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

by

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School of Architecture and Planning,
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Abstract

This thesis presents a concept of mid-air tangible interaction and a system called ZeroN that was developed to enable this interaction. Through this research, I extend the tabletop tangible interaction modalities which have been confined to 2D surfaces into 3D space above the surface. Users are invited to place and move a levitated object in the mid-air space, which is analogous to placing objects on 2D surfaces. For example, users can place a physical object that represents the sun above physical objects to cast digital shadows, or place a planet that will start revolving based on simulated physical conditions.

To achieve these interaction scenarios, we developed ZeroN, a new tangible interface element that can be levitated and moved freely by computer in a three dimensional space. In doing so, ZeroN serves as a tangible representation of a 3D coordinate of the virtual world through which users can see, feel, and control computation. Our technological development includes a magnetic and mechanical control system that can levitate and actuate a permanent magnet in 3D space. This is combined with an optical tracking and display system that projects images on the levitating object. In this thesis, I present interaction techniques and applications developed in the context of this system. Finally, I discuss initial observations and implications, and outline future development and challenges.

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The following people served as readers for this thesis:

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Chapter 1

Introduction

"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked."

'Ultimate Display', Ivan Sutherland, 1965 [26]

1.1 Journey to the Ultimate Display

The development of computer graphics has made it possible for computers to render scenes free from the constraints of the physical world, visualizing a range of computer simulations. While this has greatly enhanced the scope of human-computer interactions based on visual experiences, we are still far from realizing the 'ultimate display' illustrated in Sutherland's article [Sutherland]: full sensory experience of virtual environments such that people can feel the existence of digital information. Despite the efforts of researchers to broaden the channels of communication between the physical world and cyberspace, Graphical User Interfaces (GUIs) that rely on mice and screens have been the dominant HCI paradigm for the last several decades. GUIs allow users to manipulate graphical representations of abstract data with simple metaphors and present many scalable models for HCI. However, they fall short in embracing the rich interaction modalities between people and the physical environment [8].

The concept of tangible interfaces has appeared as a solution to bridge the gap between the physical environment and the digital representation of information [8]. In tangible interfaces, physical objects represent digital information such that users can manipulate digital media by controlling those objects. The objects are treated as physical embodiments of digital information: users alter the digital state of data by moving or modifying the objects. TUIs have demonstrated compelling applications in many domains such as design, optimization, learning and creative activities by taking advantage of physical affordances of objects.

1.2 Motivation

Constraints of these tangible interfaces come from the very properties that make them compelling: physical properties. Unlike weightless pixels, behaviors of physical objects are pre-programmed by gravity. Governed by newtonian physics, they inherently 'fall' and 'stay at rest' on the surface. Therefore, the data that tangible objects can represent are limited to surfaces on which they lie. This might not appear to be a constraint for many tabletop interfaces when contents are mapped to surface components. However, I believe there is an exciting potential in re-inventing physical objects to make them stay mid-air to represent 3D information.

Imagine a physical object that can float through the air, seemingly unconstrained by gravity. What would it be like to take a physical object off the surface and place it at a spot in the air, representing a light that casts the virtual shadow of an architectural model? What would it be like to simulate how planets move by simply placing a physical object that can float and move freely? My motivation is to create such a 3D space, where the computer can control the position and movements of physical objects that represent digital information, unconstrained by gravity.

This thesis presents the interaction with such a physical object levitated in mid-air space and the technological development of such anti-gravity space. I call it mid-air tangible user interaction. Conceptually, the goal of the research is to allow users to take physical components of a tangible system off the surface and place them in the air, enabling tangible interaction with 3D information.

1.3 Thesis Goal and Outline

This thesis attempts to develop the concept of Mid-air Tangible Interaction in two complementary respects. First, the thesis develops interface models for Mid-air Tangible Interaction: design solutions by which a levitated object moved freely by computer may be used to interact with 3D information. Second, this thesis describes the design and development of our prototype ZeroN, a system that embodies Mid-air Tangible Interaction by being able to levitate and move a physical object in 3D space. This system includes a hardware and software infrastructure for a computer to magnetically levitate and position a physical object in mid air, and to sense the users' manipulation of the object.

I will first situate this research in the context of supporting theory and past related work,

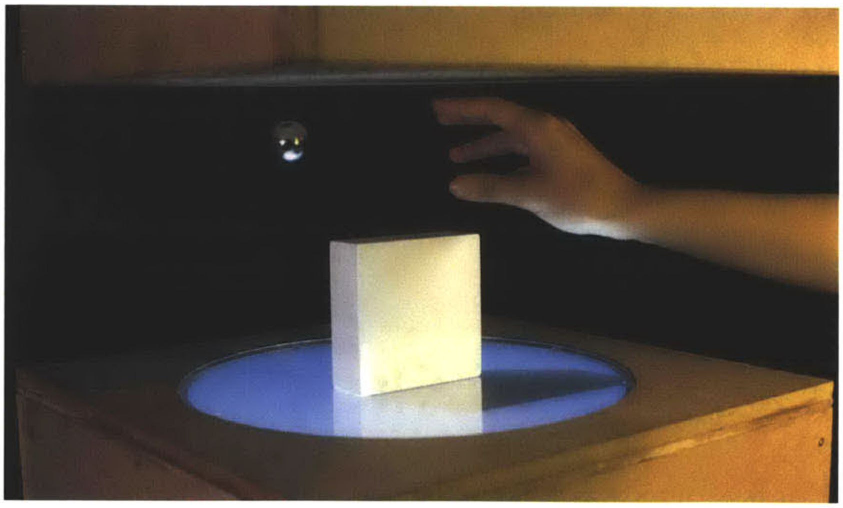


Figure 1-1: A levitated object can represent a 3D coordinate of the virtual world. A user is placing the object that represents the sun in mid air casting the virtual shadow of a block.

discuss the evolution of the concept of mid-air tangible interaction, and the variety of hardware and software design decisions involved in the construction of our prototype system ZeroN.

In the rest of the chapter I describe the underlying technology of the ZeroN system, and evaluate its performance in light of my design criteria, and describe the interaction language and application scenarios. Finally, I suggest future directions of design and technological development, and discuss the implications of mid-air tangible interaction

A significant portion of the engineering components, particularly magnetic levitation, were implemented in collaboration with Rehmi Post, a visiting scientist at the MIT Center for Bits and Atoms. The applications and conceptual frameworks were developed under the guidance of my advisor, Professor Hiroshi Ishii. Therefore, the pronoun we in this thesis refers to myself, Rehmi Post, and Professor Hiroshi Ishii, as this was a collaborative project throughout most of its technological development and design.

Chapter 2

Related Work

This thesis aims to push the envelope of tangible interfaces such that mid-air 3D space can be employed in the tangible interaction. It draws upon the literature of Tangible Interfaces, 3D display and interaction techniques and already assumes the important role of the psychological and practical benefits of tangible interfaces and motivation towards achieving 3D input and output. Therefore, this thesis does not go into great detail in discussing these areas. However, I will touch upon some key supporting principles and discuss how they can be used to argue the benefits of mid-air tangible interfaces. In the rest of the chapter, I discuss several related projects involving interactive tabletop surfaces, and movements towards employing actuation and 3D space in human computer interaction. Finally I discuss and compare various technologies for positioning a physical object in the 3D space.

2.1 Mind, Objects, Space, and Body

Tangible user interfaces find support in the psychology of 1) kinetics – the role of the physical actions of the human body, and 2) spatial reasoning – how people use space in thinking, in cognitive processes.

Zhang's research explores how the external representation of information affects problem solving [29]. He uses the term external representation to mean representing embedded abstract information in intuitively understandable forms such as shapes or objects. His series of experiments show that the physical properties of theses objects, such as shape, weight or size, severely affect task performances. Zhang particularly emphasizes the impact of the objects' affordances on problem solving.

Kirsch explores various ways that people use the space around them to think [10]. He argues that spatial arrangements of physical objects simplify users' perceptions and thought processes. Kirsch's experiments have shown that subjects who had a means of distributing a portion of computational tasks to tangible objects performed simple tasks with reduced error rates and shorter completion times.

Klemmer et al. provides an excellent summary of the roles of bodies in human cognition processes as well as their implications for designing user interfaces [11]. The studies show how body gestures help people to solve problems that they cannot easily solve merely through symbolic thinking. A variety of researchers have particularly recognized that the ability to use two hands while interacting with an interface can lead to significant performance improvements.

Such research supports both the practical and psychological benefits of utilizing tangible interfaces. They motivate and guide the design of our system based on the assumption that the principles are applicable to mid-air tangible interaction.

2.2 Tabletop Tangible Interfaces

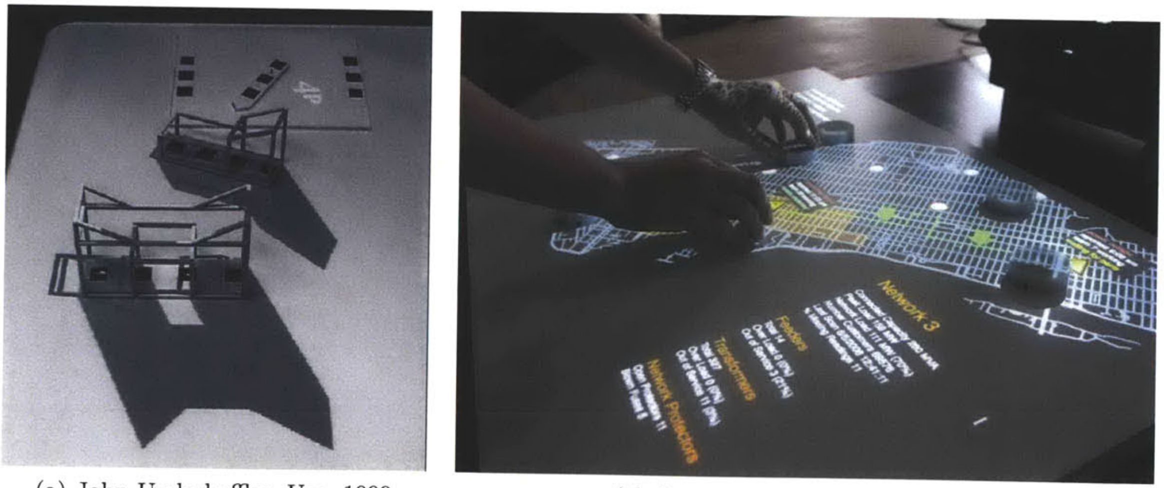
Among many, the most durable and scalable class of tangible interface systems has been tabletop tangible interfaces. Such systems track the position and movement of physical objects on a surface and respond to users' physical manipulation of these objects with graphical output. The objects are treated as physical embodiments of digital information: users can adjust the digital state of a data item by moving or rotating the objects.

2.2.1 Urp: Early Tabletop Tangible Interface

Underkoffler has studied how the collaborative manipulation of tangible input elements can enhance task performance in architectural planning [27] [27]. In his URP project, physical models of buildings cast digital shadows, which are graphical projections around the model. The position and orientation of the models are sensed by the system, changing visualization of light and wind around the buildings in real time. Through controlling tangible objects, the user can control computer simulations.

In Urp, while physical models allow the user to directly specify the position of the buildings, the user needs to rotate a physical time-dial to indirectly control lighting of the environments. However, the trajectory of the sun varies by regions and changes over time. In this case, a person may desire to take a physical object that may represent a light source and place it on a desired spot, relying on their spatial memory of where the sun or a light source was located. This motivates us to look into the potential of utilizing mid-air space in tangible interaction.

As in Urp, early research in tangible interfaces has attempted to use objects that have



(a) John Underkoffler, Urp, 1999

(b) James Patten, Sensetable, 2002

Figure 2-1: In tabletop Interfaces, physical objects represent digital information, coupled with graphical projection. The system tracks the position and movement of physical objects on a surface and changes graphical projection as a response to the user's manipulation of objects.

application-specific shapes to maximize advantages of physical affordances and tend to support specific applications. However, there has been a movement to make tangible interface platforms more generally applicable to multiple scenarios.

2.2.2 Sensetable: TUIs Using Objects of General Shapes

Sensetable brought new levels of flexibility to tabletop tangible interfaces. Instead of physical objects with particular shapes such as the model of buildings??. Sensetable employed cylindrical pucks overlaid with graphical projections. This system allowed for a wide range of compelling applications such as system dynamics simulation and musical compositions. Additional controls such as physical modifiers and dials can be added to manipulate variables associated with the pucks. While sacrificing affordances implied by various shapes, this approach broadened the applicability of tabletop tangible interaction. Reactable [5], AudioPad [6], or Datatiles [7] are other examples that demonstrate compelling qualities of bimanual interaction that involve dynamically arranging digital items such as images and sound.

Discussion of these trade-offs between general and specific shapes of interaction elements provides insight for design of the ZeroN system. Since the current aim of the research is to find a scope of applications, rather than solving a specific problem in one application, we decided to use an object that has a general shape (sphere) with graphical projections imposed on the shape.

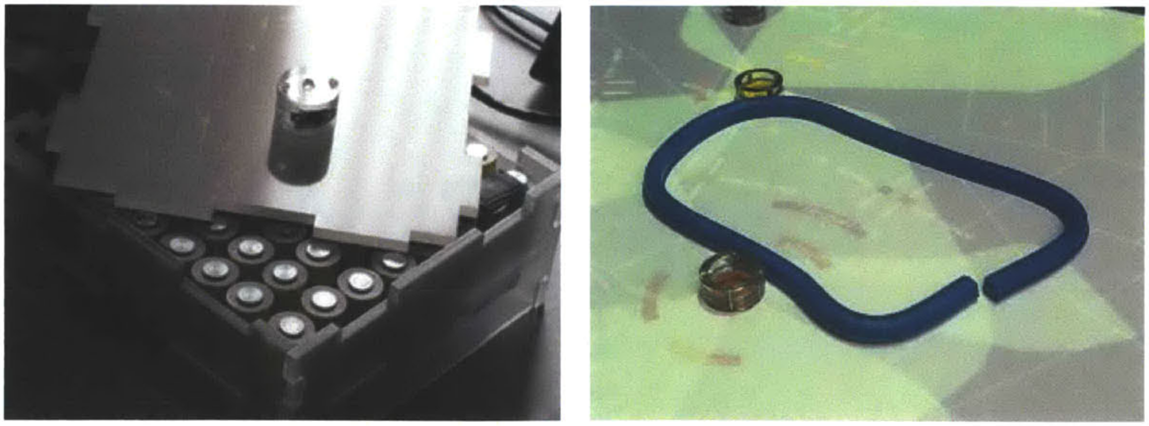
2.3 Actuation

2.3.1 Actuation as Dynamic Representation of Digital Information

There has been research into employing actuation of physical objects in interfaces to represent dynamic digital data. In previous tabletop tangible interfaces, while users can provide input by manipulating physical objects, in most cases output occurs only through graphical projection. Therefore, inconsistency between physical objects and digital information may occur when the state of the underlying digital system changes, and is not reflected as updates in position of physical objects on the table. Adding planar 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 data objects.

