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TITLE:

The Responsive Layer: Steps Towards a Digital Augmentation System to Make Everyday Objects Responsive

AUTHOR:

Yun Hao

ACCEPTED BY:

[redacted] May 25, 2020

Daniel Cardoso Llach Principal Advisor May 25, 2020

Abstract

Everyday objects are an integral part of our lives and are the daily physical interface between us and the world. The traditional way to make objects respond to human actions through digital technologies is through built-in hardware and software, combined with screen-based user interfaces. This thesis proposes an interactive system named Responsive Layer that enables users to add a layer of digital information on top of everyday objects through projection without the need for additional embedded sensors and interactive devices. The system combines projection mapping and computer vision technology to perceive the interaction between users and physical objects and responds with images and text. The thesis introduces an easy-to-operate system for designers and end-users to interact with everyday physical objects and spaces. The thesis first outlines the motivation and research goals. It then studies the background and related work to position the thesis. Next, it discusses the design and implementation details of the system, and prototypes used to test and improve the system. The development and observation of the five prototypes prove the feasibility, scalability and broad application prospects of the system. The first three prototypes simulated the interaction between a user and a folder, and tested the system's perception of users and objects, the recording and display of context information, and its playability. The fourth prototype showed how to design the reminder function of a cup. The last prototype demonstrated the feasibility of the system to track user movements in an architectural space.

The Responsive Layer:
Steps Towards a Digital Augmentation System to Make Everyday Objects Responsive

Yun Hao

Thesis Supervisor: ______________________________

Daniel Cardoso Llach

Associate Professor of Architecture

Computational Design (MS) Track Chair

Thesis Reader: ______________________________

Daragh Byrne

Associate Teaching Track of Architecture

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Chapter 1

Introduction

In the future I imagine, every ordinary object in the physical world can communicate with people and recall their stories without the need of additional equipment or devices. Everyday objects are just like our old friends. We are familiar with each other and share stories and experiences.

This thesis concerns how our daily objects can be designed to record and present the experience of users during human-object interaction. It discusses means to extend traditional design thinking to incorporate the ability of record into ordinary objects. Instead of directly design and transform objects, the thesis introduces a system as a medium to sense human activities, record context information of user experience, and convey information through objects' surfaces. It further discusses the form and content of the information that is expected to convey to users and methods to interact with the medium and objects.

1.1 Motivation

The Internet and its applications have become an indispensable part of today's human life. The concept of Ubiquitous Computing (Weiser 1999) was first advocated by Mark Weiser in 1988. He predicts that devices like computers and laptops will one day be as ubiquitous as ordinary everyday objects such as paper. It should be that smart devices adapt to human life, instead of force humans to adapt to the world where they exist. With the rapid development of the Internet of Things, the Internet has gradually connected the network and networked objects seamlessly. The most popular application of IoT is the Smart Home, which consists of wireless speakers, smart thermostats, smoke detectors, security and monitoring systems, etc. Sensors are responsible for collecting data about the environment, such as temperature, which is transmitted and stored via the internet. Users obtain these data and control the device through the display screen of the device, a third-party device such as a smartphone, or through a speaker.

Although the Internet of Things makes our lives more convenient, the entire interaction process with smart devices requires lots of hardware and software to complete. Smart devices that have been widely used often have software tailored for them and assembled hardware as user interfaces. This results in users having to access different apps and remember different operations to control multiple IoT devices. Another issue that cannot be ignored is that due to its built-in hardware and software, the popular smart items are not cheap and are not the daily necessities we expect. In our daily life, there are many ordinary things without such hardware and software, but we use them every day such as chairs and cups. Can we make them smart and communicate with us like smart speakers? Imagine that the cup you use every day can record interactions between you two and show you the information related to your past experiences, and even remind you to drink water on time. Would it be more interesting and meaningful? However, at present, this idea is very difficult to achieve. People are unlikely to pay a high price for a cup with built-in sensors and a display screen.

Compared to the embedded hardware, in recent years, digital augmentation has gained a lot of attention by enhancing the virtual state. The combination of sensory and technology creates new possibilities for our interaction with the physical world. Digital augmentation technology allows people to take advantage of the flexibility of the computational medium without losing the physical texture of our environment. Since Ullmer and Ishii introduced the concept of Tangible User Interfaces (TUIs) (Ullmer and Ishii 1997), many designs and researches have frequently applied everyday objects to the interaction process with users and regarded them user interfaces. However, objects as TUIs often act as simple tokens for users to interact with digital information: models were created for the purpose of controllers for users to play games (Wilson 2007), objects with abstract information on them were made for interacting with live music on a tabletop interface (Jordà et al. 2007). The initial purpose and physical affordance were ignored and modified by users when using them as part of the TUIs.

To this end, this thesis proposes the Responsive Layer as a general system that enables everyday objects to perceive context information related to user experience, analyze and store the data, and convey the information back to users. The Responsive Layer aims to make interactions between people and the physical world more interesting, more diverse, and further stimulating more interactions between users and objects.

1.2 Thesis Goal and Outlines

My goal is to develop a universal system that can be applied to the physical objects and spaces to detect user actions and respond to us through digital augmentation. Besides, the thesis will provide a basic system architecture for research purposes and personal experience.

The remainder of this thesis is composed of four chapters: background and related work, design and implementation, use case prototypes and observation, and conclusion and future work.

Chapter 2 introduces the concepts and theories mentioned in this thesis and explains how these concepts relate to this thesis. Besides, it articulates a review of the previous work and research on which the thesis builds. The topics that will be covered are design with experience, responsive environments & digital augmentation, interaction with digital-augmented objects. The chapter discusses the advantages and disadvantages of each project, the inspiration for the thesis, and the methods or techniques to be used.

Chapter 3 documents the design process and implementation of the Responsive Layer system. This chapter elaborates on the design ideas, the workflow and components of the system, and the configuration and implementation of each module. The first section raises the research questions based on the study of the background and related work. The second section explains the design goals and the general functionality of the system. The third section proposes the design criteria and core idea that guide the whole design process. The fourth section gives us an overview of the system workflow, which is composed of three modules. The following is a detailed description of each module.

