ZeroN: Mid-Air Tangible Interaction Enabled by Computer Controlled Magnetic Levitation

Jinha Lee[1], Rehmi Post[2], Hiroshi Ishii[1]

[1]MIT Media Laboratory
75 Amherst St.
Cambridge, MA, 02139
{jinhalee, ishii}@media.mit.edu

[2]MIT Center for Bits and Atoms
20 Ames St.
Cambridge, MA, 02139
rehmi.post@cba.mit.edu

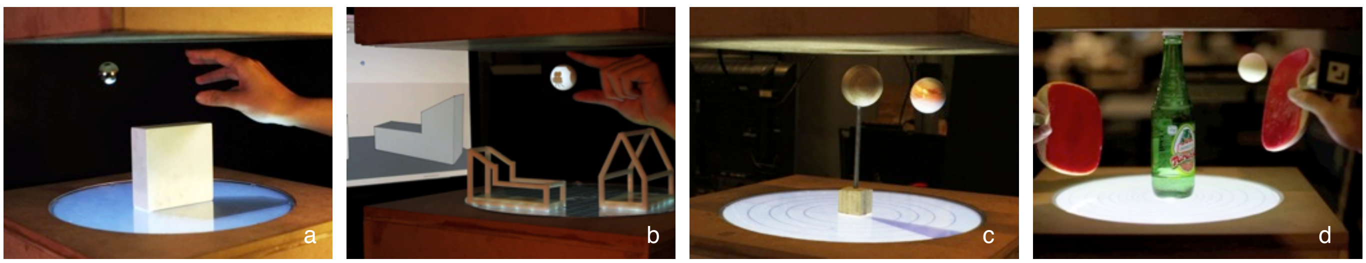

Figure 1. What if users could take a physical object off the surface and place it in the air? ZeroN enables such mid-air tangible interaction with computer controlled magnetic levitation. Various 3D applications can be redesigned with this interaction modality: a),b) architectural simulation, c) physics simulation, d) entertainment: tangible 3D pong-game.

ABSTRACT

This paper presents ZeroN, a new tangible interface element that can be levitated and moved freely by computer in a three dimensional space. ZeroN serves as a tangible representation of a 3D coordinate of the virtual world through which users can see, feel, and control computation. To accomplish this we developed a magnetic control system that can levitate and actuate a permanent magnet in a predefined 3D volume. This is combined with an optical tracking and display system that projects images on the levitating object. We present applications that explore this new interaction modality. Users are invited to place or move the ZeroN object just as they can place objects on surfaces. For example, users can place the sun above physical objects to cast digital shadows, or place a planet that will start revolving based on simulated physical conditions. We describe the technology, interaction scenarios and challenges, discuss initial observations, and outline future development.

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General terms: Design, Human Factors

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INTRODUCTION

Tangible interfaces attempt to bridge the gap between virtual and physical spaces by embodying the digital in the physical world [7]. Tabletop tangible interfaces have demonstrated a wide range of interaction possibilities and utilities. Despite their compelling qualities, tabletop tangible interfaces share a common constraint. Interaction with physical objects is inherently constrained to 2D planar surfaces due to gravity. This limitation might not appear to be a constraint for many tabletop interfaces, when content is mapped to surface components, but we argue that there are exciting possibilities enabled by supporting true 3D manipulation. There has been some movement in this direction already; researchers are starting to explore interactions with three-dimensional content using space above the tabletop surfaces [5][4]. In these scenarios input can be sensed in the 3D physical space, but the objects and rendered graphics are still bound to the surfaces.

Imagine a physical object that can float, seemingly unconstrained by gravity, and move freely in the air. What would it be like to leave this physical object at a spot in the air, representing a light that casts the virtual shadow of an architectural model, or a planet which will start orbiting. Our motivation is to create such a 3D space, where the computer can control the 3D position and movement of gravitationally unconstrained physical objects that represent digital information.

In this paper, we present a system for tangible interaction in mid-air 3D space. At its core, our goal is to allow users to take physical components of tabletop tangible interfaces off

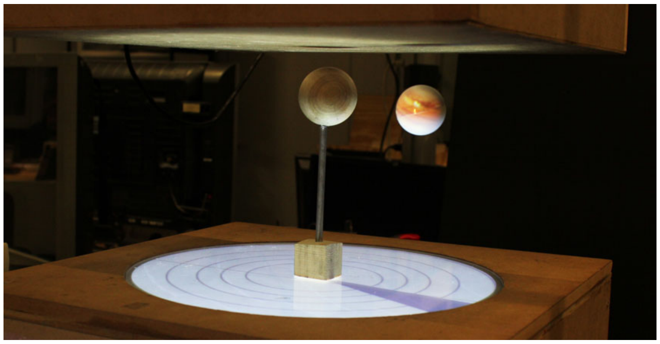

Figure 2. ZeroN can represent a 3D coordinate of the virtual world. Ex. displaying an orbit of a planet.

the surface and place them in the air. To investigate these interaction techniques, we created our first prototype with magnetic levitation technology. We call this new tangible interaction element ZeroN, a magnetically actuated object that can hover and move in an open volume, representing digital objects moving through 3D coordinates of the virtual world. Users can place or move this object in the air to simulate or affect the 3D computational process represented as actuation of the object as well as accompanied graphical projection.

We contribute a technical implementation of magnetic levitation. The technology includes stable long-range magnetic levitation combined with interactive projection, optical and magnetic sensing, and mechanical actuation that realizes a small 'anti-gravity space'. In the following sections, we describe our engineering approach and the current limitations as well as a road map of development necessary to scale the current interface.

We investigate novel interaction techniques through a set of applications we developed with ZeroN. Based on reflection from our user observation, we identify design issues and technical challenges unique to interaction with this untethered levitated object. In the following discussion, we will refer to the levitated object simply as *ZeroN* and the entire ensemble as the *ZeroN system*.