In Actuated Workbench [15], an array of computer-controlled electromagnets actuates physical objects on the surface, which represent the dynamic status of computation. Planar Manipulator [23] or Augmented Coliseum [25] achieved similar technical capabilities. Recent examples of such actuated tabletop interfaces include *madget*, a system that has the capability of actuating complex tangibles composed of multiple parts [28].

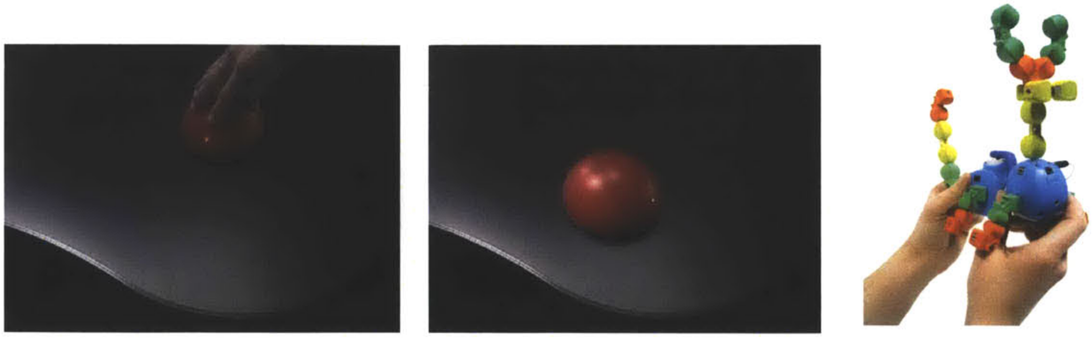
Patten's PICO [16] has demonstrated how physical actuation can enable users to improvise mechanical constraints to add computational constraint in the system. In PICO, users can control the high level structure of a software process with a mechanical process representing dynamic computation. Users can employ their physical intuition about the way physical objects interact with each other to understand how everyday objects, such as a ruler or a rubber band might be used to create constraints in the underlying computational processes.



(a) Gian Pangaro, et al., Actuated Workbench, 2002

(b) James Patten, PICO, 2007

Figure 2-2: Planar actuation technologies enable bidirectional tangible interfaces. A computer updates the position of tangible objects to reflect changes in underlying computation.



(a) A user grabs and moves the Curlybot

(b) Curlybot repeats the exact motion

(c) Kinetic memory allows users to design high level motions with their gestures

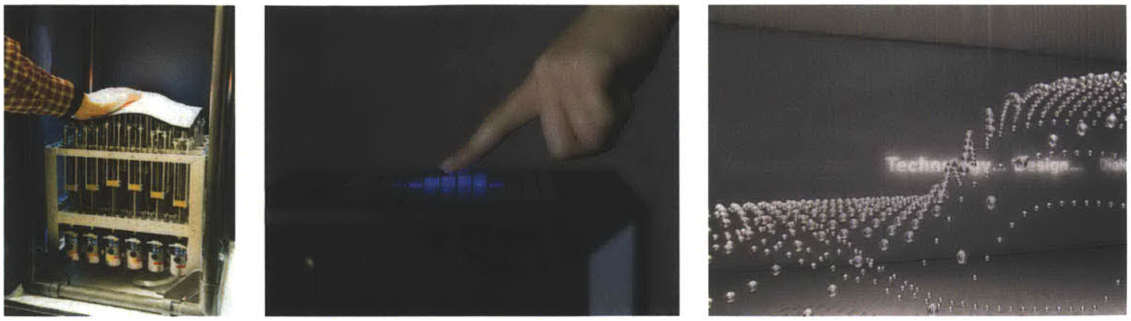
Figure 2-3: Actuated objects can represent human gestures. (a),(b): Phil Frei, Curlybot, 2000, and (c): Hayes Raffle and Amanda Parkes, Topobo, 2004

2.3.2 Actuation as Embodiment of Human Gestures

In an attempt to employ body gestures as scalable interface components, a class of kinetic interfaces has been researched. They capture and play-back motion directly from the gesture of the human body. Curlybot is a toy that can record and repeat physical motions of users on a two dimensional surface [4]. Curlybot remembers how it has been moved and can replay the same movements' pauses, accelerations and the shaking of the users' hands. Then it repeats the motion indefinitely creating mathematical patterns . The Curlybot inspired Topobo [22], an assembly robot with kinetic memory which allows users to sculpt organic motion using their gestural language. Their organic movements can embody high-level concepts of physics and mathematics and even algorithmic simulation. This work inspired the design of the ZeroN system, informing us of the power of using body gestures as tangible interface components in learning and creative tasks.

2.4 From Surface to 2.5D Shape and Deformable Surfaces

One approach to the transition of 2D modalities to 3D has been using deformable surfaces as input and output. Illuminating Clay [18] and Sandscape [7] from the MIT Media Lab



(a) Feelex, Hiroo Iwata, 1997

(b) Ivan Poupyrev, Lumen, 2004

(c) Art+Com, Kinectic Sculpture

Figure 2-4: Through vertical actuation of pin arrays, computers can create various deformable surfaces.

employs deformable physical material as a medium of input where users can directly manipulate the state of the system. In Lumino, stackable tangible pucks are used to express discrete height as another input modality [2]. While in this system the computer cannot modify physical shape, there has been research in adding height as another component to RGB pixels using computer controlled actuation. Poupyrev, et.al provide an excellent overview and taxonomy of shape displays [21]. To actuate deformable surfaces, Lumen [20] and FEELEX [9] employ an array of motorized sticks that can be raised. Art+coms kinetic sculpture actuates multiple spheres tethered with string to create the silhouette of cars [1].

Despite their compelling qualities as shape display, they share two properties in common 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.

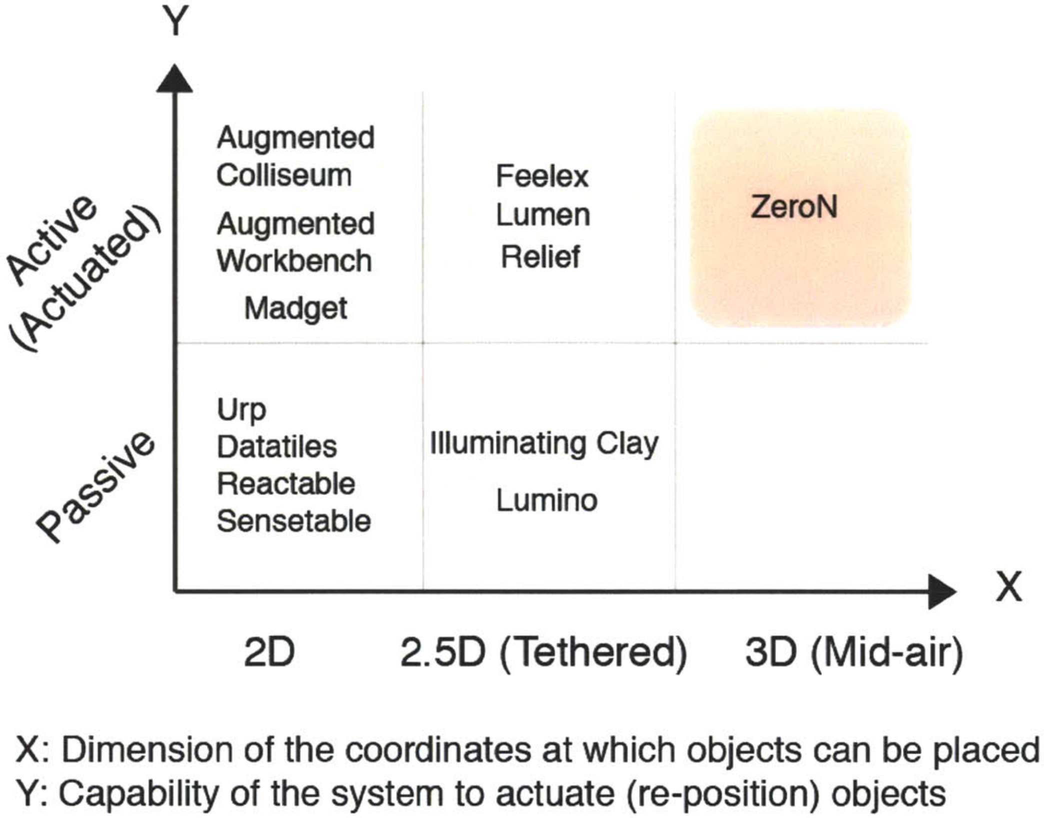


Figure 2-5: Framework for Tabletop Interfaces: Being the first system to allow users to place a physical object at a 3D coordinate in the space above the tabletop surface, ZeroN holds a unique position in tabletop tangible interfaces

2.5 Interaction in 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 Microsoft's SecondLight infrastructure [6]. Grossman et.al introduced interaction techniques with a 3D volumetric display [5].

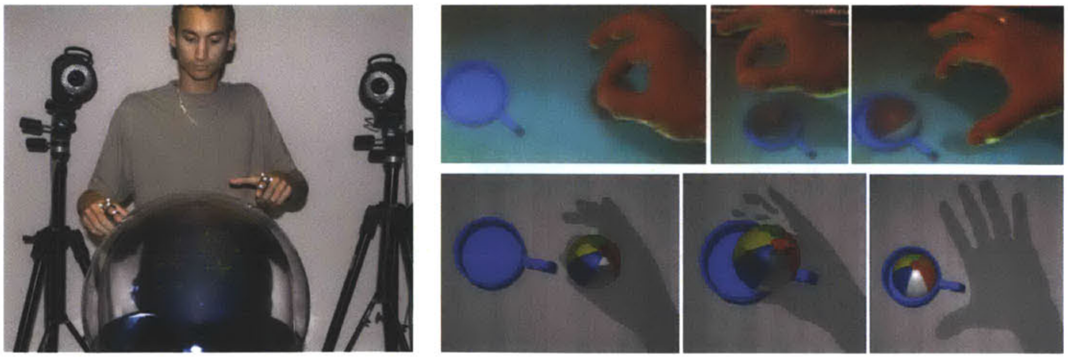
While they demonstrate a potential approach of exploiting real 3D space as an input area, the separation of a user's input from the rendered graphics does not afford direct control as in the physical world, and may lead to ambiguities in the interface. A remedy for this issue of I/O inconsistency may 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 their lack of a persistent tangible representation.

2.6 Haptic Interfaces

Studies with haptic devices, such as Phantom, have shown how accurate force feedback can increase task performance in the context of medical training and 3D modeling [13]. Most of these systems were used with a single monitor display or head-mounted display, Plesniaks system lets users directly touch a 3D holographic display to obtain input and output coincidences [19]. 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.

2.7 Technologies for positioning an object at a 3D coordinate

In this section, I briefly review technologies and mechanisms for the 3D actuation of a physical object that we considered using in order to enable mid-air tangible interaction. Actuation technologies for positioning a physical object in 3D space have been researched in industry and an academic context.



(a) Tovi Grossman, Interaction with Volumetric Display, 2004

(b) Otmar Hilliges, Interaction in the air, 2009

Figure 2-6: 3D interaction occurring in mid-air 3D space. Achieving I/O coincidence may be challenging: sensed input and output are not in contact

(a) Phantom device used with an additional monitor screen.

(b) Immersive haptic devices combined with head-mounted display.

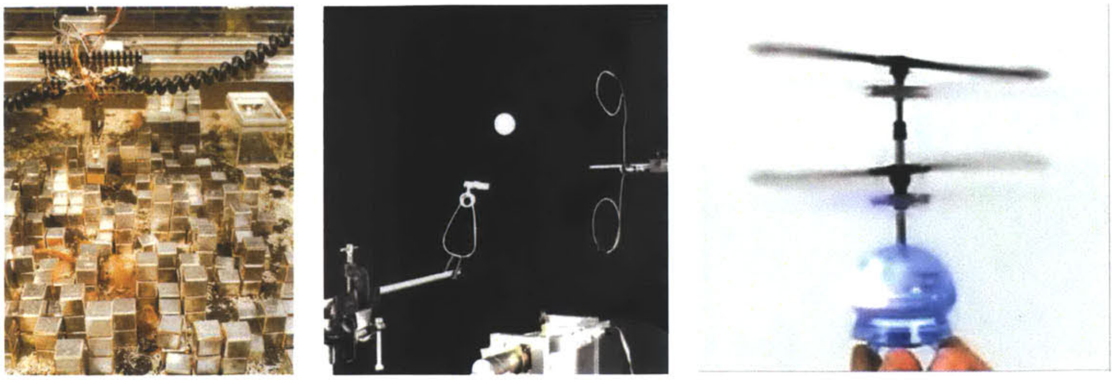
Figure 2-7: Haptic interfaces have shown that accurate force feedback increases task performances in interacting with virtual environments. Achieving input and output coincidences requires users to wear a head mounted display, which may isolate them from the real world context

Robotic Arm

A mechanical arm can be used to grab a physical object and place it at a 3D coordinate of the physical space. This technique is often used in industrial fabrication facilities such as milling machines. Negroponte's Architecture Machine Project is an example of using this technique to create computers that can reconfigure 3D objects [14]. While this approach enables the stable positioning of the object, the mechanical armature may hit the users' body and restrict the of movements of users, which makes it challenging to be used for tangible user interfaces.

Using Air Control

Controlling air pressure can be used to levitate and position a light physical object at a desired position. According to Bernoulli's principle, air flowing around a physical object can create an area of lower pressure where the object can remain stable. Becker et al. have conducted experiments of moving a physical object along 3D trajectory using this technique [3]. With similar principles, properly controlled modular helicopters can be used as a volumetric pixel that can be located at a 3D coordinate of the space. The Senseable City group at MIT has demonstrated an interesting concept of using flying helicopters as volumetric pixels to render 3D scenes in mid-air [24].