Chapter 4 demonstrates five use case prototypes of the Responsive Layer: perception of user proximity, the approaches to make users understand the importance of daily objects, the playfulness of reliving the past, the practical reminder function, tracing movement in architectural space. This chapter documents the design and implementation of each prototype, as well as the Observation and Reflection of the prototype.

Chapter 5 summarizes the findings and contribution of the research, followed by the plan of the future work. The contribution is discussed from its design value and technical value. The future work includes many-to-many interaction, digital technology integration, construction of the responsive environment, and human memory.

Chapter 2

Background and Related Work

This chapter explains the related background of the thesis, selects the works related to the research topic. This chapter is divided into four parts: the meaning of objects, recording and display the past, responsive environments and digital augmentation, and interaction with digital-augmented objects. This chapter analyzes in detail the contribution of each works, the inspiration for my research, and reflects on the shortcomings.

2.1 Meaning of Objects

Objects often convey the information about their intention and ownership through its shape, material, and the mark left on them. In ancient Greece, people would write on almost any kind of object. But often the text inscribed on these objects was composed in the first person, so that the object talks to the reader (crewsproject 2017) (Figure 2-1). Some objects claim to have owners, others tell us who dedicated them and to whom. At that time, people talked to gods in this way and prayed for a blessing. Initially, objects are our medium to the unknown world and inner emotions.

As a matter of fact, objects themselves contain lots of information. An object can be viewed as an identity, a symbol, or a pattern in the physical world. Because of its unique concreteness, man-made objects witness the history of themselves and their users. The Traces and marks left anonymously on the pavement tell us stories and histories about our living environment. Every object is different, telling the different history, different activities, and different feelings it witnessed. The artwork Modern Life is Rubbish (Figure 2-2) utilizes the permanence and everyday nature of furniture to express impermanence and the passage of time by printing text on the surface (Shiels 2014). It reminds people that we should reconstruct our understanding of the interactions and relationships with everyday objects. In a sense, these inanimate objects have become animate and have an “active existence”.

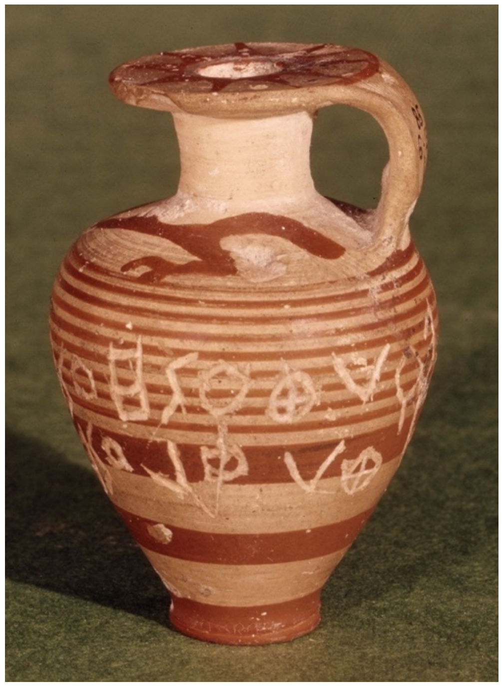

Figure 2-1 Tataie’s aryballos (Swaddling 1986)

Figure 2-2 The stories abandoned objects tell (Shiels 2014)

Objects also serve as a bridge to enhance interpersonal bonds. A music greeting card expresses our wishes to other people through words and sounds. TV connects family members together, to some extent promotes interaction within the family. Interaction with objects has changed our way of life (Watson 2009).

Another undeniable fact is that those things used, owned by people may reflect the owner's personality and preferences accurately. The psychologist Csikszentmihalyi describes the relationship between everyday objects and person in “The Meaning of Things: Domestic Symbols and the Self” (Csikszentmihalyi and Halton 1981):

> My old living-room chair with its worn velvet fabric, musty smell, creaking springs, and warm support has often shaped signs in my awareness. These signs are part of what organizes my consciousness, and because myself is inseparable from the sign process that constitutes consciousness, that chair is as much a part of myself as anything can possibly be.

The "Object Portraits" event (National Museum of American History 2012) organized by the National Museum of American History requires participants to submit photos of the five items that best represent themselves (Figure 2-3). In the uploaded photos, we can see all kinds of items, including clothing, photos, toys, books, etc. These items are not expensive daily objects. It can be seen from the degree of wear of the item that it has actively participated in the person's life. Interestingly, we can indeed glimpse the personality and lifestyle of its owner from a few items. In this way, understanding our relationship with everyday things not only helps us understand others and the physical world, but also helps us understand ourselves better.

Figure 2-3 Describe yourself in five objects (National Museum of American History 2012)

The researchers conducted interviews of 82 families in contemporary American cities and discussed the most special things in their homes for them (Csikszentmihalyi and Halton 1981). The special here means significant, meaningful, highly valued, useful, and so on. As the result shows, furniture is the most special category of objects (36%), followed by visual art (26%). What makes these items special is that they carry a lot of memories and experiences (Table 1). Surprisingly, utilitarian is not the main reason for the meaning of objects. This study shows that the connection between the human and the world of artifacts is more related to mental emotions and experiences.

Table 1 Proportion of respondents mentioning various classes and categories of meaning for cherishing special objects (N —315) (Csikszentmihalyi and Halton 1981)

Non-person-related reasons	Percentage of people mentioning
1. Experiences:	86%
Enjoyment	79%
Ongoing Occasion	48%
Release	23%
2. Memories	74%
Memento	52%
Recollection	46%
Souvenir	22%
Heirloom	20%
3. Intrinsic Qualities:	62%
Physical Description	46%
Craft	34%
Uniqueness	17%
4. Style	60%
5. Personal Values:	53%
Accomplishment	31%
Embodiment of Ideal	24%
Personification	15%
6. Associations:	52%

Gifts	40%
Collections	15%
Ethnic	9%
Religious	7%
7. Utilitarian	49%

Understanding the meaning of everyday objects and their importance in our lives helps us design the way users interact with everyday objects. However, in order to make inanimate objects to respond to users' actions, we still need the help of the external environment and technologies. Next, the thesis will explain two concepts that closely related to this research.

2.2 Recording and Display the Past

We rely on our senses — sight, hearing, smell, taste, and touch — to perceive the environment we live in. During the interaction with the physical world, all sensory modalities are open to receive information. The following projects show how designers can record and show experiences by capturing the sensory experiences of people and the physical world.