RELATED WORK

Our work draws upon the literature of Tangible Interfaces, 3D display and interaction techniques. As we touch upon the evolution of tabletop tangible interfaces, we review movements towards employing actuation and 3D space in human computer interaction.

Tabletop Tangible Interfaces

Underkoffler [22] and Patten [12] have shown how the collaborative manipulation of tangible input elements by multiple users can enhance task performance and creativity in spatial applications, such as architecture simulation and supply chain optimization. Reactable [9], AudioPad [13], or Datatiles [19] show compelling qualities of bimanual interaction in dynamically arranging visual and audio information.

In previous tabletop tangible interfaces, while users can provide input by manipulating physical objects, output occurs only through graphical projection. This can cause inconsistency between physical objects and digital information when the state of the underlying digital system changes. Adding actuation to an interface, such that states of physical objects are coupled with dynamically changing digital states will allow the computer to maintain consistency between the physical and digital states of objects.

In Actuated Workbench [11], an array of computer-controlled electromagnets actuates physical objects on the surface, which represent the dynamic status of computation. Planar Manipulator [20] or Augmented Coliseum [21] achieved similar technical capabilities using robotic modules. Recent examples of such actuated tabletop interfaces include madget, a system that has the capability of actuating complex tangibles composed of multiple parts [23]. Patten's PICO [14] has demonstrated how physical actuation can enable users to improvise mechanical constraints to add computational constraint in the system.

Going Higher

One approach to the transition of 2D modalities to 3D has been using deformable surfaces as input and output. Illuminating Clay employs deformable physical material as a medium of input where users can directly manipulate the state of the system [15]. In Lumino, stackable tangible pucks are used to express discrete height as another input modality [1].

While in this system the computer cannot modify physical representation, there has been research in adding height as another output component to RGB pixels using computer-controlled actuation. Poupyrev, et.al provide an excellent overview of shape displays [18]. To actuate deformable surfaces, Lumen [17] and FEELEX [8] employ an array of motorized sticks that can be raised. Art+com's kinetic sculpture actuates multiple spheres tethered with string to create the silhouette of cars [24]. Despite their compelling qualities as shape display, they share two common limitations as interfaces. First, input is limited by the push and pull of objects, whereas more degrees of freedom of input may be desired in many applications; users might also want to push or drag the displayed object laterally. More importantly, because the objects are physically tethered, it is difficult for users to reach under or above the deformable surface in the interactive space.

Using Space above the Tabletop surface

Hilliges and et al. show that 3D mid-air input can be used to manipulate virtual objects on a tabletop surface using the second-light infrastructure [5]. Grossman et.al introduced interaction techniques with 3D volumetric display [3]. While they demonstrate a potential approach of exploiting real 3D space as an input area, the separation of a user's input from the rendered graphics does not afford direct control as in the physical world, and may lead to ambiguities in the interface. A remedy for this issue of I/O inconsistency may come from technologies that display free-standing volumetric images, such as digital holography. However these technologies are not yet mature, and even when they can be fully implemented, direct manipulation of these media would be challenging due to lack of a persistent tangible representation.

Haptic and Magnetic Technologies for 3D Interaction

Studies with haptic devices, such as Phantom, have shown that accurate force feedback can increase task performance in the context of medical training and 3D modeling [10]. While most of these systems were used with a single monitor or head-mounted display, Plesniak's system lets users directly touch a 3D holographic display to obtain input and output coincidences [16]. Despite their compelling practical qualities, tethered devices constrain the degree of freedom in user input. In addition, constraining the view angle often isolates the user from real world context and restricts multi-user scenarios.

Magnetic levitation has been researched in the realms of haptic interfaces [2] and robotics [6] to achieve increased degrees of freedom. Berkelman and et al. developed a high-performance magnetic levitation haptic interfaces to enable the user to better interact with simulated virtual environments [2]. Since their system was designed to be used as a haptic controller of graphical displays, the emphasis was on creating accurate force feedback with a stable magnetic field in a semi-enclosed hemispherical space. On the other hand, our focus was on achieving a collocated I/O by actuating an I/O object along the 3D paths through absolute coordinates of the physical space. Consequently, more engineering efforts were made to actuate a levitated object in an open 3D space in a reasonably stable manner.

3D and Tangible Interaction

Grossman and Wigdor present an excellent taxonomy and framework of 3D tabletop interfaces based on the dimensions of display and input space [4]. Our work aims to explore a realm where both display and input occur in 3D space, mediated by a computer-controlled tangible object, and therefore enabling users' direct manipulation. In the taxonomy [4], physical proxy was considered an important 2D I/O element that defines user interaction. However, our work employs a tangible proxy as an active display component to convey 3D information. Therefore, to fully understand the implication of the work, it is necessary to create a new framework based on spatial properties of physical proxies in tabletop interfaces. We plotted existing tabletop interfaces in figure 3 based on the dimension of the I/O space and whether the tangible elements can be actuated.

Our paper explores this novel design space of tangible interaction in the mid-air space above the surface. While currently limited in resolution and practical quality, we look to study what is possible by using mid-air 3D space for tangible interaction. We aim to create a system where users can interact with 3D information through manipulating computationally controlled physical objects, without physical

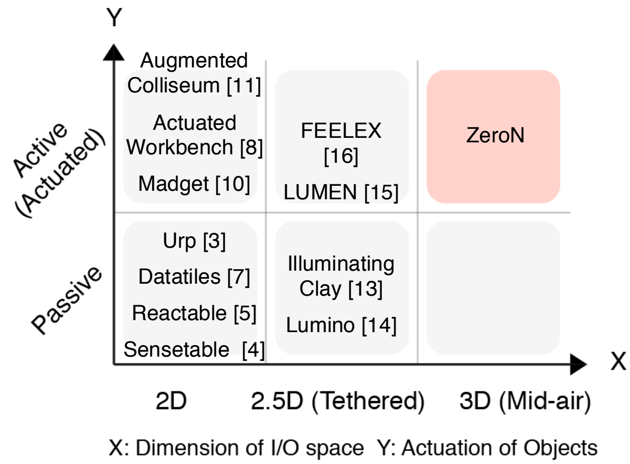

Figure 2. A framework for tabletop tangible interfaces based on the dimension of I/O space and actuation

tethering by mechanical armatures or requiring users to wear an optical device such as a head-mounted display.