(a) Nicholas Negroponte, Seek, 1970

(b) Aaron Becker et al. Pneumatic Ball-Levitation, 2009

(c) MIT Senseable City, Concept of Firefly, 2010

Figure 2-8: Technologies for positioning a physical object at a 3D coordinate

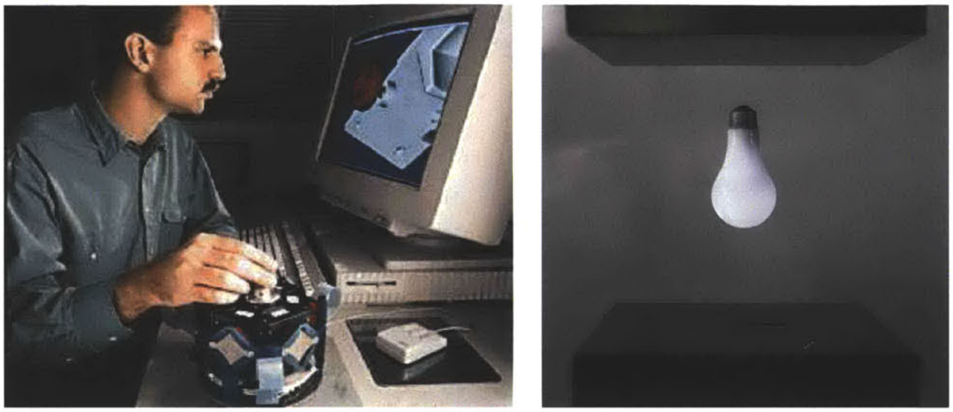
While these techniques may be further developed to serve an interesting display, it may be difficult to appropriate these techniques for tangible interaction with the object, since users' hands will interrupt with air flow and make the object fall when trying to reach out to the object. In addition, they are not stable enough to provide haptic sensations of touching the object at a fixed point in the 3D space.

This analysis of various mechanisms led us to desire implementing untethered and stable 3D actuation mechanism to enable mid-air Tangible Interaction.

2.8 Magnetic Levitation

Magnetic Levitation Technology has been researched and widely utilized in research into haptic interfaces, robotics and transportation, as well as kinetic art projects. It increases mechanical performances by eliminating friction between surfaces of objects such as bearings and allowing for increased degrees of freedom of movements of physical devices. Birklmann and et al. developed high-performance magnetic levitation haptic interfaces to enable the user to interact with simulated environments [22][25]. The system was able to achieved low-latency force feedback. Most of them were used with a single monitor as visual output, rather than collocating graphical projections with physical input.

Outside academic research, magnetic levitation has been used in a series of kinetic art projects. Levitated objects that are seemingly unconstrained by gravity provide people with a provocative perception of space and time. A recent example includes a Levitating Light bulb by Lieberman [12]. The light bulb floating in mid air and can be powered through wireless transfer of electricity.



(a) P.J. Berklmann, Magnetic Levitation Haptic Interface, 1995

(b) Jeff Lieberman, Levitating Light Bulb, 2005

Figure 2-9: Magnetic Levitation Technology in (a) Haptic Interfaces, and (b) art projects.

Chapter 3

Mid-Air Tangible Interaction

In this chapter, I introduce the development and evolution of the concept of mid-air tangible interaction, and initial approaches that I have taken in the course of its development.

3.1 Analysis of Properties of Tangible Interfaces

Since it first appeared challenging to appropriate tabletop tangible interfaces to use them in the 3D mid-air space, I first considered whether it might be possible to emulate properties of tangible interfaces in other mechanisms for 3D interaction as discussed in the previous chapter. To think about this possibility and define the desired interaction properties of our system, I identified three further concepts that characterize tangible interaction.

- Input and output coincidence: This defines the extent to which the input and output–rendered graphics or tangible objects that represent data–are spatially collocated in an interface system. Our design goal is to keep this input and output as collocated as possible.
- Bidirectional physical interaction: This measures the extent to which the physical representation of the interface can be coupled with the digital state. The computer

actuation technology should be able to move physical objects or devices when the digital system is updated. This way, it can maintain a digital-physical consistency with objects or devices that the user manipulates simultaneously.

- Required wearable equipment: This measures to what extent users must be equipped with mechanical or optical devices to use the interface. An important goal of our system was to require minimal instrumentation, similar to existing 2D tangible interfaces.

With these properties as metrics, I plotted the existing literature of 3D interaction to analyze preliminary approaches and trends of research for interacting with 3D digital media (figure 3-1).

As researchers move towards exploiting 3D space above the surface, interactions tend to lose I/O coincidence or require users to be instrumented with mechanical or optical devices.

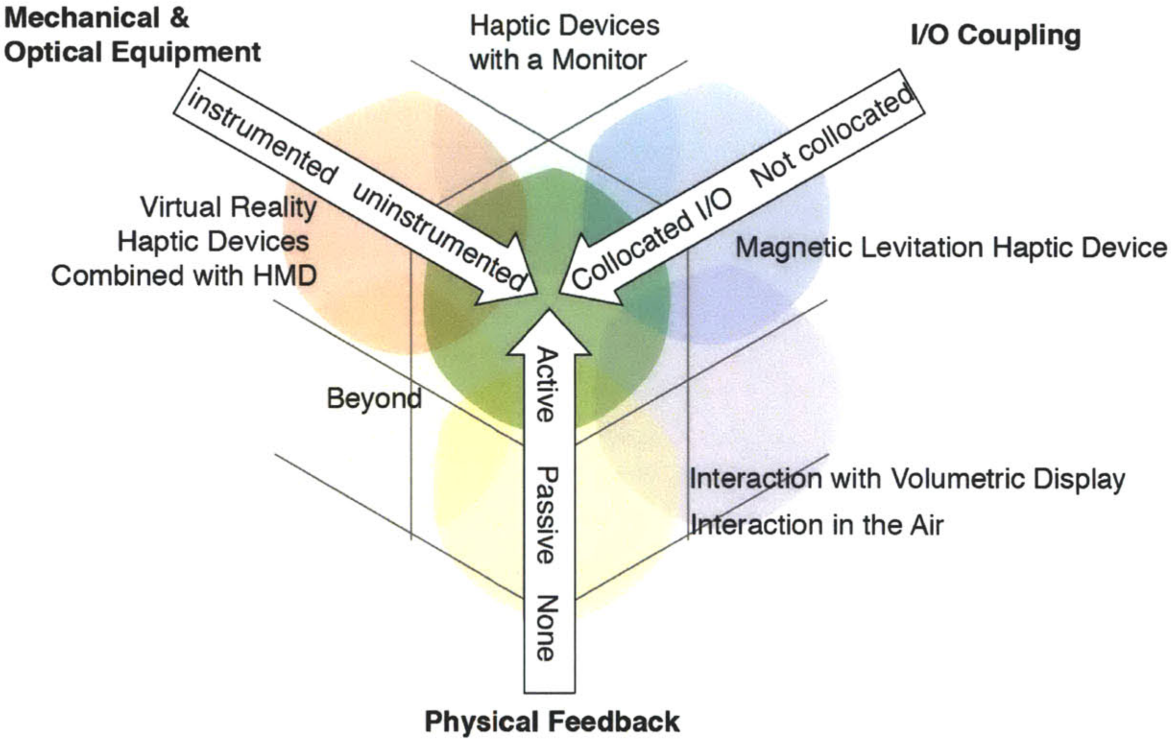


Figure 3-1: 3D Interfaces

Interacting with dynamic, 3D digital media as in the real world (green color in figure 3-1) remains challenging. If we can program the 3D position of physical objects, we may begin exploration of this new space. However, 3D mid-air physical space is not suited for 'storing' data or objects since the objects will not stay put there.

3.2 Prior Exploration: *Beyond* - Physical object submerging into the virtual 3D space

While physical space has this constraint, virtual objects can be placed at an arbitrary 3D coordinate if the computer displays 2D projection of 3D objects properly on the surface. This way, computers can 'place' objects composed of pixels underneath the table, and the user perceives the existence of this virtual 3D space below the surface as an extension of the space above. My initial hypothesis was that if the physical objects on the surface can be seamlessly connected to such 3D information projected beneath the surface, users will be able to perceive and control 3D information with similar interaction modalities of tangible interfaces.

How can physical objects reach into the virtual 3D space? This question led me to create the

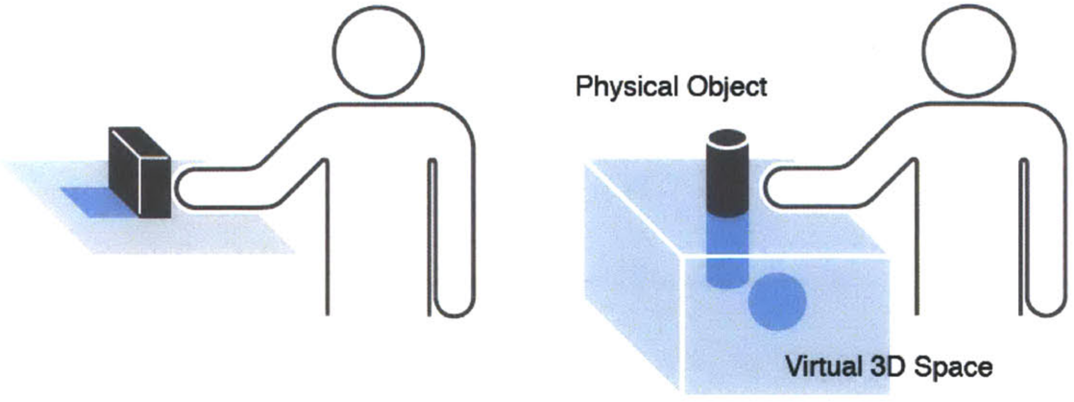
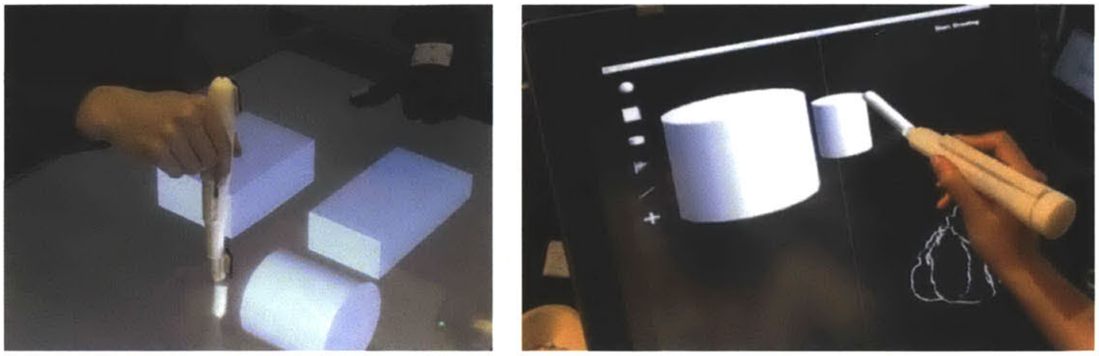


Figure 3-2: The concept of submerged physical objects implies thinking of the virtual 3D space below the flat surface as an extension of the space above.



(a) The first version of *Beyond* implemented with Vicon System[1]. 3D Scene in the picture was rendered based on the cameras perspective instead of the users to illustrate how it looks from the users point of view.

(b) The final version of *Beyond* interface implemented with Wacom Tablet

Figure 3-3: *Beyond* interface creates an illusion of a physical object submerging into the 3D virtual space and digitally extending into the virtual space.

concept of submerged interfaces: the idea of allowing tangible tools to physically collapse and digitally extend into the virtual space. To explore this idea, I designed and developed *Beyond*, a collapsible input device. When pressed against a screen, the *Beyond* device collapses in the physical world and extends into the digital space of the screen, so that users have an illusion that they are inserting the tool into the virtual space. *Beyond* enables users to interact directly with 3D media without having to wear stereo glasses or a head-mounted display.

This visual connection between a physical object and the virtual 3D space improved perceived directness of manipulation. However, the result of several user observations did not support the hypothesis that such a connection would provide rich interaction modalities tabletop tangibles provided. The system did not allow users to employ the dexterity of their fingertips to manipulate images, nor did it allow multiple users to perceive 3D information at the same time. These facts severely affected the usability and scope of potential applications.

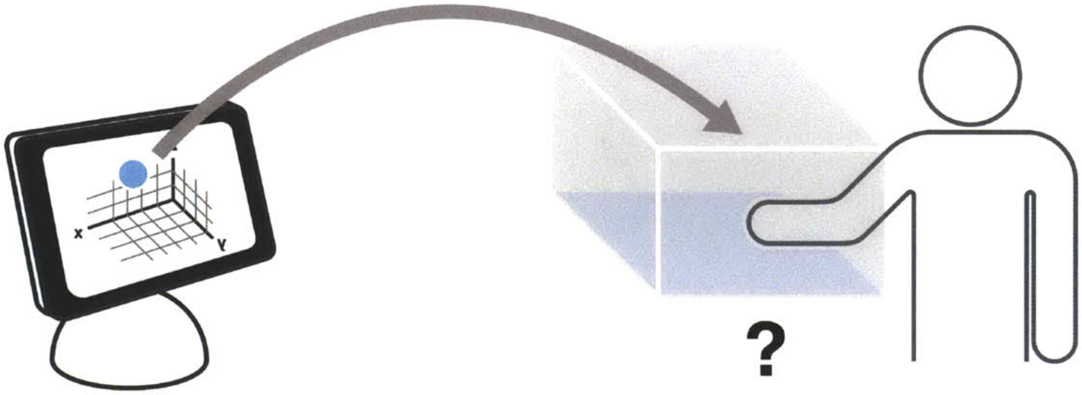


Figure 3-4: How can we represent a 3D coordinate of the virtual space in the physical 3D space?

3.3 Tangible Interaction in Mid-Air

The focus of my research was shifted to the 3D physical space above the tabletop surface. If the tangible interaction can happen here, one could use the dexterity of one's fingertips to directly manipulate or arrange 3D information, and share the visual and tangible experience with multiple users. To do so, one would want the 3D data to gain a physical form that is displayed in this space. This way, 3D components of existing interfaces, such as the flight path of an airplane, the orbits of planets, or a camera path through an architectural model, can be visualized and easily controlled by the users through tangible manipulation.