Memory Shapes are physical objects generated by data, used as personal memory storage, and is derived from the statistics of individual records (Gmeiner 2007). From the designer's perspective, these objects together form a sculpture that grows with a person's life. The memory collectors are made of boxes and plastic buttons and each shape is being calculated and customized. The Memory Shapes gradually growing as individual life documentation which can be edited and reviewed (Figure 2-4). The uniqueness of this design is that it transforms the lifetime period into data that can be recorded through graphics or text. Small and easy-to-make objects as mementos encourage people to interact with them through their compelling shapes. Although the work inspires us in the way of presenting experience, the interaction is based on human initiative, and the recording and storage of memory also need to be done manually.

Figure 2-4 Memory Shapes (Gmeiner 2007)

“reMi” (Choi et al. 2018) is a portable tangible memory notebook that uses deformable paper records the surrounding sounds and converts them into tangible and shareable memory (Figure 2-5). Designers utilize the nature of paper and its affordance to make a paper follow users’ commands. Folding the paper will trigger the recording process of the microphone and store the sound. Ripping the paper allows users to share the previous recorded memories. With a customized wood blinder clipper that functions as a power connector, the paper can continuously play sound and expand and contract with it. This project considers sounds as a carrier of memories and uses everyday object – paper as a tangible interface for memory display. The core idea of the design of “reMi” is similar to my research topic that makes everyday objects record and display the past. It is an interesting idea to make use of the paper's own foldable characteristics to make the lifeless items look alive. However, this idea is limited and cannot be applied to other objects that do not have this property.

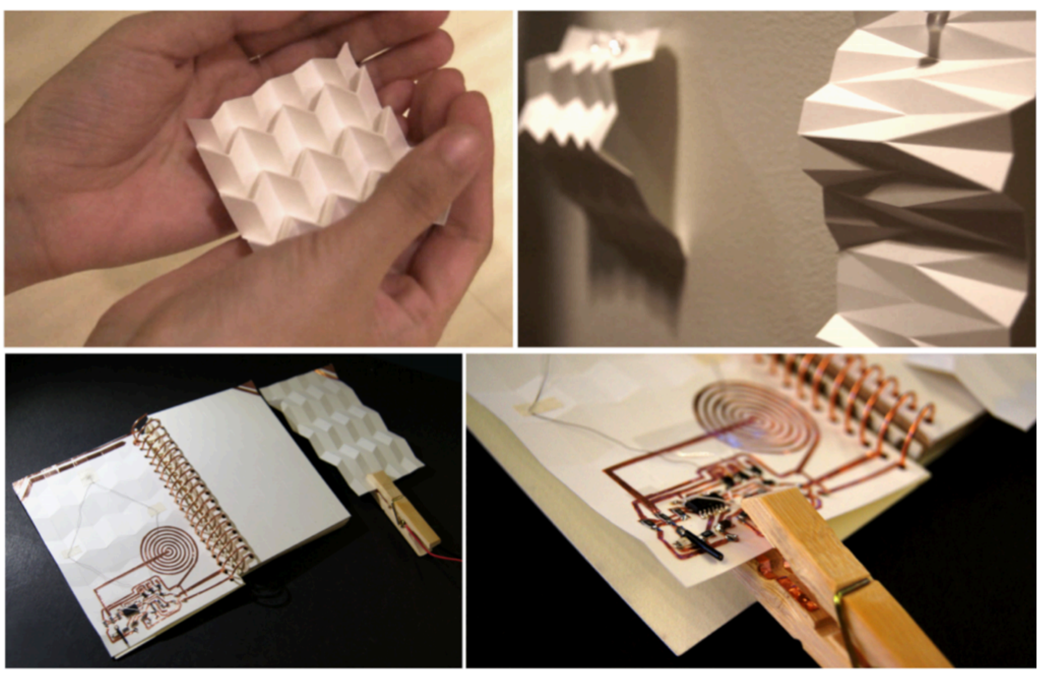

Figure 2-5 reMi: tangible memory notebook (Choi et al. 2018)

Rather than recording all the details of experiences, it is sometimes more meaningful to record the highlights of the past. The Memory Device was built to collect and retrieve personal data (Bertran 2014). In the past, people used their fingers to tie rope or nail paper to help them remember things. The designer believes that the rope and paper are just triggers, which do not store any information in themselves. Bertran argues “Recording is a deliberate action, giving full control over what needs to be remembered and what doesn’t”. Past moments here stored as simple time stamps and displayed as lines in a daytime window on the small built-in screen (Figure 2-6). This idea of remembering while respecting forgetting is fun. It makes me think about what is necessary and what is negligible in the interaction between users and the physical world I am concerned about.

Figure 2-6 Memory Device (Bertran 2014)

The transformation and design of the object itself can sometimes make it easier and more interesting to record past stories. The work Digital Christmas studies the collection of autobiographical memories and reminiscing in collective remembering (Petrelli et al. 2012). Petrelli and Light care about the Christmas traditions in the family, which is gradually meaningful through shared repetition. The designers incorporated digital devices with traditional Christmas trees' decorations to enable them to capture the memories of Christmas each year in the form of digital photos (Figure 2-7). Because of its easy capturing, accumulation, recombination, and play, the family can then decide which content will be captured and treasured for future generations. This work begins with the forgetful instinct of human beings, uses special items to record memories in specific scenes. The special objects possess both reminder and entertainment functions. This work shows us the potential of special items related to specific scenes as a carrier of records.