OVERVIEW

Our system operates over a volume of 38cm x 38cm x 9cm, in which it can levitate, sense, and control the 3D position of the ZeroN, a spherical magnet with a 3.17cm diameter covered with plastic shell onto which digital imagery can be projected. As a result, the digital information bound with a physical object can be seen, felt, and manipulated in the operating volume without requiring users to be tethered by mechanical armatures or to wear optical devices. Due to the current limitation of the levitation range, we made the entire interactive space is larger than this 'anti-gravity' space, such that users can interact with ZeroN with reasonable freedom of movement.

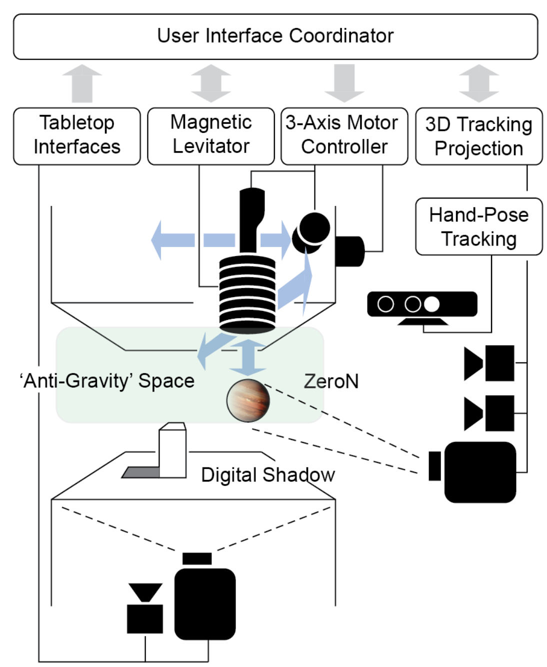

Figure 4. Overview of the ZeroN System

TECHNICAL IMPLEMENTATION

The current prototype comprises five key elements as illustrated in figure 4.

- A magnetic levitator (a coil driven by PWM signals) that suspends a magnetic object and is capable of changing the object's vertical suspension distance on command.
- A 2-axis linear actuation stage that laterally positions the magnetic levitator and one additional linear actuator for moving the coil vertically.
- Stereo cameras that track ZeroN's 3D position.
- A depth camera to detect users' hand poses.
- A tabletop interface displaying a scene coordinated with the position of the suspended object and other objects placed on the table.

Untethered 3D Actuation

The ZeroN system implements untethered 3D actuation of a physical object with magnetic control and mechanical actuation. Vertical motion was achieved by combining magnetic position control which can levitate and move a magnet relative to the coil, and mechanical actuation that can move the entire coil relative to the entire system. Two approaches complement each other. Although the magnetic approach can control the position with lower latency and implies promising direction for scalable magnetic propulsion technology, the prototype with pure magnetic controls demonstrated limits in its range: when the permanent magnet gets too close to the coil it becomes attached to the coil even when the coil is not energized. 2D lateral motion was achieved with a plotter using two stepper motors. Given a 3D path as input, the system first projects the path on each dimension, and linearly interpolates the dots to create a smooth trajectory. Then the system calculates velocity and acceleration of each axis of actuation as a function of time. With this data, the system can actuate the object along a 3D path approximately identical to the input path.

Magnetic Levitation and Vertical Control

We have developed a custom electromagnetic suspension system to provide robust sensing, levitation, and vertical control. It includes a microcontroller implementing a proportional-integral-derivative (PID) control loop with parameters that can be set through a serial interface. In particular, ZeroN's suspension distance is set through this interface by the UI coordinator. The PID controller drives the electromagnet through a coil driver using pulse-width modulation (PWM). The field generated by the electromagnet imposes an attractive (or repulsive) force on the suspended magnetic object. By dynamically canceling gravity by exerting a magnetic force on ZeroN, the control loop keeps it suspended at a given distance from the electromagnet. This distance is determined by measuring the magnetic field immediately beneath the solenoid.

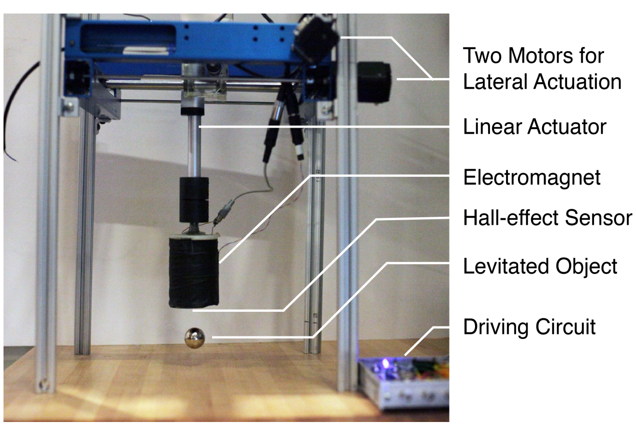

Figure 5. Mechanical actuation combined with magnetic vertical control enables 3D untethered actuation of an object.