Can we make the position of a tangible object represent 3D information in mid-air space? To do so, computers need to re-program the behavior of physical objects such that they can be placed at arbitrary 3D coordinates in mid-air. Examining interaction with physical objects that can be freely moved by a computer in 3D space can become the first step towards exploring design space that fulfills the goal that we set at the beginning of this chapter.

Chapter 4

ZeroN – A Levitated Object as Tangible Representation of a 3D Virtual Coordinate

In this chapter, I describe the development of a ZeroN system to achieve tangible interaction in the mid-air. The system includes a new tangible interface element that can be levitated and moved freely by computer in a three dimensional space. I first describe the design criteria that we set at the beginning, and I then present the final prototype.

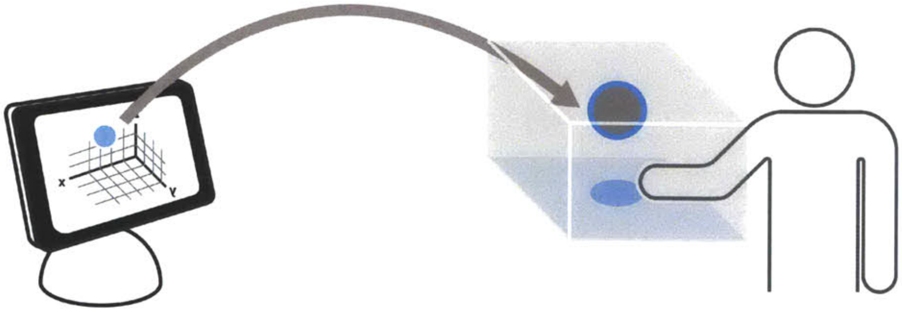


Figure 4-1: A Levitated object freely moved by computers in a 3D space can represent dynamic 3D information in virtual space.

4.1 Design Criteria

To achieve tangible interaction in mid-air space, we chose to implement the system that can levitate and actuate a physical object and place it at 3D coordinates. Considering interaction that we discussed above, we set the following design criteria of such a 3D actuation mechanism as follows:

Stability:

The actuated physical object should remain at the 3D location at which it is placed. Users should be able to touch and grab the object, feeling mechanical detente between the object and a fixed point.

Untethered-ness:

To allow users to freely place, move, and interact with objects with maximized degrees of freedom, the system should not be firmly tethered to the ground or to mechanical devices. This approach also minimizes visual distraction of users from perceiving data itself and maximizes compatibility with the existing tangible interfaces setup.

Graphical Projection:

As in existing tabletop tangible interfaces, graphical images can be projected onto the object to integrate physical input and graphical output in the same space. To achieve this, the object should have large, continuous, white surfaces suited to displaying graphical images.

Compatibility with tangible tabletop interfaces:

While this thesis focuses on 3D tangible interaction in mid-air, mixed 2D and 3D elements can be combined to create functional user interfaces. Therefore, from both design and technological perspectives, the actuation mechanism should be able to incorporate 3D elements into existing 2D tabletop interfaces.

Smooth Motion:

To use system to display dynamic 3D data such as the position of orbiting planets or flight paths of an airplane, smooth motion will be a significant requisite to have.

Ability to Sense Users' intent:

> The system should be able to respond to users' input in real time, and to do so, the system should be able to understand the users' intent, such as whether the user is trying to move the object to a different position.

After considering several design options as discussed in the section 2.7, I decided that magnetic levitation was the most promising approach for moving and placing an object at 3D coordinates in a stable manner. We implemented our first prototype with computer controlled magnetic levitation technology. We call this system ZeroN, since the sum of gravitational force and magnetic force on a static object is zero Newtons (0N). In the following discussion, we will refer to the levitated object simply as *ZeroN* and the entire ensemble as the *ZeroN* system.

4.2 Final Design Scheme

The ZeroN system operates over a volume of 15x15x3.5 inches, in which it can levitate, sense, and control the 3D position of the ZeroN object, a 1.25 spherical magnet covered with plastic 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, I made the entire interactive space larger than this 'anti-gravity' space, such that users can interact with ZeroN with reasonable freedom of movement. In the following discussion, I will refer to the levitated object simply as ZeroN and the entire ensemble as the ZeroN system.

The current prototype comprises four key elements, illustrated in figure ??.

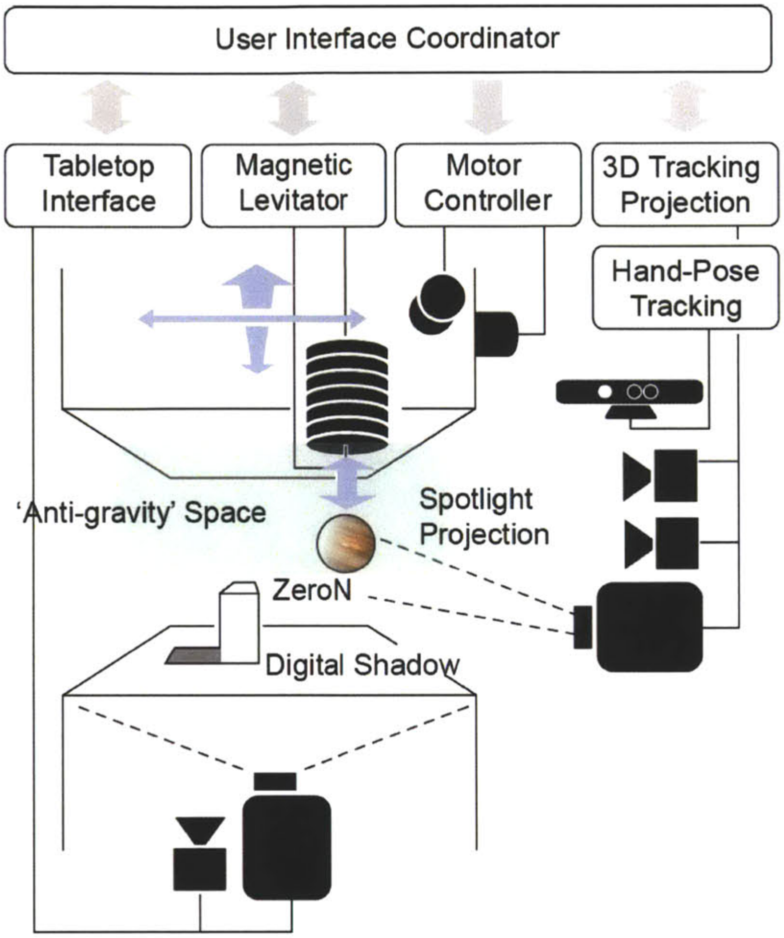


Figure 4-2: Overview of the ZeroN system.

- A single-axis magnetic levitator 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
- Stereo cameras that track ZeroN's 3D position in real time.
- 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.

4.3 Displaying 3D Point and Path

ZeroN serves as a dynamic tangible representation of a 3D coordinate, without being tethered by mechanical armature. The 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. These graphical images or icons may be projected upon the white surface of ZeroN levitating, such as cameras, flying airplanes 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 prototype systems that can only control the 3D position of a magnet, but has little control over its orientation. In the following chapter, I describe the technical details of the ZeroN system.

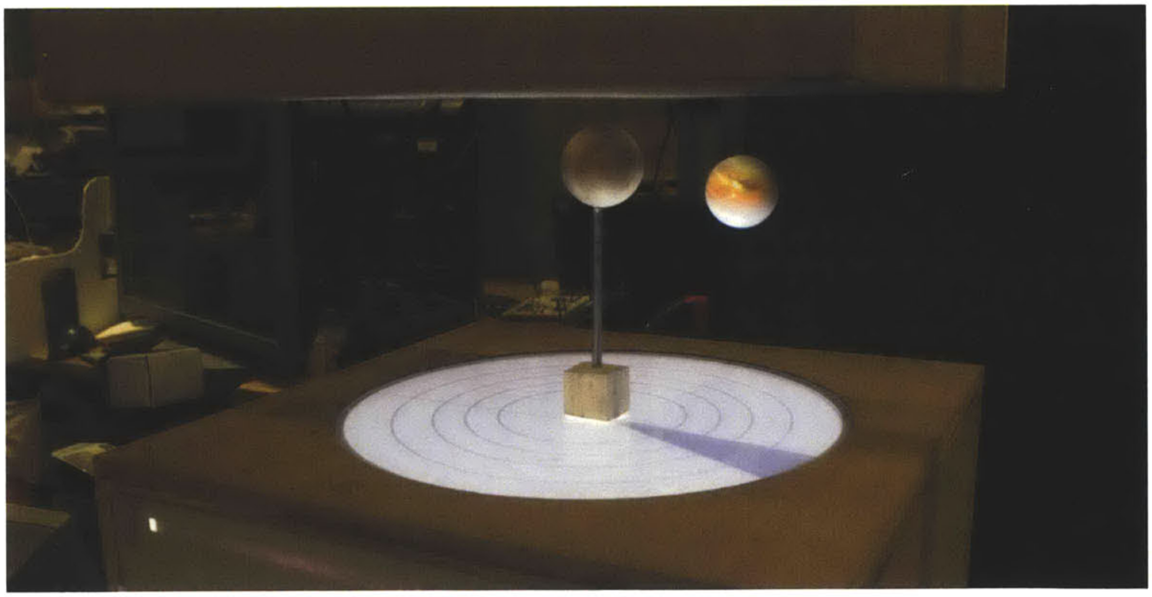


Figure 4-3: ZeroN can represent a 3D coordinate of the virtual world. Ex. displaying an orbit of a moving planet.

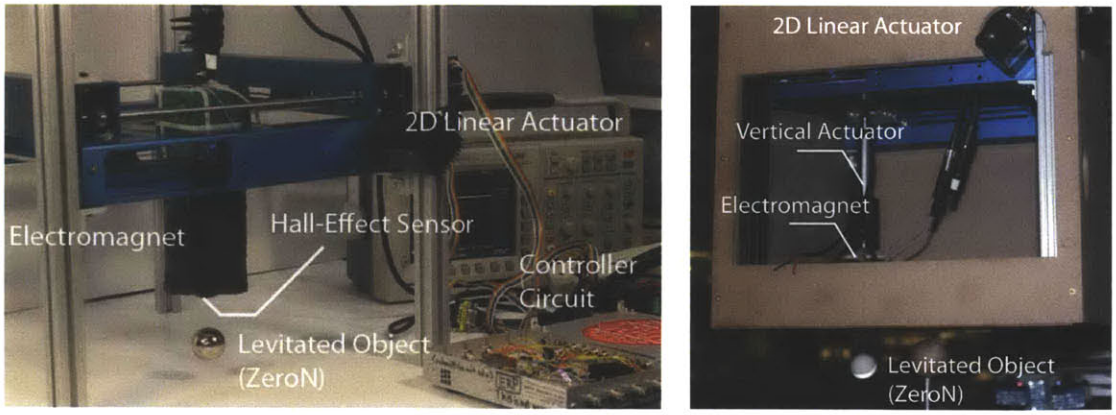
Chapter 5

Technical Implementation

The design and implementation of the ZeroN system have brought forth significant innovations in the computer controlled movement of objects. It is the first system that utilizes the 3D positioning of a physical object in mid-air in human computer interaction, using external forces without any physical attachment to the object. This chapter contains a detailed description of the prototypes we implemented between February 2010 and May 2011. It discusses the electronic, mechanical, and optical components used and the data-handling sequence between the computer and these components.

5.1 Untethered 3D Actuation Technology

In our first prototype, 3D actuation of the magnet was achieved by combining 2D mechanical actuation with vertical magnetic actuation. While this magnetic vertical control demonstrated promising implications in magnetic propulsion technology, the vertical range was limited: when the permanent magnet got too close to the electromagnet it became attached to the electromagnet even when the coils were not energized. In the final prototype, we chose to implement a 3D mechanical actuation system that can move the coil and the levitated object in the 3D space.



(a) The first prototype of 3D actuation system. 2D mechanical actuation combined with 1D magnetic vertical actuation creates 3D paths of a levitated magnet.

(b) The final prototype includes three-axis actuators that can mechanically move the coil in a 3D space

Figure 5-1: Untethered 3D actuation

Given a 3D path as input, the system first projects the path on each dimension, and linearly interpolates between the points to create a smooth trajectory. Then the system calculates the velocity and acceleration of each actuated axis as a function of time. With this data, the system can actuate the object along a 3D path similar to the input 3D path.

5.1.1 Magnetic Levitation and Vertical Control

We have developed a custom electromagnetic suspension system (illustrated in figure 5-2) to provide robust sensing, levitation, and vertical control. It includes a micro-controller 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 the desired distance from the electromagnet. This distance is determined by measuring the magnetic field immediately beneath the solenoid. The levitation circuit used in the final prototype was designed by Rehmi Post.

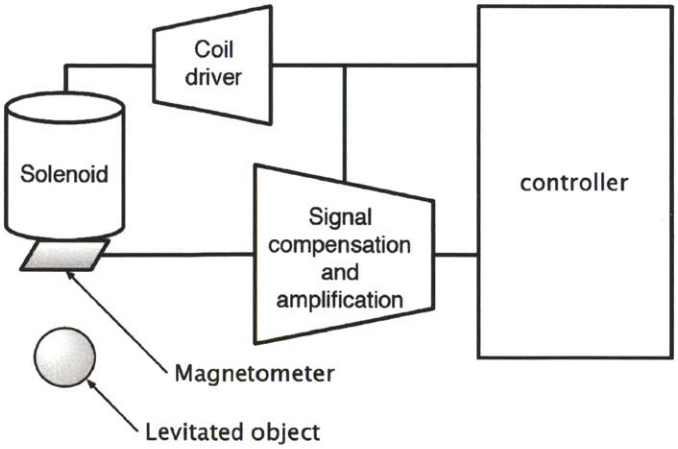


Figure 5-2: A simplified version of magnetic range sensing and levitation circuit.

Pulse-Width Modulation (PWM)

PWM is a widely used technique for driving electrical motors or coils at certain speeds by sending them pulses of various duty cycles depending on the speed at which one wants them to turn. In our implementation, PWM drives the coils with an average current depending on a voltage signal coming from a hall-effect sensor to balance the gravity and magnetic forces posed on the permanent magnet.

