force on a glass orrery.**

is currently selected through the pointing method. This enclosure understands the user's selection and could interpret a deep push for selection, to differentiate from simply pointing, to convey more input information. This application also shows the possibility that our inDepth system could improve the accessibility of the ordering process as it does not require verbal communications.

5.3 Anatomical Section Cutting

For some 3D content in medical or geoscience applications, it is critically important to see the planar intersection of the volumetric model. To demonstrate this function, we implemented a 3D human skull model with manipulable 2d plane. The user can manipulate its position and surface normal of the plane through force input to see the model from a better point of view, as shown in Figure 7 (Left). The user could provide more force through pushing to see the contents at a deeper intersection, and push less to see it at shallower position. If the user would like to watch the intersection from a different point of view, one can achieve that only by applying force on different points on the enclosed dome.

5.4 Seeing Inside an Electric Drill

A user could put an object of interest onto our system, and then start to explore the internal structure of the product, by applying force on the surface around from a variety of direction. A user could leverage the viewpoint manipulation feature for this purpose. As shown in Figure 7 (Center), with the 3D model of a motor driver, a system could generate the graphics of the model from different perspectives according to way of contact. For the educational use, a user could see the inside through directly applying force on the target of interest, even from ten different perspectives. This feature will take the user to in-depth understanding of mechanical design.

5.5 Into the Orrery Universe

With an orrery, the aesthetic tangible model of a solar system enclosed in a small glass ball, children use their imagination to explore and travel through the universe from the Earth to the Mars. By putting the orrery on inDepth system, the system could capture how they interact with the orrery, as shown in Figure 7 (Right). In this scenario, viewpoint manipulation feature provides a smooth interaction with imaginations in computer graphics. One way of interpreting the contact force could be to translate the direction and intensity to control the observer's point of view in a small universe. The trajectory of the interplanetary exploration can be visualized in computer graphics through embodied interaction on the orrery.

6 FUTURE WORK

We implemented prototypes of the inDepth system to demonstrate its application domain, while there still remains unrevealed human factors, which seems unique and essential for force-based interaction enabled by the inDepth. A major factor to be revealed is how a user switches and chooses a set of interaction techniques as suggested in Figure 2(Left). For example, while a user is thought to be able to access to a 3D point by both ways of 'pivot' and 'reposition', it is still uncovered what makes a user choose either interaction.

7 CONCLUSION

In this paper, we proposed inDepth, a system that enables force-based interaction with physical or digital objects beyond a physical barrier by using force sensor modules. We demonstrated the design space of inDepth in a variety of application scenarios. For the future works, we could perform user study in detail to reveal specifications, and collect feedback from users in practical settings, such as museum exhibitions. We envision the world where the 3D force vector measurement in ubiquitous scenarios, from home to office, provides people with in-depth information hidden and embedded deep inside of objects.

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