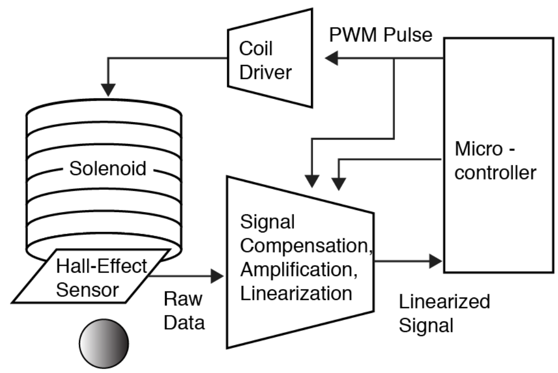

Figure 6. A simplified version of the magnetic range sensing and levitation circuits.

Magnetic Range Sensing with Hall-effect sensor

Properly measuring the distance of a magnet is the key component in stable levitation and vertical control. Since the magnetic field drops off as the cube of the distance from the source, it is challenging to convert the strength of the magnetic field to the vertical position of a magnet. To linearize signals sensed by the hall-effect sensor, we developed the two-step gain logarithmic amplifier. It logarithmically amplifies the signal with two different gains, based on whether the signal exceeded a threshold voltage value.

Designing ZeroN Object

We used a spherical dipole magnet as a levitating object. Due to the geometry of magnetic field, users can move the spherical dipole magnet while still keeping it suspended, but it falls when they tilt it. To enable input of a user's desired orientation, a loose plastic layer is added to cover the magnet as illustrated in figure 7.

Stereo Tracking of 3D position and 1D orientation

We used two modified Sony PS3Eyecams[1] to track the 3D position of ZeroN using computer vision techniques with a pair of infrared images as in figure 8. To measure orientation, we applied a stripe of retro-reflective tape to the surface of ZeroN. We chose this approach because it was both technically simple and robust, and didn't add significant weight to ZeroN: an important factor in a levitating object.

[1] http://codelaboratories.com/products/eye/sdk/

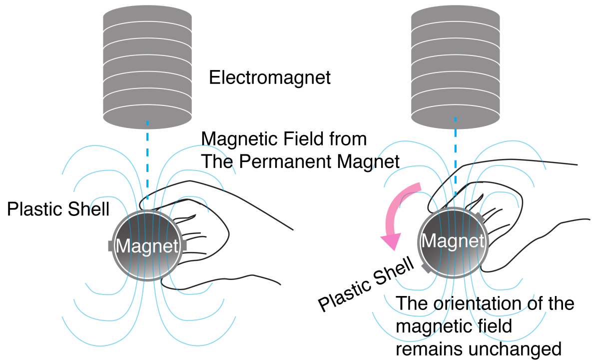

Figure 7. ZeroN Object comprises a permanent magnet loosely covered with a plastic shell. Users can tilt the shell without changing the orientation of the levitated magnet.

Determining Modes

A challenge in emulating the 'anti-gravity space' is to determine if ZeroN is being moved by a user, or is naturally wobbling. Currently, ZeroN sways laterally when actuated, and the system can misinterpret this movement for user input and continue to update a new stable point of suspension. This causes ZeroN to drift around. To resolve this issue, we classify three modes of operation (idle, grabbed, grabbed for long) based on whether, and for how long, the user is holding the object. In the idle mode, when ZeroN is not grabbed by the user, the control system acts to keep the position or trajectory of the levitating object as programmed by the computer. When grabbed by the user, the system updates the stable position based on the current position specified by the users, such that the users can release their hands without dropping the object. If the user is grabbing the object for longer than 2.5s, it starts specific functions such as record and play back.

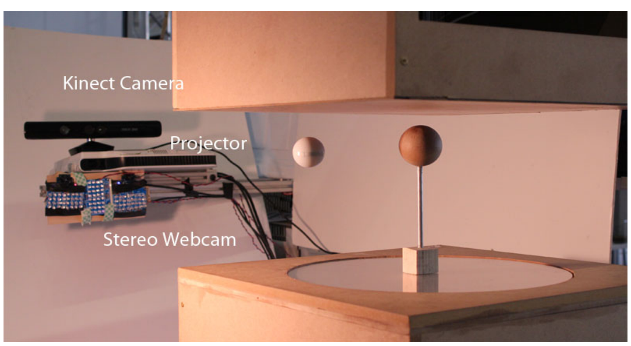

Figure 8. Tracking and Projection System of ZeroN.

While stereo IR cameras were useful in obtaining the accurate position and orientation of the object using retro-reflective tape, it was challenging to distinguish users' hands from background or objects. We chose to use an additional depth camera Microsoft Kinect to detect the user's hand pose with computer vision techniques built on top of

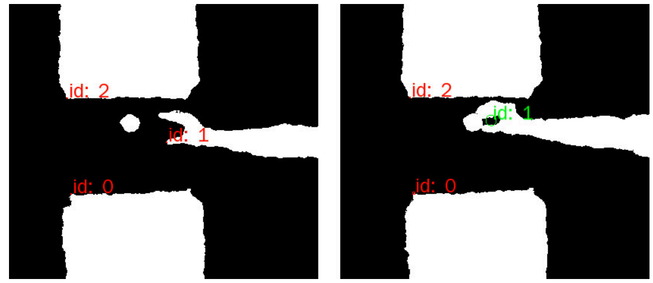

Figure 9. Kinect camera can be used to sense if the user is holding the levitated object or not.

open-source libraries[2]. Our software extracts binary contours of objects at a predefined depth range and finds the blob created between the user's hands and the levitated object.

Calibration of 3D Sensing, Projection, and Actuation

To ensure real time interaction, careful calibration between cameras, projectors and 3D actuation system is essential in our implementation. After finding correspondence between two cameras with checkerboard patterns, we register cameras with the coordinate of interactive space. We position the ZeroN object at each of these fixed four non-coplanar points. Similarly, to register each projector to real-world coordinates, we match the ZeroN positioned at the four non-coplanar calibration points and move a projected image of a circle towards the ZeroN. When the circular image is overlaid on the ZeroN, we increase or decrease the size of the circle image so that it matches the size of ZeroN. This data is used to find two homogenous matrices that transform raw camera coordinates to real world coordinates of the interactive space, and the real coordinates to x, y position and the diameter of the circle. We have not made much effort to optimally determine the focal plane of the projected image - focusing the projectors roughly in the middle of the interactive space is sufficient.