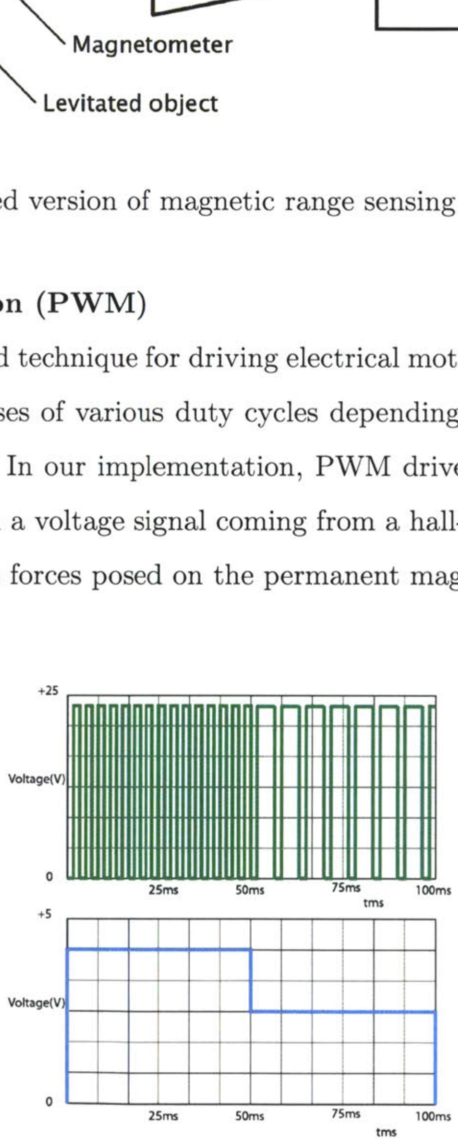


Figure 5-3: An example of PWM Signal to enable levitation. The duty of the pulse (top) changes according to the voltage signal from the hall-effect sensor to compensate for the vertical oscillation of a levitating magnet.

5.1.2 Magnetic Range Sensing with Hall-Effect Sensor

Properly measuring the distance of a spherical 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 properly convert the strength of the magnetic field to the vertical position of the magnet. To linearize the signals produced by the hall-effect sensor, we developed the two-step logarithmic amplifier shown in figure 5-2. It logarithmically amplifies the signal with two different gains, based on whether the signal exceeds a threshold value.

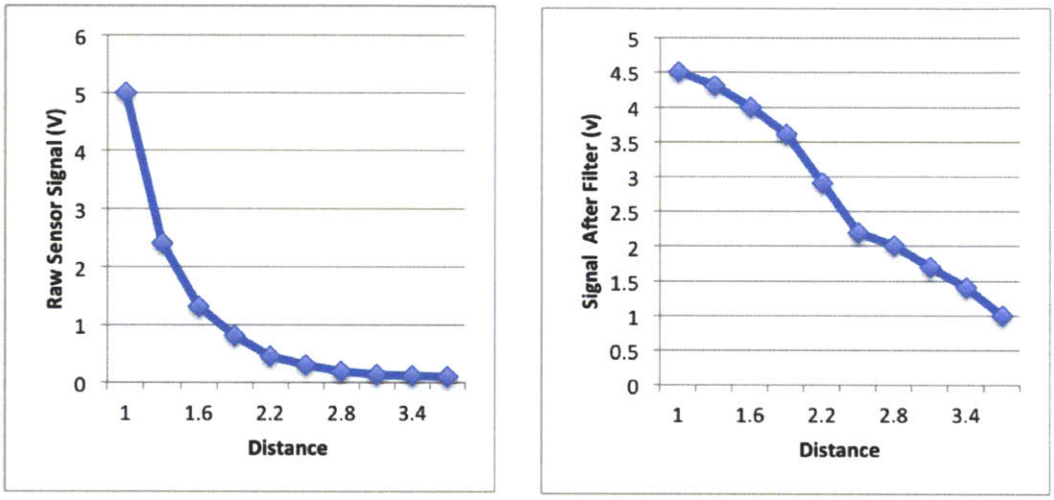


Figure 5-4: Raw Signal (left) and signals after com- pensation and amplification.

5.1.3 Designing ZeroN Object

We chose a sphere as the shape of the ZeroN object for technical reasons and affordances of the shape. Our original goal was to allow users to not only move but also rotate the object in the air with 6 degrees of freedom. However, tilting the permanent magnet will create distortion in a stable magnetic field, which will make the magnet fall. My solution to enable this feature is to cover a magnet with a plastic layer loosely covering the magnet such that users can tilt the layer to express rotation without changing the orientation of the permanent magnet. To enable this feature, the magnet should take on a spherical shape which is radially symmetrical from all angles. Adopting a spherical shape also provides right affordances that imply the freedom of movement of the system, since users are allowed to move the ZeroN in an omnisymmetrical direction. The permanent magnet used in our system weighs 4.430 oz and it has 1.25inch diameter.

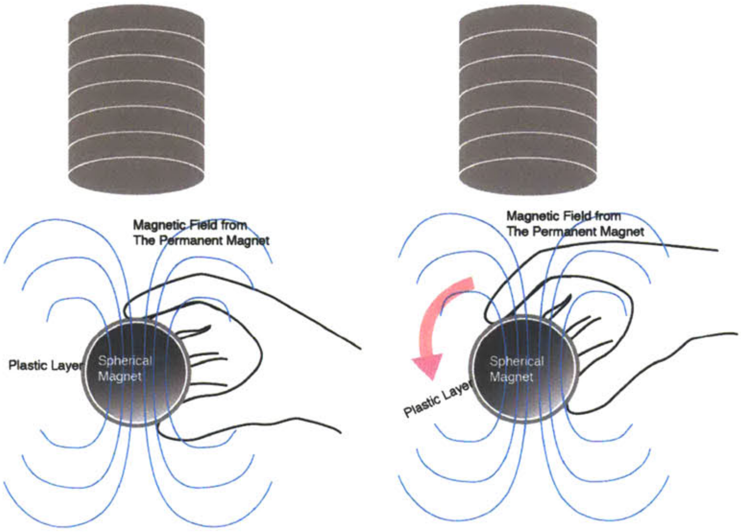


Figure 5-5: Design of ZeroN object.

5.2 Tracking Technology

The ZeroN system implements machine vision techniques for determining the 3D position of a levitated object. To enable even more robust tracking and to resolve occlusion issues, electromagnetic 3D tracking was proposed. However, we chose to implement a computer vision-based system as we encountered preliminary difficulties in appropriating electromagnetic sensing for 3D tracking within our timeframe.

5.2.1 Stereo Tracking of 3D position

I used two modified Sony PS3Eyecams to track the 3D position of the ZeroN object using computer vision techniques with a pair of infrared images as shown in figure 5-6 X. At

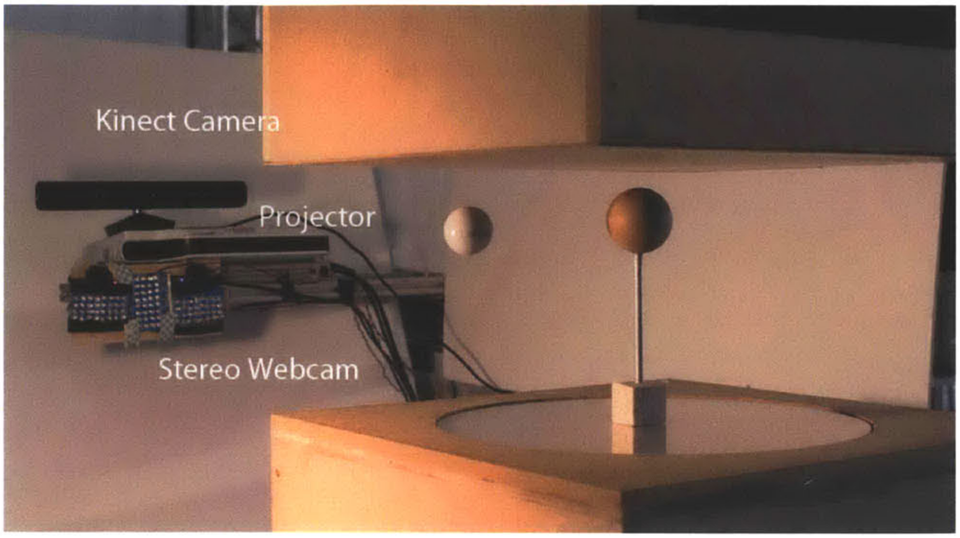


Figure 5-6: Tracking and Projection System of ZeroN.

the beginning of our design stages, we encountered the following two technical constraints. First, to maximize the white surface area on the ZeroN object for projecting images, fiducial markers, if placed, should be very small or invisible. Second, although we can achieve stable magnetic levitation after adding weight up to 60g, the weight should be distributed evenly over the spherical object. This makes it challenging to add active electronic components to the ZeroN object. Filtering images with color or depth to extract the contour of the object is a possible approach; however, it is hard to distinguish the contour of the ZeroN object from users' hands while it is being manipulated.

To resolve these issues, I chose to apply a stripe of retro-reflective tape to the surface of ZeroN and let the stereo cameras see the reflected infrared light. I developed vision-based tracking software that converts and smoothes out the grayscale images of the stereo cameras into binary images and employs standard blob-analysis techniques to find the largest horizontal segments. The software then correlates the two binary images coming from the stereo cameras to compute the 3D position of the object.

5.2.2 Tracking Orientation

Stereo cameras can track the rough 1D rotation of its plastic surface. While our original plan was to extract the 3D orientation of the object by placing continuous patterns on the surfaces similar to those used in a VICON motion capture system, we were only able to detect the approximate tilt of a horizontal stripe pattern of retro-reflective tape.

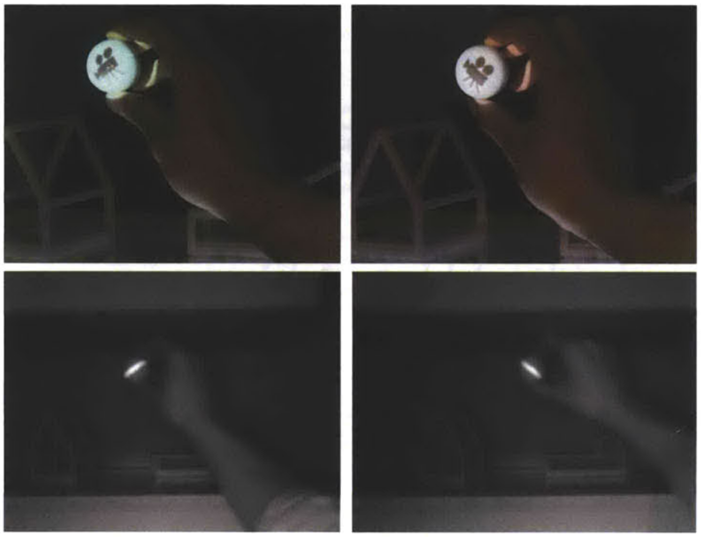


Figure 5-7: As the users tilts the outer plastic layer, the system senses the orientation and updates the projected images, while the spherical magnet stays in the same orientation.

5.2.3 Calibration of 3D Sensing, Projection, and Actuation

To ensure real time interaction, careful calibration between the cameras, projectors and 3D actuation system is essential in our implementation. After finding correspondences between two cameras with checkerboard patterns, we register the cameras with the coordinate frame of the interactive space. We position the ZeroN object at each of four fixed, non-coplanar points. Similarly, to register each projector to real-world coordinates, we match the ZeroN positioned at the four calibration points and move the 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

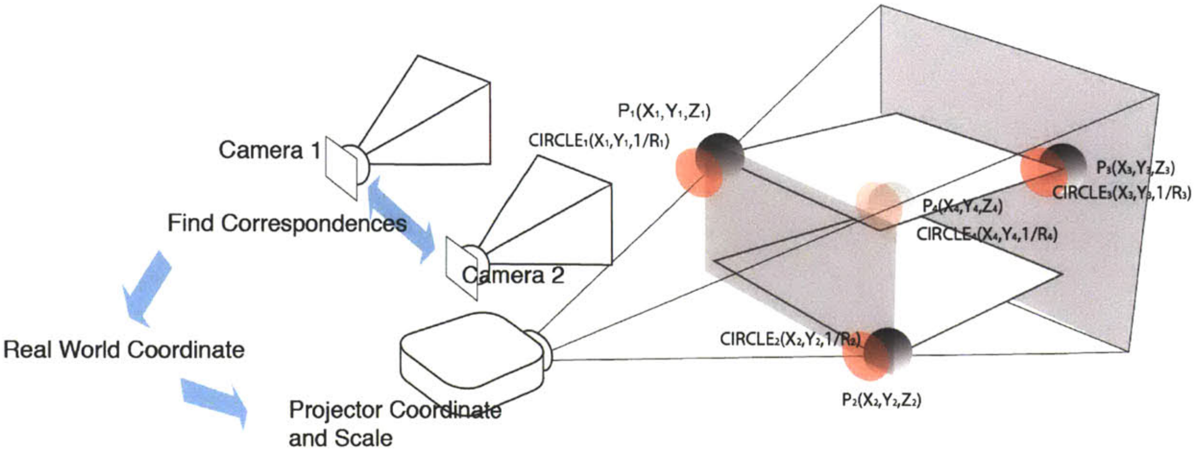


Figure 5-8: Calibration between stereo cameras, real world coordinates and a projector.

of the interactive space, and the real coordinates to the projector's x, y position and the inverse of the radius of the circle.

$$\begin{pmatrix} x_{proj} \\ y_{proj} \\ \frac{1}{R_{circle}} \end{pmatrix} = \begin{pmatrix} a_x & b_x & c_x \\ a_y & b_y & c_y \\ a_z & b_z & c_z \end{pmatrix} \times \begin{pmatrix} x_{real} \\ y_{real} \\ z_{real} \end{pmatrix} + \begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix}$$

$$\begin{pmatrix} x_{real} \\ y_{real} \\ z_{real} \end{pmatrix} = \begin{pmatrix} k_x & l_x & m_x \\ k_y & l_y & m_y \\ k_z & l_z & m_z \end{pmatrix} \times \begin{pmatrix} x_{raw} \\ y_{raw} \\ z_{raw} \end{pmatrix} + \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}$$

I have not attempted to optimally determine the focal plane of the projected image: focusing the projectors roughly in the middle of the interactive space is sufficient.

5.2.4 Detecting Manipulation

It is important to determine the user's intent, since the system has to constantly sense and update the position of the ZeroN object to realize mid-air tangible interaction. I created modes of interaction based on whether and how long the user is holding the object. A depth camera (Microsoft Kinect[1]) is used to determine if users' hands are grabbing the levitated object or not. The 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 as in figure 5-9.