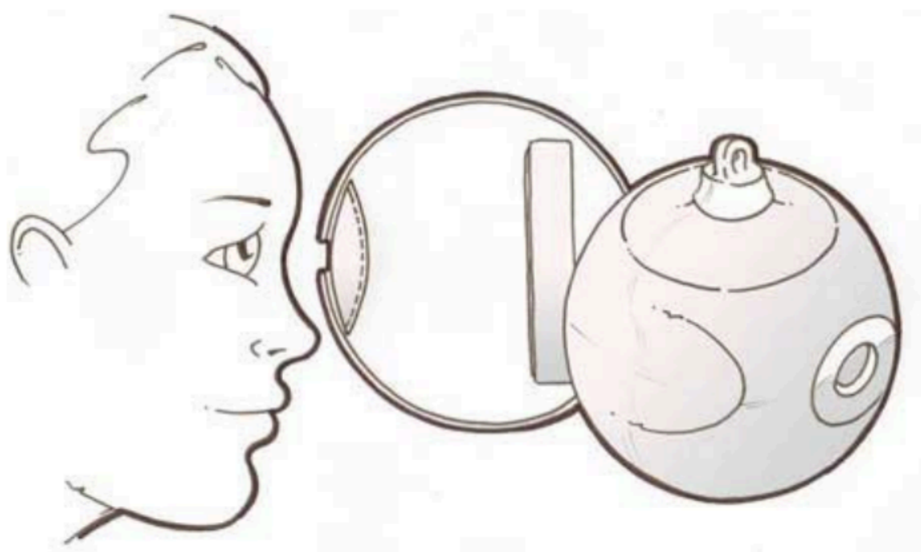

Figure 2-7 A thumbnail size digital frame is encased inside the bauble (Petrelli et al. 2012)

Physical objects can bring us an intuitive experience of the past through their shape and materials, while digital media can provide users with more diverse forms of past records through rich display content. The Affective Diary is designed to capture the physical, bodily aspects of experiences and emotions. Those data about the human body and feelings are collected and uploaded by the user via their mobile phone. The purpose of this design is to incite reflection and allow users to organize their own stories (Lindström et al. 2006). There are seven different predefined body postures used to represent different levels of arousal or movement (Figure 2-8). This project shows the possibility of using body posture and movement to record user experience. However, the postures are default and used as icons. The ability of these graphics to record the user's mood and experience is very limited.

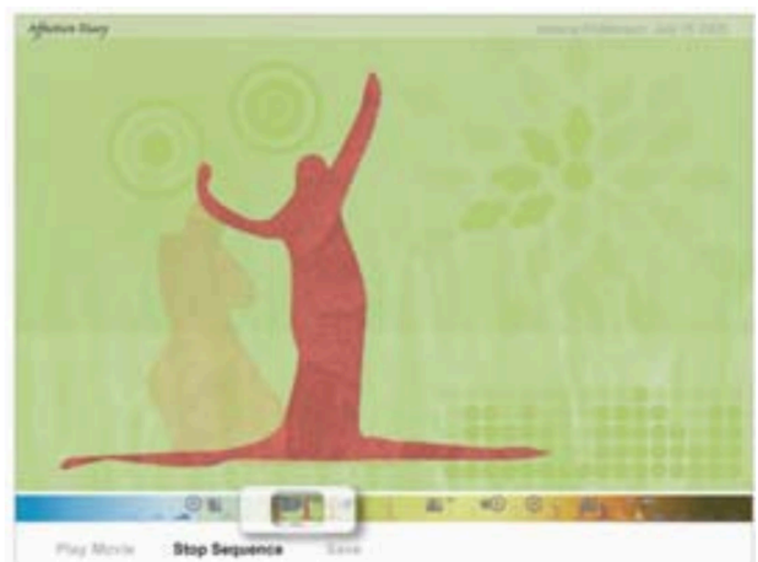

Figure 2-8 The concept of Affective Diary (Lindström et al. 2006)

2.3 Responsive Environments and Digital Augmentation

The term "Responsive Environments" was coined by Myron Krueger in the early 1970s (Krueger 1977). It uses sensory technology and computer equipment to establish a cooperative relationship between the movement of humans and objects in the environment. Responsive environments utilize sensors and other technologies to transmit information about human motion to the computer. The computer then performs corresponding reactions in the environment which enables movement and gestures of the human body to interact with physical objects within the environment.

Digital augmentation refers to the enhancement of virtual presence through the use of digital content (Satchell 2009). Essentially, responsive environments are achieved with the help of digital augmentation. Researchers observed through comparative experiments that by applying digital augmentation to traditional games, user participation and interest are greatly improved (Durães et al. 2018).

Previous research in the field of human-computer interaction has shown that screen-based interfaces often lead to isolated user experience, which hinders social interaction and human-object interaction (Lanir et al. 2013). In contrast, by applying digital augmentation technology to a common space, visitors can have a more intimate and emotional experience with the space (Claisse, Ciolfi, and Petrelli 2017).

Nowadays, digital augmentation is often applied to architectural spaces to realize responsive environments. For example, light is used to stimulate social interaction in public spaces to trigger interaction with people and the space (Monaci et al. 2012). In the design of responsive architecture and landscape, the surface of the architecture and the element of the landscape are designed as deformable to respond to participants' actions (Meyboom, Johnson, and Wojtowicz 2011).

This thesis adopts some principles of responsive environment design and the method of applying digital augmentation technology in architectural space to realize the response of the physical world to user behaviors.