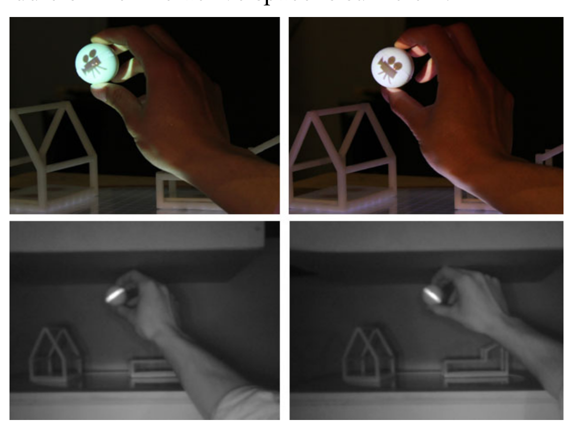

Figure 10. As the user tilts the outer plastic layer, the system senses the orientation and updates the projected images, while the spherical magnet stays in the same orientation.

[2] https://github.com/ofTheo/ofxKinect

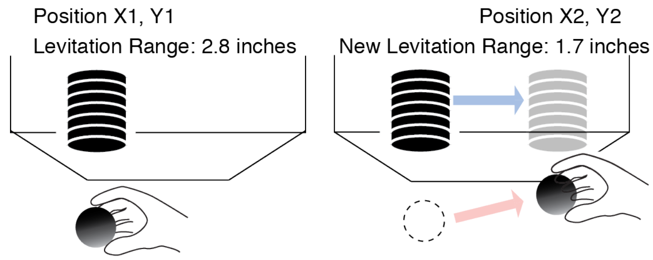

Figure 11. The system can update the stable point of suspension when the user moves the ZeroN to another position.

Engineering 'Anti-Gravity' Space

These various sensing and actuation techniques coordinate to create a seamless 'anti-gravity' I/O space. When the user grabs the ZeroN and places it within the defined space of the system, the system tracks the 3D position of the object, and determines if the user's hand is grabbing ZeroN. The electromagnet is then carried to the 2D position of ZeroN by the 2-axis actuators, and is programmed to reset a new stable point of suspension at a sensed vertical position. As a result, this system creates what we will call a small 'anti-gravity' space, wherein people can place an object in a volume seemingly unconstrained by gravity. The user's hands and other non-magnetic materials do not affect levitation.

Since the levitation controller acts to keep the floating object at a given height, users experience the sensation of an invisible but very tangible mechanical connection between the levitated magnet and a fixed point in space that can be continually updated.

3D POINT AND PATH DISPLAY

ZeroN serves as a dynamic tangible representation of a 3D coordinate, without being tethered by mechanical armature. 3D Position of ZeroN may be updated upon computer commands to present dynamic movements or curved lines in the 3D space such as flight paths of the airplane or orbits of planets. Graphical images or icons may be projected upon the white surface of ZeroN levitating, such as a camera or the pattern of a planet. These graphical images can be animated or 'tilted' to display change of orientation. This complements the limitation of current magnetic actuation system that can only control the 3D position of a magnet, but has little control on its orientation.

INTERACTION

We have developed a 3D, tangible interaction language that closely resembles how people interact with physical objects on a 2D surface – put, move, rotate, and drag, which now serves as a standard metaphor, widely used in many interaction design domains including GUIs and tabletop interfaces. We list the vocabulary of our interaction language (figure 12).

Place

One can place ZeroN in the air, suspending it at an arbitrary 3D position within the interactive space.

Translate

Users can also move ZeroN to another position in the anti-gravity space, without disturbing its ability to levitate.

Rotate

When users rotate the plastic shell covering the spherical magnet, digital images projected on the ZeroN will rotate accordingly.

Hold

Users can hold or block ZeroN to impede computer actuation. This can be interpreted as computational constraint as also shown in PICO [14].

Long Hold

We implemented a long-hold gesture that can be used to initiate a specific function. For example, in a video recording application, we might have an interaction where users could hold the ZeroN for longer than 2.5 seconds to initiate recording, and release to enter "play-back" mode.

Attaching / Detaching Digital Information to the ZeroN

We borrowed a gesture for attaching / detaching digital items to tabletop interfaces [12] It is challenging to interact with multiple information clusters, since the current system can only levitate one object. For instance, in the application of urban planning simulation [22], users might first want to use ZeroN as the Sun to control lighting, and then as a camera to render the scene. Users can attach ZeroN to a digital item projected on the tabletop surface on the ground, just by moving the ZeroN close to the digital item to be bind with. To unbind a digital item from a ZeroN, users can use shaking gestures or remove the ZeroN from the interactive space.

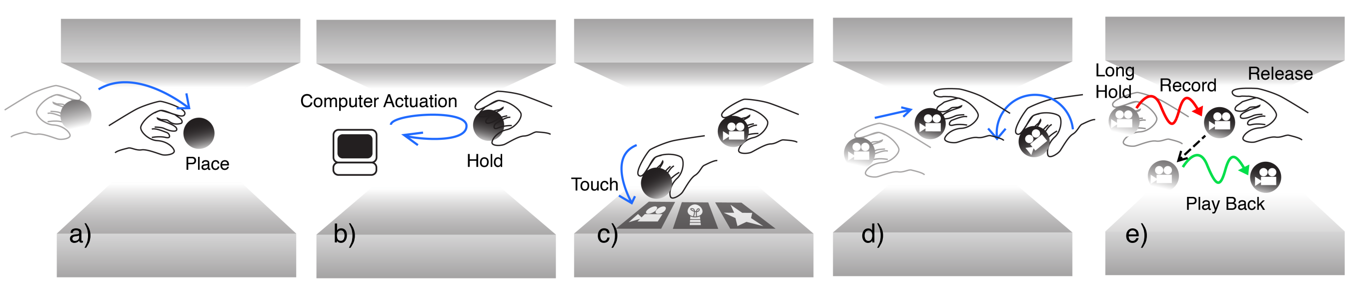

Figure 12: ZeroN introduces a novel interaction language: (a) Users places ZeroN in the air; (b) the computer actuates ZeroN and users intervene with the movement of ZeroN; (c) digital item attached to ZeroN; (d) ZeroN translated and rotated in the air; (e) long hold used to record and play back.