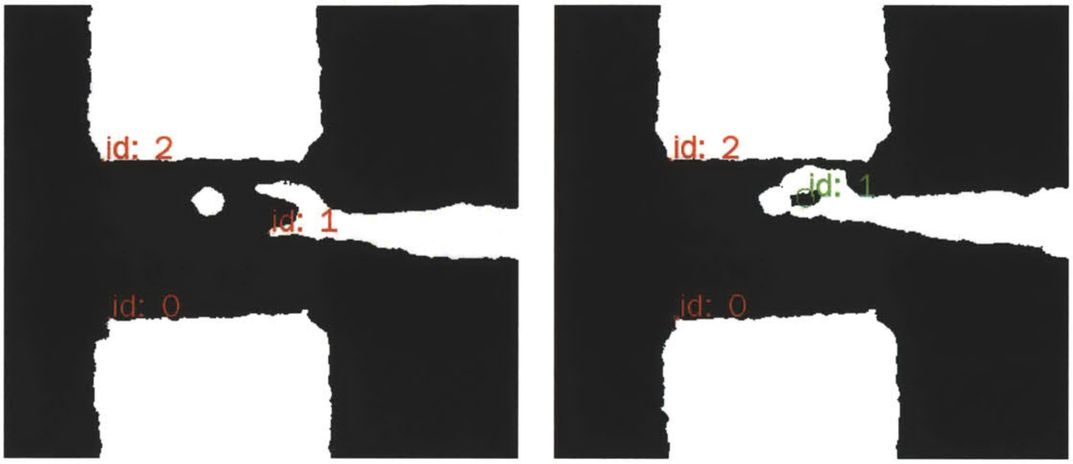


Figure 5-9: The Kinect camera can sense whether the user is holding the levitated object or not.

5.3 Putting Together

5.3.1 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 place 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 moved 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. A challenge in implementing this anti-gravity space with the current prototype is to determine if ZeroN is being moved by

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[1] http://www.xbox.com/en-US/kinect

a user, or is naturally wobbling. When levitating, ZeroN sways laterally, 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 classified three states of operation (free, grabbed, and grabbed for a long time) based on the user's hand pose sensed by the depth camera, such that the system only updates the stable position when ZeroN is grabbed by the user.

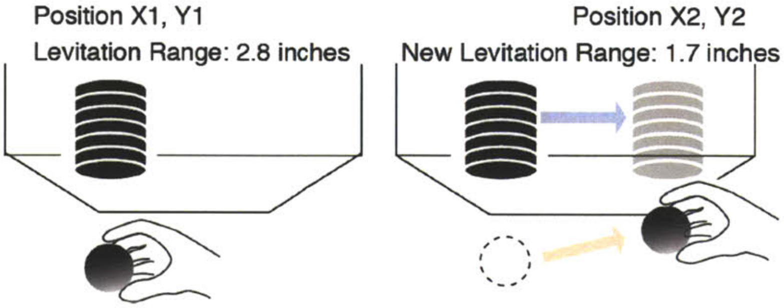

Figure 5-10: The system can update the stable point of suspension when the user moves the ZeroN to an- other position.

5.3.2 Entire Installation

These components are built into two wooden boxes to maximize the use of interactive space. The upper box hanging from a truss contains the mechanical and electromagnetic hardware for levitation, and the bottom box contains a vision-based tabletop interface setup. We used a Reactivision[2] platform to detect the position and orientation of physical objects placed on the tabletop. The space in between the two boxes is the anti-gravity space used for mid-air tangible interaction, with four sides open to ease multiple users' access (figure 5-11).

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[2] http://reactivision.sourceforge.net/

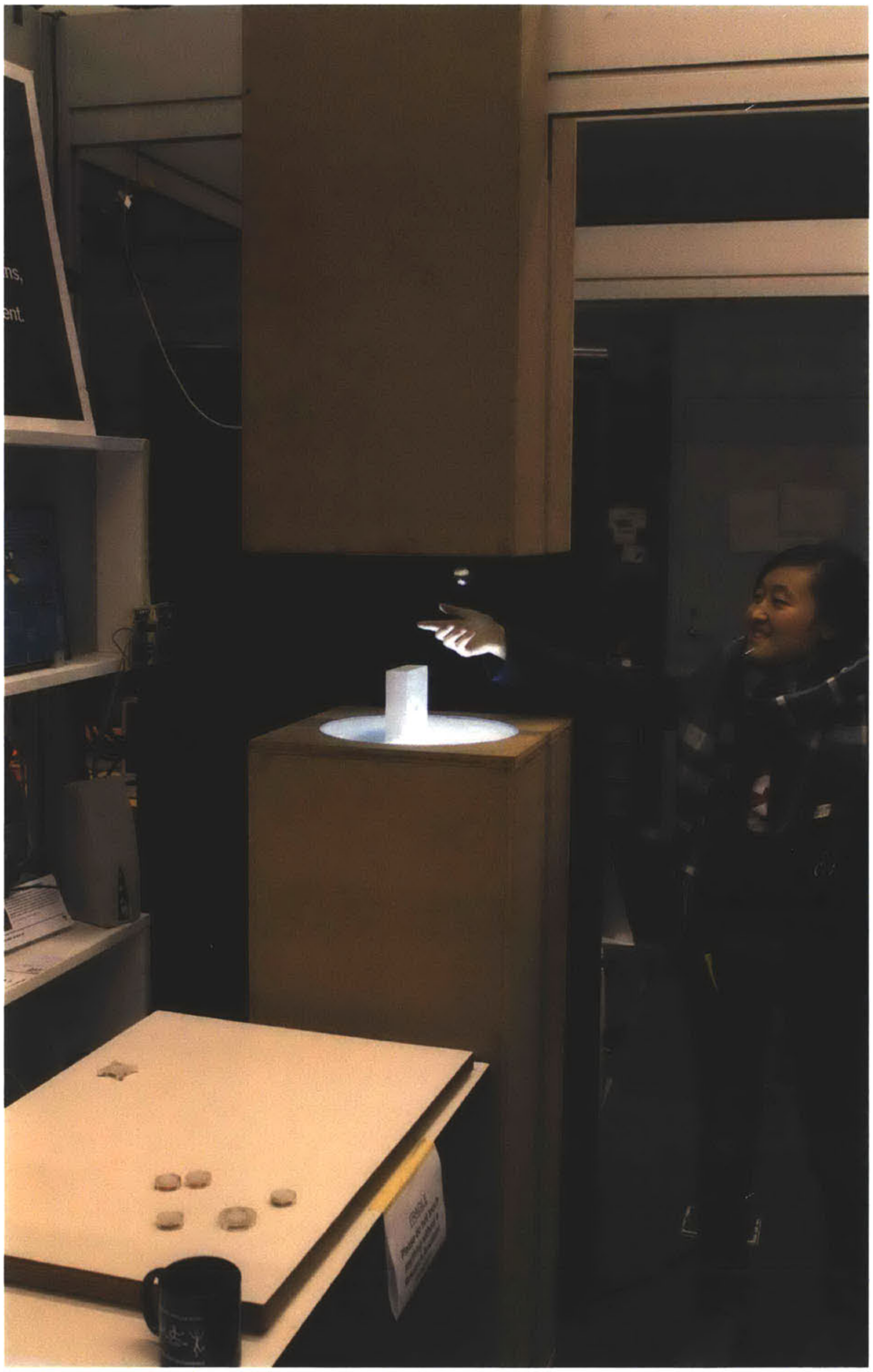


Figure 5-11: Entire Setup of the ZeroN system, installed at the 3rd floor of the MIT Media Laboratory

Chapter 6

Interaction Techniques

In this chapter, I introduce a language for 3D tangible interaction. In addition to extending language for interacting with physical objects on a 2D surface, – put, move, rotate, and drag– to 3D, I implemented a symbolic vocabulary that enables the users to attach digital items or functions to a ZeroN object. We identify design issues and technical challenges unique to interaction with an untethered, levitated object. We list the new vocabulary of our interaction language below:

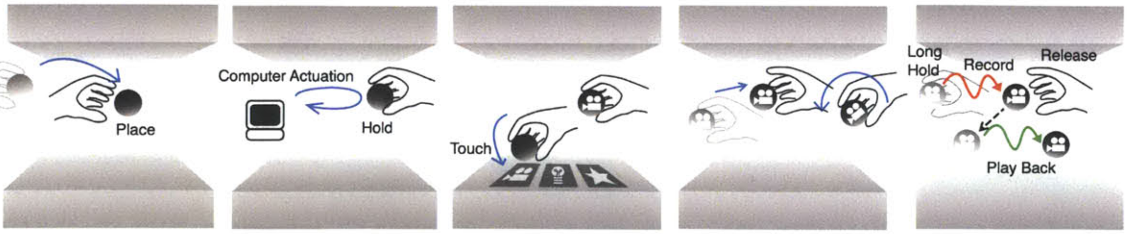


Figure 6-1: Vocabulary for Tangible Interaction in mid-air : (a) Users can place ZeroN in the air; (b) Computer can actuate ZeroN and users can intervene with the movement of ZeroN; (c) Attaching Digital item to ZeroN; (d) Translation and rotation in the air; (e) Long hold to record and play back.

6.1 Basic Vocabulary

Place and Remove : One can place ZeroN in the air, suspending it at an arbitrary 3D position within the interactive space. Similarly, one can always remove the ZeroN from the 3D system to 'unregister' the data from the system.

Translate : The user can move ZeroN to another position in the anti-gravity space without disturbing its ability to levitate.

Rotate : When the user rotates the plastic shell covering the spherical magnet, digital images projected on the ZeroN will rotate accordingly.

Computer Actuation : ZeroN can also be actuated by a computer in this anti-gravity space. The movement represents dynamic change in the underlying digital system.

6.2 Symbolic Vocabulary

Hold : The user can hold or block ZeroN to impede computer actuation. This can be interpreted as computational constraints.

Long Hold : A long-hold gesture can be used to initiate a specific function. For example, in a video recording application, we might have an interaction where the user could hold the ZeroN for longer than 2.5 seconds to initiate recording, and release it to enter playback mode.

6.3 Attaching Digital Information to the ZeroN

We borrowed a gesture for attaching and detaching digital items from existing tabletop interfaces such as Sensetable [17]. 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 [3], 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 just by moving the ZeroN close to the digital item to which it is to be bound.

6.4 Interaction with Tabletop Tangible Interfaces through Digital Shadow

In incorporating ZeroN system into existing tabletop tangible interfaces, one of the challenges is to provide the users with a semantic link between the levitated object and the tabletop tangible interfaces on the surface. Since ZeroN is not physically in contact with the tabletop system, it is hard to recognize the relative position of the levitated object to the objects placed on the ground. To address this issue, I designed several types of interactive digital projection to provide the users with visible links between ZeroN and other part of the tabletop tangible interfaces. In applications where the users may want to use tabletop surface as a reference point, ZeroN casts its digital shadow whose size is mapped to the height of the ZeroN (see figure 8-2). For applications where the users may want to use tangible elements as reference points, the digital shadow can be rendered to show the geometric relationship between ZeroN and objects of the tabletop system (see figure 6-3).

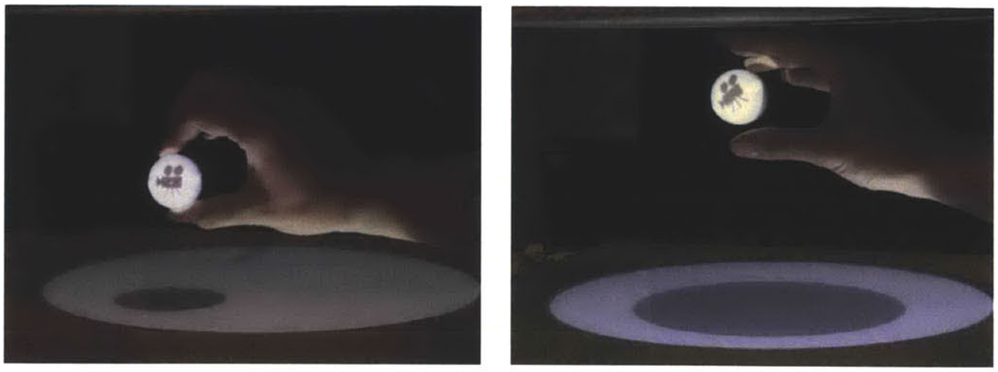


Figure 6-2: The size of the digital shadow is mapped to the height of ZeroN.

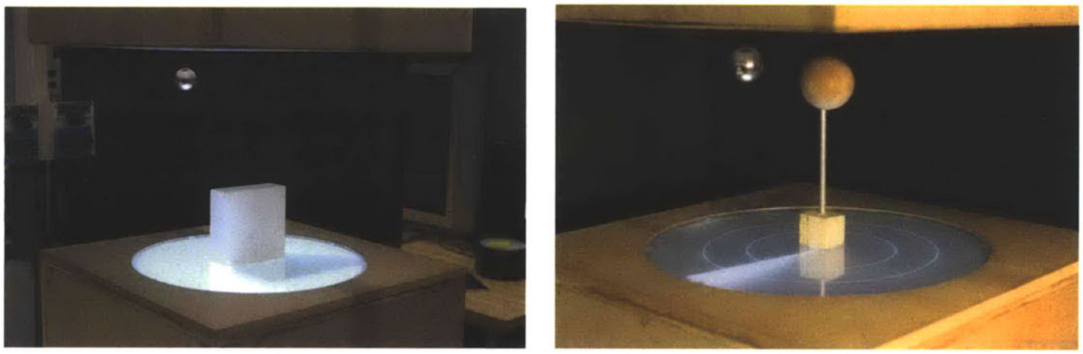

(a) (b)

Figure 6-3: Different types of digital shadow that imply geometric relationship between ZeorN and other objects used in interfaces.