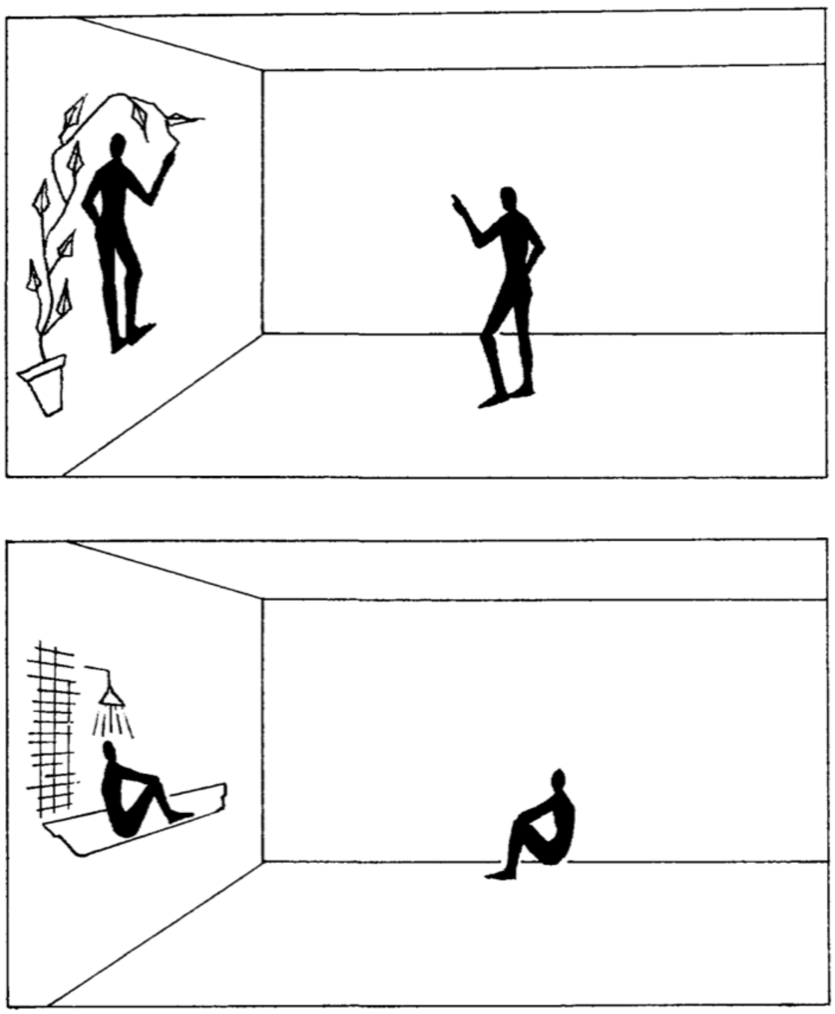

Figure 2-9 Metaplay drawing (Krueger 1977)

A variety of objects make up the physical world we live in. Our interaction with objects is essentially the interaction with the surrounding space and the environment.

From this perspective, before study how to make objects respond to us, we should first explore the works that make spaces responsive.

Krueger describes several ways to construct the responsive environments. One way is to combine computer graphics, video projection, and two-way video communication (Krueger 1977). The METAPLAY art exhibition provides the audience with unique real-time interaction with the artwork projected on the gallery screen. Sensors and computer equipment are responsible for passing information between participants and the artist who was in another building (Figure 2-9). In this way, participants can interact with the environment and get responses from the live videos. The exhibition also attempts to involve the audience in artistic creation by merging the drawings of participants and artists. Another project, PSYCHIC SPACE, with the help of digital enhancements, further makes the response environment more intelligent.

In this project, a flooring sensing module senses participants' positions on the floor and the program automatically react to the footsteps with electronic sound and graphics projected on the wall. PSYCHIC SPACE aims to encourage participants to express themselves while interacting with the environment, which is achieved through a series of carefully combined relationships (Krueger 1977). These applications demonstrate the rich application of the response environment in aesthetic expression and enormous potential in education and psychology field.

Illuminating Clay is designed for real-time computational analysis of landscape models (Piper, Ratti, and Ishii 2002). This interface allows users to explore and analyze free-form spatial models. The project shows the potential advantages of combining physical and digital representations. The physical clay model simulates real terrain can bring users the most intuitive feeling (Figure 2-10). The projected dynamic graphics help users understand changes in natural landscapes. The most inspiring part of the project is that the authenticity of the physical model and the richness of the digital projection can make their combination produce the optimal effects.

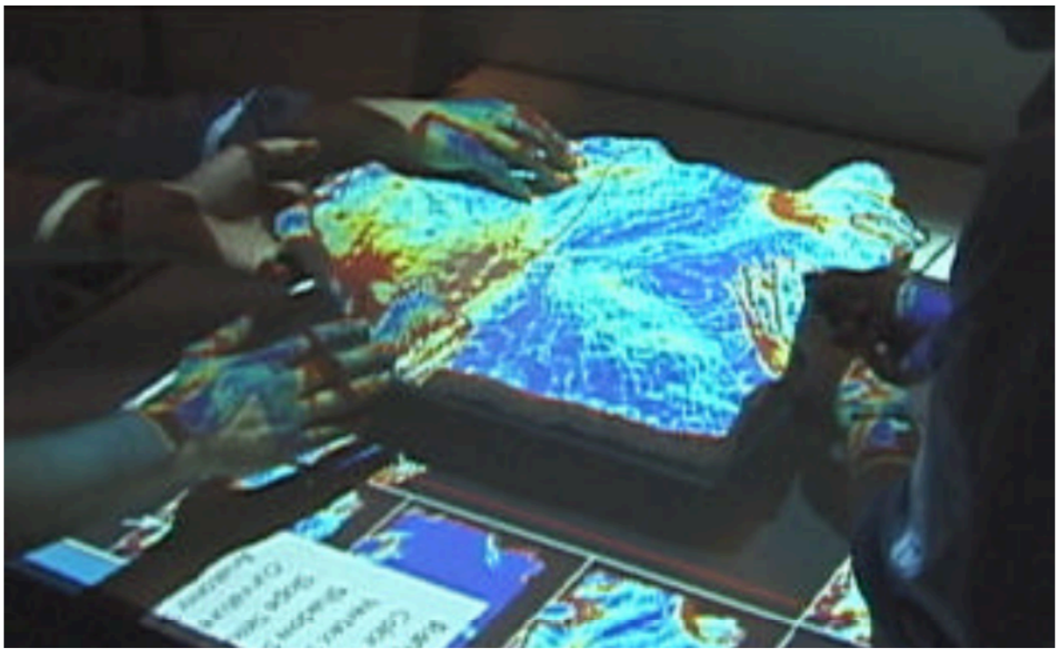

Figure 2-10 User's hand interacting with the Illuminating Clay (Piper, Ratti, and Ishii 2002)

With the assistance of the projection mapping technique, Tang's research mimics two popular illustration techniques, namely transparent and cutaway drawings, to visualize 3D internal information for a tangible user interface (Tang 2014). Projection mapping is used to create a tangible user interface for users to visually inspect 3D internal information (Figure 2-11). Although the researcher used physical objects to display digital graphics, the physical objects are still served as a 3D screen with no further meaning or usage.