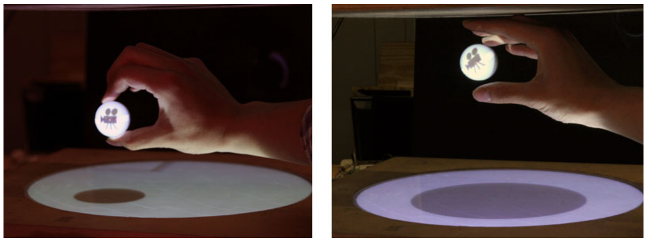

Figure 13. The size of digital shadow is mapped to the height of ZeroN.

Interaction with Digital Shadows

We aim to seamlessly incorporate ZeroN into existing tabletop tangible interfaces. One of the challenges is to provide users with a semantic link between the levitated object and tabletop tangible interfaces on the 2D surface. Since ZeroN is not physically in contact with the tabletop system, it is hard to recognize the relative position of the ZeroN to the other objects placed on the ground. We designed an interactive digital shadow to provide users with visible links between ZeroN and other part of the tabletop tangible interfaces. For instance, levitating ZeroN itself can cast its digital shadow whose size is mapped to the height of the object (see figure 13). For the time being, however, this feature is not yet incorporated in the application scenarios.

APPLICATIONS AND USER REFLECTION

We explore the previously described interaction techniques in context of several categories of applications described below. While the physics and architecture simulation allows users to begin using ZeroN to address a practical problem, the prototyping animation and Zero-pong applications are proof of concepts to demonstrate the interactions one might have with ZeroN.

Physics Simulation and Education

ZeroN can serve as a tangible physics simulator by displaying and actuating physical objects under computationally controlled physical conditions. As a result, dynamic computer simulation can turn into tangible reality, which had previously been possible only in the virtual world. More importantly, users can interrupt or affect the simulation process by blocking actuation with their hands or by introducing other physical objects in the ZeroN space.

Understanding Kepler's Law

In this application, users can simulate a planet's movement in the solar system by placing at the simulation's center, a static object that represents the center of mass as the Sun, around which the ZeroN will revolve like a planet. Users can change the distance between the Sun and the planet, which will make the ZeroN snap to another orbit. Resulting changes can be observed and felt in motion and speed. Digital projection shows the area that a line joining a ZeroN and the Sun sweeps out during a certain period of time, confirming Kepler's 2nd law (see figure 15).

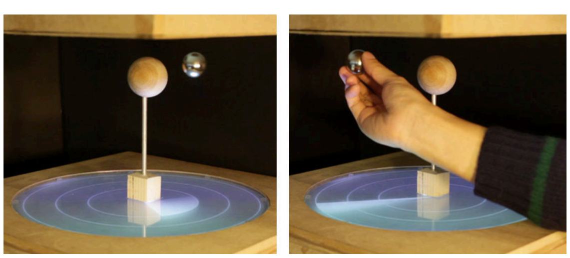

Figure 14. A user is changing the orbit of the ZeroN.

Three-Body Problem

In this application, users can generate a gravity field by introducing multiple passive objects that represent fixed centers of gravity. A placed ZeroN next to the object will orbit around based on the result of the 3–body simulation. Users can add or change the gravitational field by simply placing more passive objects, which can be identified by a tabletop interface setup (see figure 15).

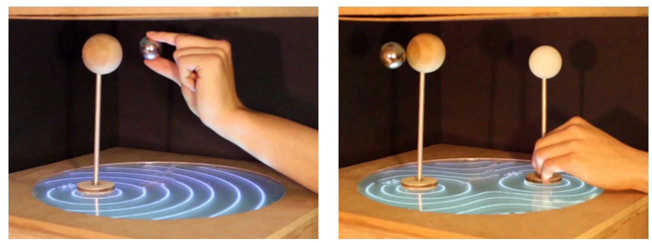

Figure 15. Visualizing 3-body problem.

Architectural Planning

While there has been much research exploring tangible interfaces in the space of architectural planning, some of the essential components, such as lights or cameras, cannot be represented as a tangible object that can be directly manipulated. For instance, Urp system [22] allows users to directly control the arrangement of physical buildings, but lighting can only be controlled by rotating a separate time-dial. While it is not our goal to stress that direct manipulation outperforms indirect manipulation, there are certainly various scenarios where having direct manipulation of tangible representation is important. We developed two applications for gathering users' feedback.

Lighting Control

We developed an application for controlling external architectural lighting in which users can grab and place a Sun in the air to control the digital shadow cast by physical models

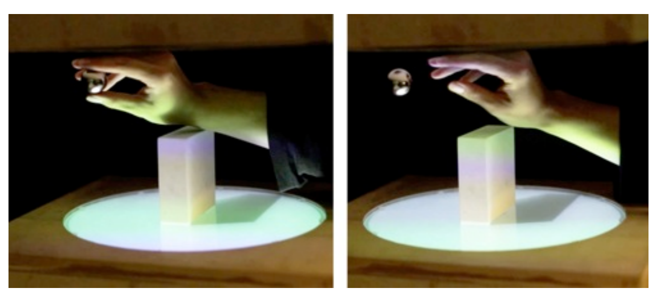

Figure 16. Users can place the Sun above physical models to cast its digital shadow.