Chapter 7

Applications

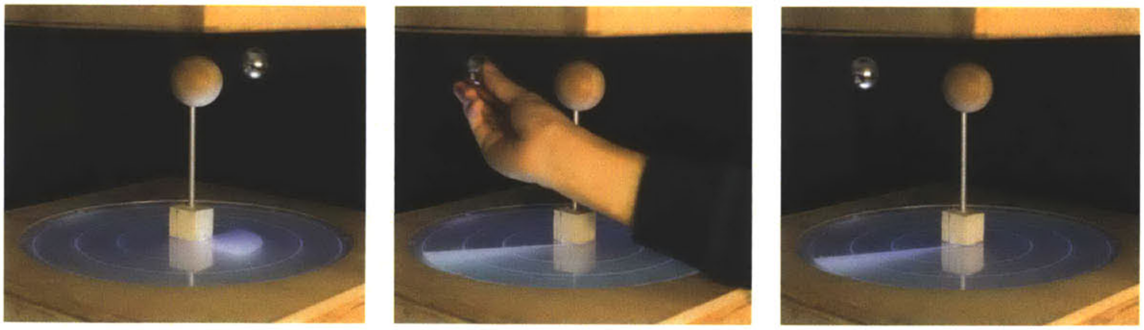
In this chapter, I explore the previously described interaction techniques in the context of several categories of applications described below. While the physics and architecture simulation allow the user to begin using ZeroN to address a practical problem, the prototyping animation and tangible pong applications are proof of concepts that demonstrate the interactions one might have with ZeroN.

7.1 Physics Simulation and Education

ZeroN can serve as a tangible physics simulator by display-ing 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, the user 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, the user 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



(a) When placed near an object that represents the center of mass , ZeroN revolves around like a planet

(b) The user can grab the orbiting ZeroN and move it farther from the center

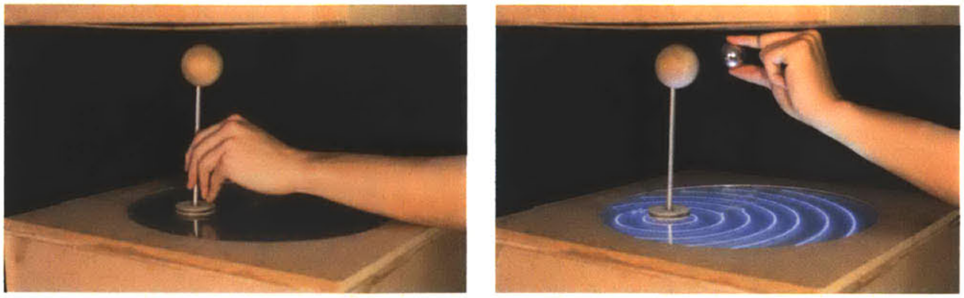
(c) ZeroN snaps to another orbit, reducing its speed confirming Kepler's 2nd law

Figure 7-1: Application for Physics Education

the Sun, around which the ZeroN will revolve like a planet. The user 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 of the ZeroN. 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.

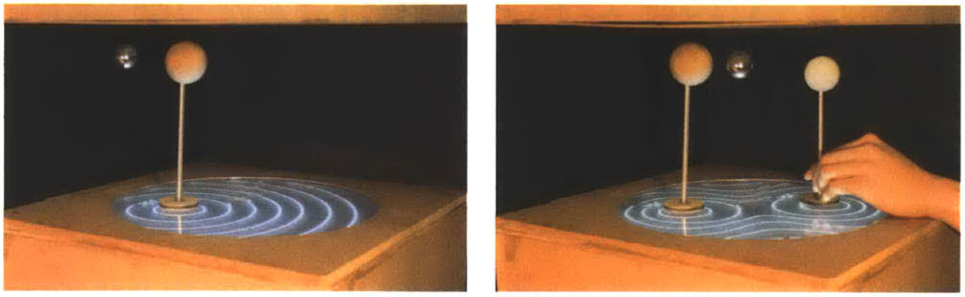
3-body problem

In this application, users can generate a gravity field by introducing multiple passive objects that represent fixed centers of gravity. A ZeroN placed next to the object will orbit around based on the result of the 3–body simulation. The 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 7-6).



(a) Introducing a center of mass.

(b) Introducing ZeroN.



(c) ZeroN will revolve around the center of mass.

(d) Introducing another center of mass will change the orbit of the ZeroN, simulating and visualizing a 3-body problem

Figure 7-2: Visualizing 3-body problem

7.2 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 [Underkoffler:1999:ULW:302979.303114] allows the user 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 appli-cations for gathering the users' feedback.

Lighting Control We developed an application for controlling external archi-tectural lighting in which the user can grab and place a Sun in the air to control the digital shadow cast by physical models 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.

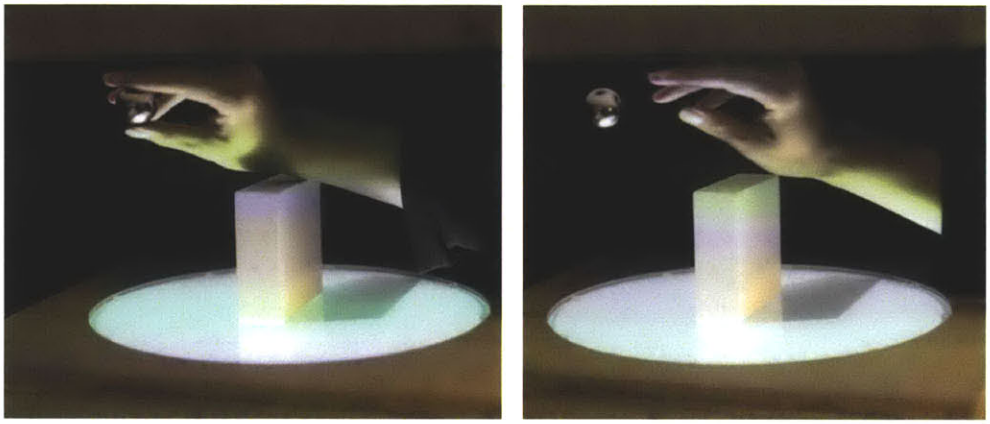


Figure 7-3: The user can place the 'sun' above physical models to cast its digital shadow

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 ZeroN into a camera object. The user can then hold the ZeroN for a number of seconds in one position to initiate a recording interaction. When the user draws 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, the user 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. The user will naturally hope to control the orientation of the camera, however we could not incorporate the full orientation control feature in the application for the time being. We instead fix the orientation of the camera to the center of the interactive space.

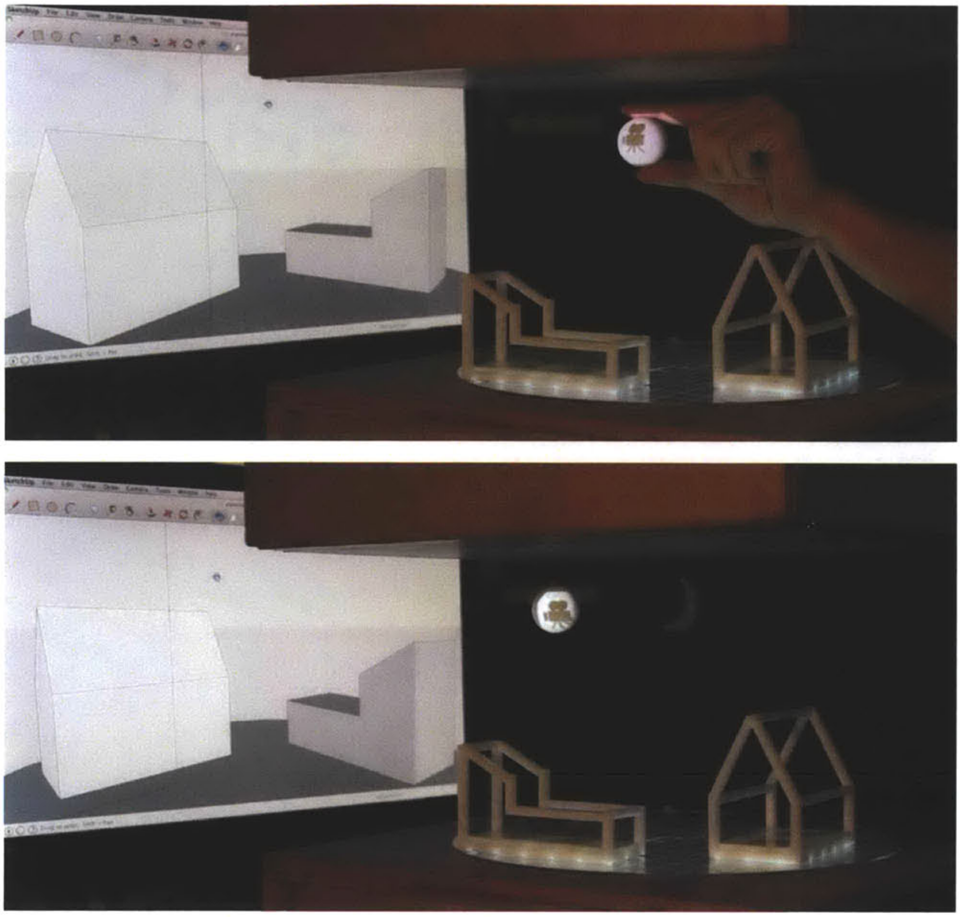
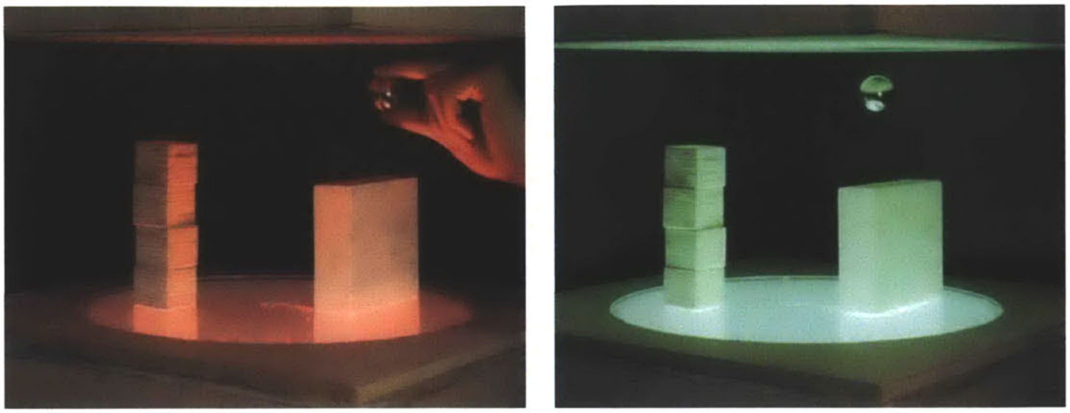


Figure 7-4: Users can create and edit 3Dcamera paths above the physical model and see the cam- era flying along the path (Cameraview orientation is constrained to the center of the interactive space).

7.3 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, the user 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 in dynamic virtual space. As a result, the user can not only see, but also feel the 3D motion of the object they created. They can go through this interaction through a series of gestures; long-hold and release.



(a) Record (b) Play-back

Figure 7-5: Record and Playback: the color tone of graphical projection turns from red to green, informing which mode the user is in.

(a) The user creates a flight path of an airplane

(b) When released, the airplane goes back to the initial position and flies along the path that a user created. The user can move another object that represents camera around the flying airplane to create dynamic scenes

Figure 7-6: Prototyping the motion of a flying airplane, and filming it with a virtual camera.

7.4 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 built and demonstrate 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. The users can hit or block the movement of ZeroN to change the trajectory of the pingpong ball. They can add computational constraints in this game by placing a physical object in this interactive space as in figure 7-7. This application is only partially implemented as a proof of concept and demonstrates interesting challenges; users cannot smash the ZeroN as in the real world. However 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.

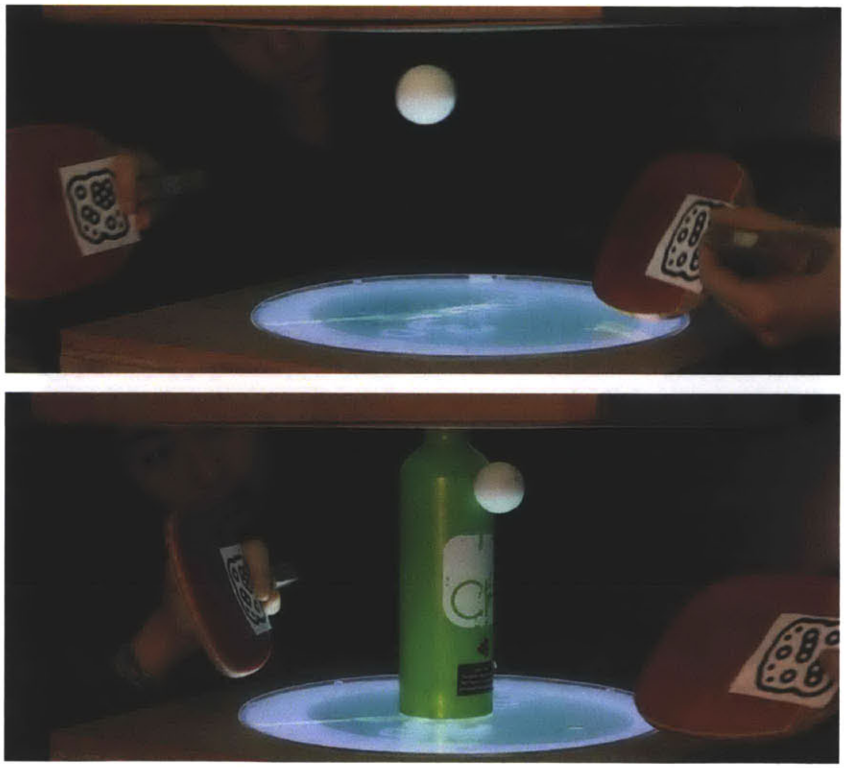


Figure 7-7: Tangible Pong in the physical space.

7.5 Other Application Domains

Ghostly Presence

An intriguing application is to collect the physical motions of people in this medium to preserve and play them back indefinitely. This will allow a unique, tangible record of a user's physical presence and motion.

Tangible Oscilloscope and Sound Synthesizer

I am excited about exploring the possibility of using ZeroN as a tangible oscilloscope where physical motion of levitated objects can represent dynamic signals. This principle can be also applied to musical synthesizing applications. Characteristics of sound forms can be translated to subtle motions of ZeroN and likewise, the user can create, edit, remix new sound and effects by creating or modifying motions of levitated objects. One possible performance scenario involves performers record a musical piece composed of multiple sound sources. Each of these wavelengths can be translated to the vertical motion of each ZeroN object, making them move with a different frequencies and wavewidths. Performers can not only hear but feel the sound form by grabbing the moving levitated objects. They can amplify the signals by giving a larger motion to ZeroN or zoom in or out with their gestures or additional controllers to feel and view the sound form in more detail. Multiple performers can spatially rearrange levitated objects embodying each sound sources to remix, and change the original sound track.