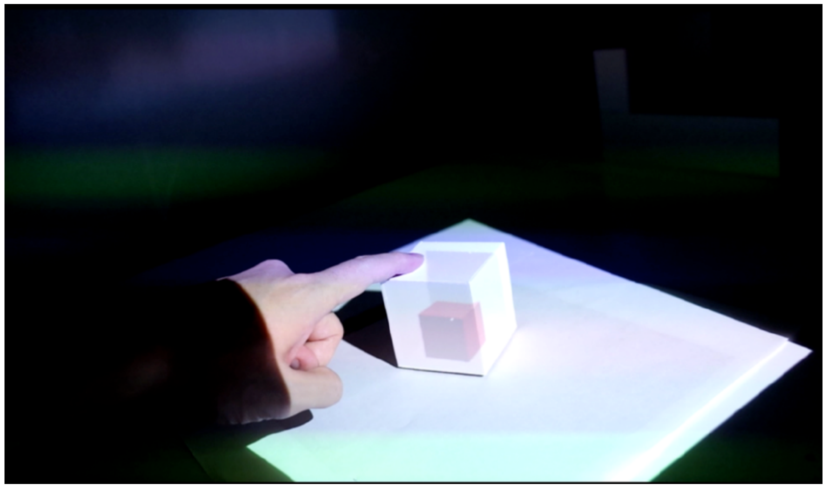

Figure 2-11 Simulating Transparency and Cutaway to Visualize 3D

These works show the wide application of digital projection in responsive environments. Digital projection can be applied to almost any object surface, which meets our requirement of the universality for the tools and techniques. To realize the interaction and response between users and daily objects, we also need to investigate the method used to interact with digital-augmented objects.

2.4 Interaction with Digital-augmented Objects

Interaction through gestures has long been a hot topic for researchers. By adopting computer vision algorithms and IR-based cameras that register depth, the computer can detect the gesture of our hands (Starner et al. 2000; Bergh and Van Gool 2011). Designers later make use of the techniques, combining free-hand gestures and direct touch, to extend the interaction with physical objects (Leithinger et al. 2011) (Figure 2-12). Gesture control eliminates spatial limitations. Digital images and physical models can change with gestures, which provides users with a lot of fun and leads to more interactions.

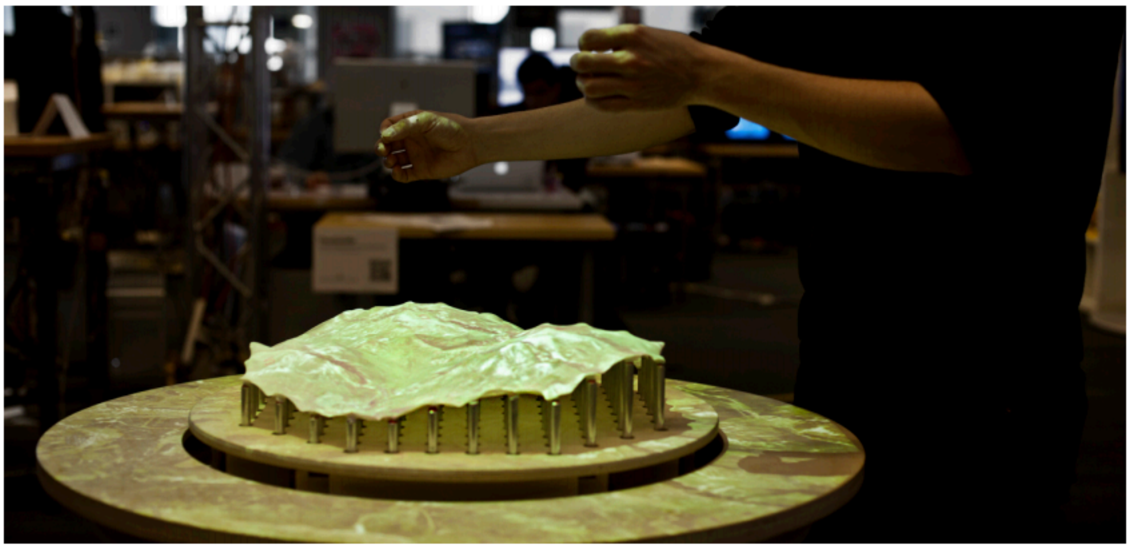

Figure 2-12 A 2.5D Shape Display (Leithinger et al. 2011)

Human Dynamic Medium adapts computational media to education and social works ("Dynamicland" n.d.). They use physical materials — paper and clay, tokens, and toy cars — brought to life by technology in the ceiling. With digital augmentation, the room itself is a computer where people literally work together, face-to-face, with eye contact, and many hands (Figure 2-13). In this condition, the meaning and function of the physical objects are modified by digital augmentation. The tokens and cars are viewed as buttons and controllers.