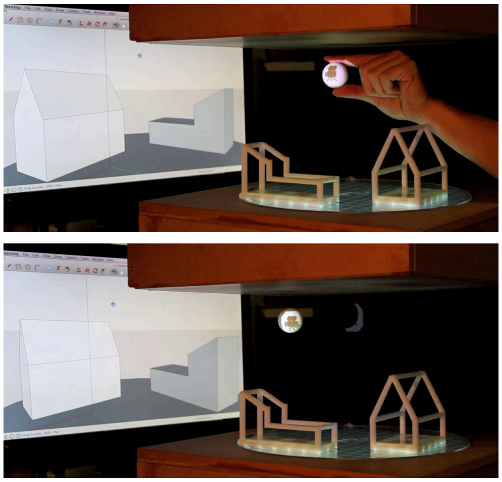

Figure 17. The user can create and edit 3D camera paths above the physical model and see the camera flying along the path.

on the tabletop surface. The computer can simulate changes in the position of the lighting, such as chances over the day, and the representative Sun will be actuated to reflect these changes.

Camera Path Control

Users can create 3D camera paths for rendering virtual scenes using ZeroN as a camera. Attaching ZeroN to the camera icon displayed on the surface turns the sun into a camera object. Users can then hold the ZeroN for a number of seconds in one position to initiate a recording interaction. When users draw a 3D path in the air and release the ZeroN, the camera is sent back to initial position and then moved along the previously recorded 3D trajectory. On an additional screen, users can see the virtual scene of their model taken by the camera's perspective in real time. If the user wants to edit this path, they can intervene with the camera's path and start from the exact current position of the camera to redraw another path.

3D Motion Prototyping

Creating and editing 3D motion for animation is a long and complex process with conventional interfaces, requiring expert knowledge of the software, even for simple prototyping. With record and play-back interaction, users can easily prototype the 3D movement of an object and watch it playing back in the real world. The motion can possibly be mapped to a 3D digital character moving accordingly on the screen with dynamic virtual environments. As a result, users can not only see, but also feel the 3D motion of the object they created. They can go through this interaction through a simple series of gestures; long-hold and release.

Entertainment: Tangible 3D Pong in the physical space

Being able to arbitrarily program the movement of a physical object, ZeroN can be used for digital entertainment. We partially implemented and demonstrated a Tangible 3D Pong application with ZeroN as a pingpong ball. In this scenario, users can play computer-enhanced pong game with a floating ball whose physical behavior is computationally programmed. Users can hit or block the movement of ZeroN to change the trajectory of the ping-pong ball. They can add computational constraints in this game by placing a physical object in this interactive space as in figure 18. While this partially implemented application demonstrates interesting challenges, it suggests a new potential infrastructure for computer entertainment, where human and computation embodied in the motion of physical objects are in the tight loop of interaction.

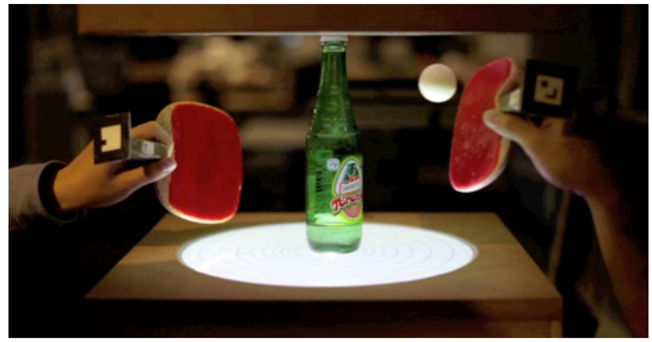

Figure 18. Tangible Pong in the physical space.

INITIAL REFLECTION AND DISCUSSION

We demonstrated our prototype to users to gather initial feedback and recruited several participants to try out each application. The purpose of this study was to evaluate our design, rather than to exemplify the practicality of each application. We further discuss several interesting unique issues that we discovered through this observation.

Leaving a Physical Object in the Air

In the camera path control application, users appreciated the fact that they could leave a physical camera object in the air and review and edit the trajectory in a tangible way. There were commented that latency in the electromagnet's stability update (between users' displacement and the electromagnet's update of the stable position) creates confusion. In the lighting control application, a user commented that they could better discuss with a collaborator using a system that enables the object to be held in a position in the air. Many of participants also pointed out the issue of lateral oscillation, which we are working to improve.

Interaction Legibility

In the physics education application, a several users commented that not being able to see physical relationship between 'planets' make them harder to expect how to interact with this system, or what would happen if they touch and move the parts. Being able to actuate an object without mechanical linkages in free space allows a more degrees of freedom of movements and allows access from all orientations. On the other hand, this decreases the legibility of interaction by making the mechanical linkages invisible. In contrast a historical orrery (figure 19) machine where the movement of 'planets' are constrained by its mechanical connections, users can immediately understand the freedom of movement that the mechanical structure affords.

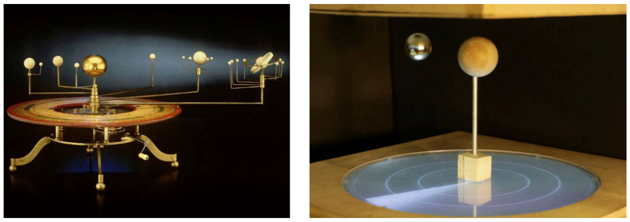

Figure 19. Physical orrery and ZeroN: hiding mechanical structures increases degrees of freedom, but decreases legibility of interaction.

One of the possible solutions to compensate this loss of legibility is to rely on graphical projection or subtle movements of the objects to indicate the constraints of the movement. Carefully choosing an application where the gain of freedom outweighs the loss of legibility was our criteria for choosing application scenarios.