Combination with Other Interaction Modalities

In the area of interaction techniques, I plan to continue the investigation of how ZeroN can be combined with other approaches to the user interface, such as GUIs, existing TUIs, and gestural interfaces. Hopefully, as I continue this investigation, I will find a reasonable role division and transition of the interaction styles that will allow the user to take advantage of each approach. One interesting aspect of this exploration is the use of ZeroN system and a display screen in which a user could transition between using GUI for precision requiring tasks, and ZeroN system for intuitive tangible simulation. In this scenario, a user can design a mechanical components such as a spring with

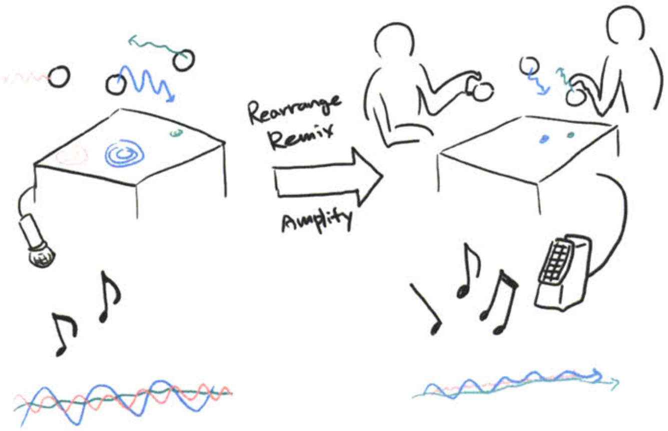


Figure 7-8: Tangible Oscilloscope.

GUI-based CAD system. As the user designs the spring, its physical reaction under certain physical conditions is calculated and is represented by the movement of ZeroN with which the user can feel and control the spring.

Figure 7-9: Combination and role-division with other interface modalities.

Chapter 8

User Observation and Discussions

I demonstrated our prototype to users to gather initial feedback. During the Media Lab Sponsor week of 2010 and 2011, ZeroN was demonstrated to and tested by approximately 150 visitors. The purpose of this demonstration was to evaluate our design, rather than to exemplify the practicality of each application. Here, we further discuss several interesting unique issues that we observed.

Figure 8-1: ZeroN demonstrated to visitors during the Media Lab Sponsor week.

8.1 Leaving a Physical Object in the Air

Users were impressed with the fact that they can leave a physical object in the mid-air, and interact with them. In the camera path control application, users appreciated the fact that they can review and feel the trajectory in the real world, which otherwise would have been only visible in the virtual space otherwise. In the lighting control application, a user commented that they could better discuss with a collaborator using the object that maintains its position in the air.

8.2 Dropping the Object Issue

A confusing part of the current system design is that the 'anti-gravity' space only covers the upper part of the interactive space. Even with instruction, users tended to try to move ZeroN to anywhere in the whole interactive space. I plan to address this issue by changing the color of the graphical projection on the tabletop surface: as ZeroN tries to move out of 'anti-gravity' space, the color of the surface will turn to red to notify users that they are about to drop the ZeroN object.Many users also commented that latency in electromagnet's

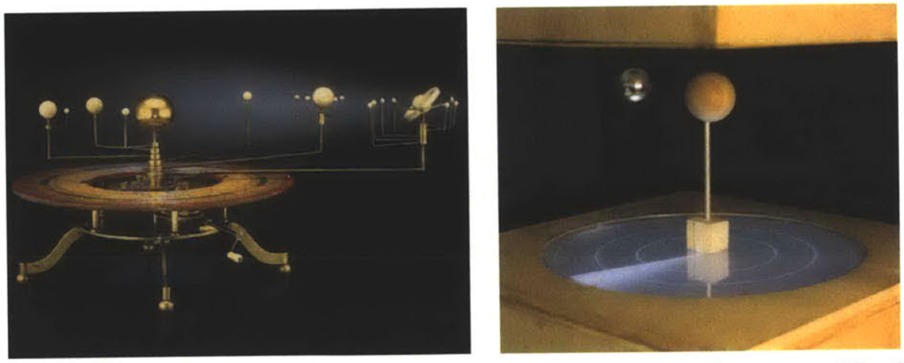
Figure 8-2: Having a physical representation of a 3D point helps multiple users to discuss the data

updating stable position (between the user's displacement of the object and electromagnets updating the stable position) caused confusions. The participants also pointed out the issue of lateral oscillation, which we are working to improve.

8.3 Interaction Legibility

In the physics education application, users were excited about the fact that 3D computer simulations can have a tangible form that they can touch, feel and modify with their hands. A few users commented that not being able to see physical relationships between planets make them more difficult to anticipate how they should interact with this system, or what would happen if they touch and move the objects.

Being able to actuate an object without mechanical linkages in free space allows for a more degrees of freedom and access from all orientations. On the other hand, this decreases the legibility of interaction by making the mechanical linkages invisible. By contrast to a historical orrery (figure 8-3) machine in which the movements of planets are constrained by mechanical connections, in ZeroN users can immediately understand the freedom of movement that the mechanical structure affords. One of the possible solutions to compensate for this loss of legibility is to rely on graphical projections or subtle movements of the objects to indicate the constraints of the movement. Carefully choosing an application where the


(a) Physical Orrery

(b) The ZeroN displaying an orbit of a planet

Figure 8-3: Physical Orrery and ZeroN: hiding mechanical structures increases degrees of freedom, but decreases legibility of interaction gain of freedom outweighs the loss of legibility was our criteria for choosing application scenarios.

Chapter 9

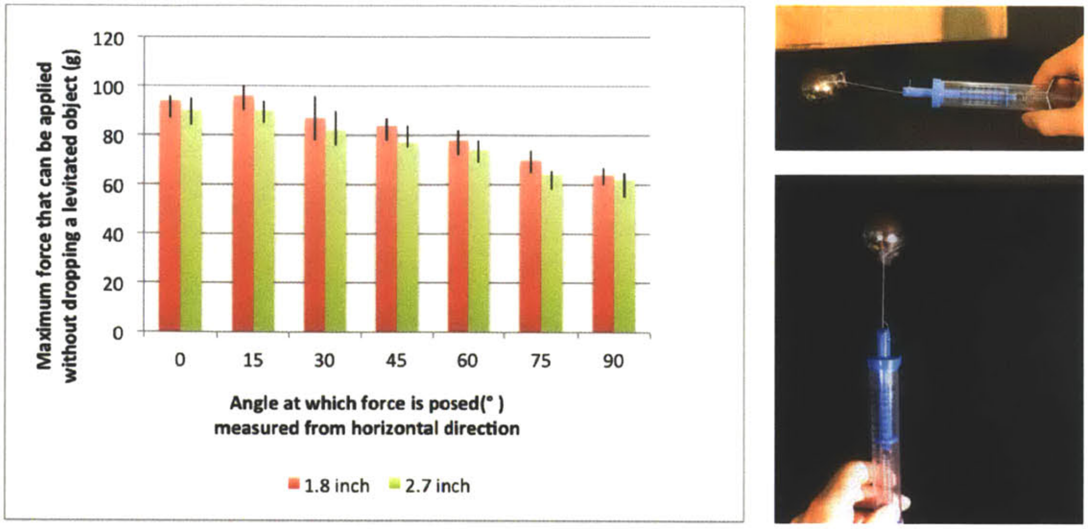
Technical Evaluation

9.1 Maximum Levitation Range

The maximum range of magnetic levitation is limited by several factors. While our circuits can handle higher currents than are now 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 2.8 inches 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 electromagnet.

9.2 Speed of actuation

The motor used in the prototype can carry the electromagnet with a maximum velocity of 30.5cm/s and a top acceleration of 6.1m/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 3.9m/s^2 of the lateral acceleration can drop the ZeroN.



(a) (b)

Figure 9-1: (a) Maximum force that can be applied to ZeroN without dropping. (b) Forces were measured from various angles using a spring scale.

9.3 Resolution and Oscillation

If we frame our system as a 3D volumetric (physical) dis-play in which only one cluster of volumetric pixels 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 (wiggling) of the levitated object makes it difficult to define this as the true system resolution. In the current prototype, ZeroN oscillates within 0.5 inches horizontally and 0.25 inches vertically around the set position when moved. We call the regions swept by oscillation"blurry" with a "focused" area at its center. We discuss the remedy for lateral oscillation in the technical limitation section.

9.4 Robustness of magnetic levitation

Robust magnetic 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 mag-net to a linear spring scale that can measure up to 100g of weight. We pulled it towards the direction of 0°(horizontal), 15°, 30°, 45°, 60°, 75°, and 90°(vertical). We conducted these experiments under two different levitation ranges (1.8, 2.7 inches). We measured 5 times for each case and plotted the average. The camera feedback system was disabled during all the measurements. We plot the result in figurefigure 9-1. Levitation is more robust along the vertical axis than along the horizontal axis. It is interesting to note that ZeroN can stand 70g of the vertical force, which shows that simple electronics, such as a small OLED display and battery, can be mounted on the levitated object.

Chapter 10

Technical Limitations and Future Improvements

In this chapter, I identify the limitations of the current ZeroN systems and outline the directions of future development of technologies for scaling up mid-air tangible interaction.

Lateral Oscillation

Lateral oscillation was reported as the primary issue to correct in our application scenarios. We plan to implement satellite coils around the main electromagnet which can impose a magnetic force in a lateral direction. This will provide improve haptic feedback.

Number of Levitated Objects

While the current prototype can only levitate and actuate one object, we are currently designing a system that can levitate and control movements of multiple ZeroN objects. This will be enabled by replacing a single solenoid carried by linear actuators with an array of multiple solenoids that have more control over the entire magnetic field.

Vertical Range of Levitation

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.

Magnetic 3D Tracking

A desirable extension is to use magnetic sensing technology in 3D tracking. We originally planned to implement an array of hall-effect sensors attached to the ceiling of the interactive space to track the 3D position and orientation of the spherical magnet. While this technology 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 fields generated by electromagnets through the precise calibration of dynamic magnetic fields. To avoid these difficulties in the short term, we added vision tracking to our system prototype. This limits the hand input to areas that do not occlude the view of the camera.

Chapter 11

Conclusion and Future Direction

This thesis presents a novel concept of mid-air tangible interaction and ZeroN, a system that is developed to enable this interaction. Through this research, we extend the tabletop tangible interaction modality that has been confined to 2D surfaces to 3D space above the surface. To support this interaction, we designed and developed the ZeroN system which presents significant innovations in computer-controlled actuation. It is the first system that utilizes the 3D positioning of a physical object in mid-air in human computer interaction, using external forces without any physical attachment to the object. The technology includes stable long-range magnetic levitation combined with interactive projection, optical and magnetic sensing, and mechanical actuation.

We augmented and appropriated interaction vocabulary for tabletop tangible interfaces to employ mid-air 3D space in tangible interaction. To explore the interaction techniques, we developed applications that include architectural modeling, physics simulation, and education and 3D motion prototyping. While the current prototype presents many interesting challenges, we are encouraged by what is enabled by the system and will continue to develop scalable mid-air tangible interfaces. Our observations throughout the past months have given us insights into the future implications of the mid-air tangible interaction and the mechanism of untethered 3D actuation of physical objects. I discuss those in the following sections.

11.1 Pervasive Display : Displaying Information between and around objects and people

The approach of untethered 3D actuation of objects implies that the data can be displayed at any point within a 3D space, even between or around human bodies and objects. Further research into this aspect could develop an infrastructure to convey information in a pervasive way, filling out unexplored mid-air space with information.

Displaying Around Body

Immersing human bodies and objects in computational 3D display mediums has long been featured in science fiction films. The closest example would be a scene from the film 'Iron Man', 2008, where the lead character places his hands in a holographic display of armor. This feature can be implemented with ZeroN. For example, users choosing clothes on the internet could place their arm in a ZeroN space, and levitated objects could revolve rapidly around the arm to indicate the size and 3D shape of the clothes.

Displaying Around Objects

With the proposed mechanism, a ZeroN object can also be programmed to fly around everyday objects to convey information in a pervasive way. For example, ZeroN flying around a Jenga-tower could provide users with hints about the order in which they should take off the blocks to minimize the risk of the towers collapsing. In another scenario, a novice tennis player may be able to use the ZeroN system to learn how to hold and use a tennis racquet. For instance, a ZeroN object can be arranged around a racquet placed in the ZeroN system to indicate a user' grasp and move in space to demonstrate the motion of an ideal swing.

11.2 From Representation Toward Reality

How is the ZeroN's approach fundamentally different from actuated interfaces on 2D surfaces [16], [15]? When using 2D actuated tabletop interfaces, users seem to be able to differentiate the system from the 3D world that they inhabit. As soon as they stop working on the computer and lift their fingertips off the surface, users feel that they are detached from the 2D surfaces where dynamic computations happen. Since this dimensional transition is possible, users can easily distinguish the 'interface system' and the real world.

However, this transition does not happen when interacting with ZeroN that can move in a 3D space. The behavior of the users' body adapts to the movement and behavior of the ZeroN object, and the users find it hard to distinguish the interface system from the rest of the real world. I assume that this is due to the fact that the users' body and physical output of computers belong to the same dimensional space and can symmetrically interact with each other. The users therefore tend to recognize the ZeroN object as a part of reality rather than merely as a representation of information (even though it also represents information). From this, I deduce that it will be worth looking deeper into how this feature affects users' cognitive processes.

The Zero-pong application is a direct example of such phenomena. When the computer program of the pingpong ball's physical behavior was changed, the user's behavior and responses were also directly affected: they tried to adapt their bodily reaction. In another scenario, one could imagine the ZeroN system to be used as a tool for simulating responses of machinery. The levitated object may be connected to a part of working machinery and be actuated by computers to apply a certain motions or forces to test the system.

11.3 A Final Challenge

In closing, I propose a challenge to future researchers of tangible user interfaces. If behaviors and properties of physical objects become programmable by computers, as supported by the recent movements of human computer interaction, will the benefit of tangible interfaces still hold? Observations of ZeroN suggest that affordance – one of the most important qualities in tangible interfaces – can change when physical objects move or behave in unexpected ways. In such interfaces, providing proper visual or physical feedback may play more important roles than physical affordances in guiding users through interface systems . Designers of such interfaces may have to carefully contemplate what they gain or lose by making physical objects actuated and programming their behaviors.

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