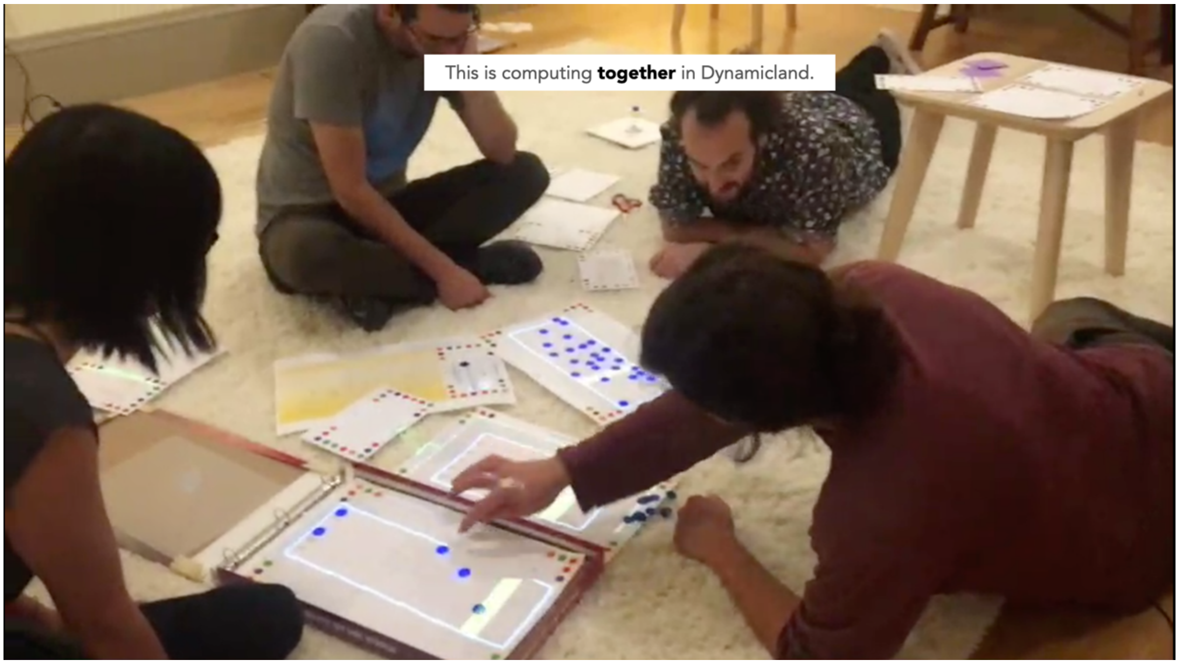

Figure 2-13 The Sociability of Dynamicland work

Gesture control demonstrates its superiority, that is, it is not limited by the object material and the surrounding space while providing users with greater flexibility. The applicable scenarios of gesture control are also consistent with the use cases I envisioned. In the next chapter, I will further analyze the pros and cons of gesture control and direct control.

Chapter 3

Design and Implementation

This chapter is based on the previous investigation on the research background and related works, proposes research questions and design ideas, and explains in detail the implementation of the design. In addition, this chapter also introduces the architecture and the workflow of the Responsive Layer system in detail and discusses the selection and consideration of the applied technology and components.

3.1 Research Questions

The thesis started with the study of the problem and the understanding of related concepts. After investigating the related works, the research questions is raised:

> Can we make everyday objects respond to user activities and convey information without embedded hardware and software? How does digital augmentation achieve this vision?

3.2 Design Goals and General Functionality

The overall goal of the Responsive Layer is to enhance interaction and emotional connection between humans and the physical world. With the help of digital augmentation, the system enables inanimate everyday objects to respond to human actions and communicate and with us.

The main functions of the Responsive Layer are 1. Detect the interaction state between the user and the object; 2. Collect and store context information during the interaction, which is used for the user to view; 3. Remind and accompany the user to relive experiences through digital augmentation.

3.3 Design Criteria

Through in-depth study of background concepts and related works, I summarize several design criteria:

Respect the Original Functions

The design should respect the intrinsic attributes and functionality of everyday objects as much as possible, and at the same time does not hinder the original interaction between the user and the object. The response layer can be seen as an extension of the functions of daily necessities. For everyday objects, the most important usage is their original function, such as cups for drinking water, chairs for sitting, notebooks for recording and reading. Therefore, when designing and expanding the use of such items, we should avoid major changes to the original function, appearance, and materials of the items, and try to add new functions in a gentle and lightweight manner.

Versatile and Extensible

The system should be highly versatile and extensible, not limited to specific objects or scenes. As mentioned in the design goals in the previous section, the application targets of the response layer are multiple objects and multiple scenarios. Therefore, its versatility and editability should be considered in the design of the system and the selection of application technology. Under the premise of being applicable to multiple objects and scenes, how to display relevant information according to the characteristics of different objects is another important consideration in the design. The content and type of information to be presented to users should also be customized later based on user preferences.

Simple and Easy-to-follow

The setup and the configuration of the system and its required equipment should be simple and easy-to-follow. As previously discussed, the Responsive Layer system needs to reduce the firmware that needs to be installed on the object itself or the user as much as possible to achieve a more convenient and flexible interaction. Since the system is designed for designers and readers of non-professional technicians, the configuration and the structure of the system should be as simple as possible. A clear and understandable system framework needs to be provided.

Appeal to Users

The design of the Responsive Layer should be able to arouse the user's interest in interacting with it. This is reflected in the system interaction content and usability. Information and images delivered to users through digital enhancement should be able to attract users' attention and interest. The way users interact with the response layer should also be simple and easy to operate, so that users can communicate more smoothly with the physical world. The Responsive Layer is designed to allow users to interact with objects more directly, rather than through third-party devices such as mobile phones or screens. This requires selecting an interesting and easy-to-operate interaction method without affecting the original function interaction method with the object.

3.4 Core Ideas

Although there are already many designs and products that make physical objects communicable with people, those solutions are difficult to apply to everyday objects such as a notebook. The focus of this research lies in common items that we use a lot in daily life. They can neither be powered on nor connected to the internet. Even if we can connect them to the Internet through external devices, it is not necessary and makes no sense.

The design aims to preserve the original appearance and function of objects and enable them to proactively pass information to users. Just like people dressing themselves with clothes, we put invisible high-tech "clothes" for everyday objects (Figure 3-1). The invisible clothes for objects are achieved by projection mapping. The perception of the interaction status is achieved by sensing devices that constitute a responsive environment. The construction of the responsive environment only requires a few sensing devices, which is relatively less compared to installing sensors on every object. Through the recognition of the interaction status by the sensing device and the projection of digital information, the Responsive Layer makes responses to user activities and conveys information. By this means, everyday objects seem to become animate, but in fact they are used as agents to display information related to them. The only change to the everyday objects is to attach visual identifiers to their surface.

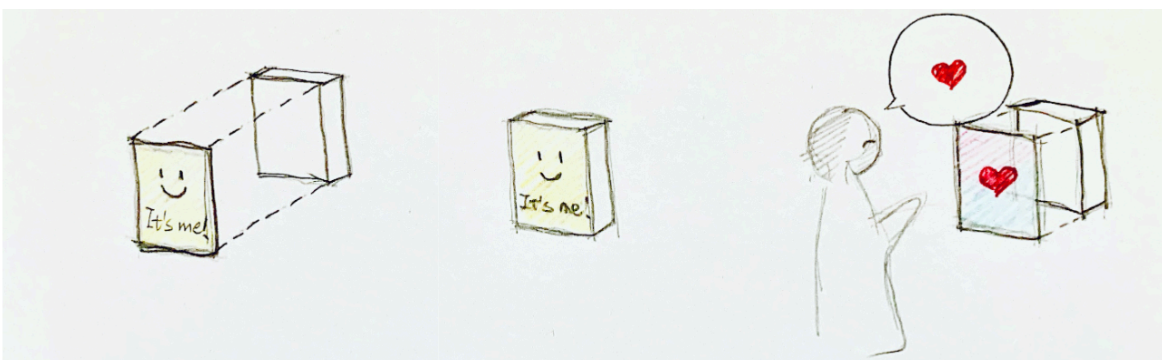

Figure 3-1 The idea of wearing invisible high-tech "clothes" for everyday objects

In terms of the interaction between the user and the Responsive Layer, we chose to use indirect contact – hand gesture control – as the main interaction method. As mentioned in the related work in Chapter 3, gesture control is not limited by space and interactive media and can provide users with more flexible and variable control. Because the interaction between people and everyday objects is mainly based on direct touch, the choice of hand gesture interaction can distinguish between interaction with the Responsive Layer and interaction with everyday objects to avoid confusion.