TECHNICAL EVALUATION

Maximum Levitation Range

The maximum range of magnetic levitation is limited by several factors. While our circuits can handle higher currents than currently used, an increased maximum range is limited by the heat generated in the coils. We used a 24V power supply, from which we drew 2A. Above that power, the heat generated by the electromagnet begins to melt its form core. The current prototype can levitate up to 7.4 cm measured from the bottom of the hall-effect sensor to the center of our spherical magnet. To scale up the system, a cooling system needs to be added on top of the coil.

Speed of actuation

The motor used in the system can carry the electromagnet with a maximum velocity of 30.5cm/s and top acceleration of $6.1 m/s^2$. The dynamic response of ZeroN's inertia is the main limit on acceleration. Because of the response properties of this second-order system (e.g. the electromagnet and ZeroN), larger accelerations fail to overcome ZeroN's inertia and would lead to ZeroN being dropped. The result of experiments measuring maximum intertia shows $3.9 m/s^2$ of the lateral acceleration can drop the ZeroN.

Resolution and Oscillation

If we frame our system as a 3D volumetric (physical) display in which only one cluster of voxels can be turned on at a time, we need to define the resolution of the system. Our 2D linear actuators can position the electromagnet at 250,000 different positions on each axis, and there is also no theoretical limit to the resolution of vertical control. However, vertical and horizontal oscillation of the levitated object makes it difficult to define this as the true system resolution. In the current prototype, ZeroN oscillates within 1.4 cm horizontally and 0.2 cm vertically around the set position when moved. We call the regions swept by oscillation "blurry" with "focused" area at its center.

Robustness of Magnetic Levitation

Robust levitation is a key factor for providing users with the sensation of an invisible mechanical connection with a fixed point in the air. We have conducted a series of experiments to measure how much strength can be posed on ZeroN without displacing it from a stable point of suspension. For these experiments, we attached the levitated magnet to a linear spring scale that can measure up to 1.2N of weight and pulled it towards the direction of 0° (horizontal), 15° 30°, 45°, 60°, 75°, and 90° (vertical). The average of 5 times' measurements is plotted in figure 20.

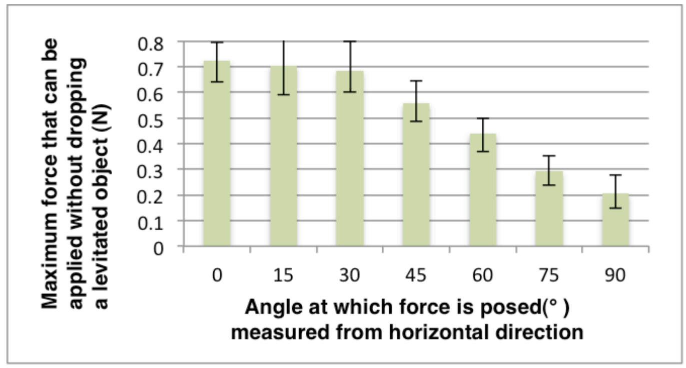

Figure 20. The system can update the stable point of suspension when users move the ZeroN to another position.

TECHNICAL LIMITATION AND FUTURE WORK

Lateral oscillation was reported as the biggest issue to correct in our application scenarios. We plan to implement satellite coils around the main electromagnet that can impose a magnetic force in a lateral direction to eliminate lateral wiggling and provide better haptic feedback. Another limitation with the current prototype is the limited vertical actuation range. This can be addressed by carefully designing the magnetic controller with better range sensing capabilities and choosing a geometry for the electromagnet that increases the range without overheating the coil.

A desirable extension is to use magnetic sensing technology with an array of hall-effect sensors in 3D tracking which would have provided more robust and low-latency object tracking without occlusion. We encountered difficulties using hall-effect sensor arrays in conjunction with our magnetic levitation system because of the strong magnetic field distortions caused by our electromagnets. We believe that this problem can be overcome in the future by subtracting magnetic field generated by electromagnets through precise calibration of dynamic magnetic field. But to avoid these difficulties in the short term, we added a vision tracking to our system prototype despite that this limits the hand input to areas that do not occlude the view of the camera.

Levitating Multiple Objects

While the current research was focused on identifying challenges in interacting with one levitated object, it is natural to imagine interaction with multiple objects in mid-air. A scalable solution will be using an array of solenoids. Under such setup, a magnet can be positioned at or moved to an arbitrary position between the centers of two or more solenoids by passing the necessary amount of current to each solenoid. It is analogous to pulling and hanging a ball with multiple invisible magnetic strings connected to the center of solenoids. However, it will be challenging to position two or more magnets within a small proximity due to magnetic field interference, or to position them on similar x, y coordinates. One approach to tackle this issue might come from levitating switchable magnets, turning them on and off to time-multiplex the influence that each object receives from the solenoids. We would like to leave this concept for future research.

CONCLUSION

This paper presents the concept of 3D mid-air tangible interaction. To explore this concept, we developed a magnetic control system that can levitate and actuate a permanent magnet in a three dimensional space, combined with an optical tracking and display system that projects images on the levitating object. We extend interaction scenarios that were constrained to 2D tabletop interaction to mid-air space, and developed novel interaction techniques. Raising tabletop tangible interfaces to 3D space above the surface opens up many opportunities and leaves many interaction design challenges. The focus of the paper is to explore these interaction modalities and although the current applications demonstrate many challenges, we are encouraged by what is enabled by the current system and will continue to develop scalable mid-air tangible interfaces.

We also envision that ZeroN could be extended for the manipulation of holographic displays. When 3D display technologies mature in the future, levitated objects can be directly coupled with holographic images projected in the air. We believe that ZeroN is the beginning of an exploration of this space within the larger field of future interaction design. One could imagine interfaces where discrete objects become like 3D pixels, allowing users to create and manipulate forms with their hands.

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