3.5 System Overview

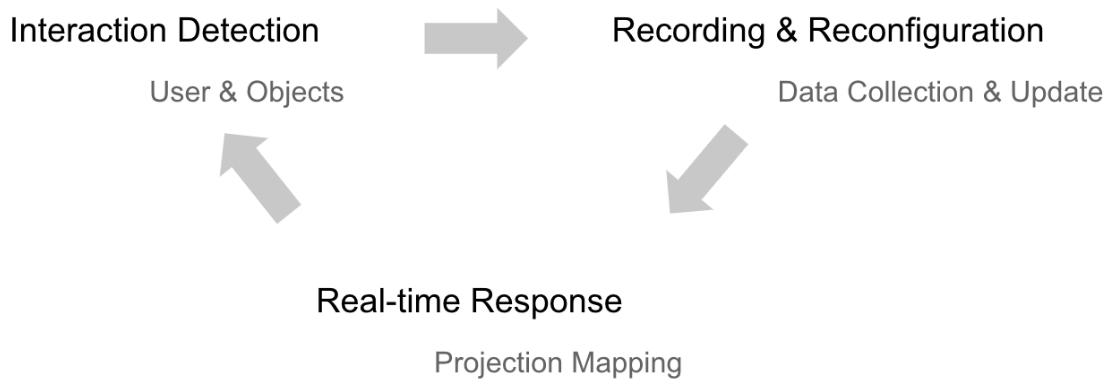

Figure 3-2 Responsive Layer System Modules

The system pipeline consists of three major software and hardware components: interaction detection module, recording & reconfiguration module, and real-time response module (Figure 3-2). The interaction detection module is responsible for user detection, object detection, and interaction state determination based on the detection results. Once the interaction between the user and the responsive environment happens, the recording and reconfiguration module starts to collect and analyze the context information in the interaction process and update the data in the underlying shared database. The real-time response module then relies on the output of the recording and reconfiguration module to configure and render the projection which will be mapped to the surfaces of objects. These three modules interact and influence each other in the system.

Interaction Detection Module

This module mainly performs two kinds of detection work: object detection and user detection.

Pre-generated markers with encoded identification serves as a visual identifier for the system to locate. One or more markers are attached to physical objects that ensure a precise projection mapping on the surfaces.

An IR-based camera is used to capture the images of users. By detecting the human body and analyzing the depth of the body in the images, the system is able to tell whether a user is approaching or leaving. A regular camera with high resolution is used to detect human hand gestures and with computer vision techniques.

Recording and Reconfiguration Module

The context information of physical objects and interaction state is stored in the shared database of the system which is accessible by unique object IDs. The recording & reconfiguration process is basically a feedback loop that keeps updating the context information associated with the specific ID of objects and users. Data collection is accomplished through two methods: automatic system capture and user manual upload. Manually uploading data is an optional way to provide users with more flexibility. Once the interaction state changes, the module will update the data in the database and reconfigure the data content output to the real-time response module.

Real-time Response Module

This module is responsible for mapping the output of digital information from the previous module to the objects that the user is interacting with and get user actions and responses which will be sent to the interaction detection module. Users directly interact with this module through gestures and control the displayed information.

The workflow, design consideration, and implementation of these three modules will be elaborated in the following sections.

3.6 Hardware Setup

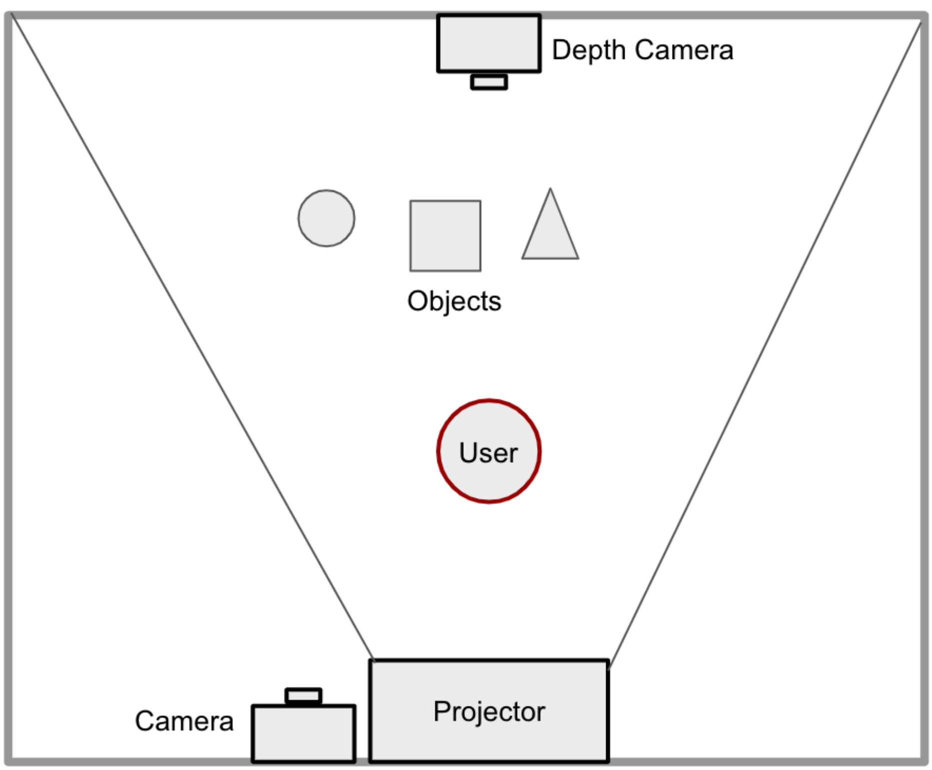

Figure 3-3 Hardware Setup

The basic hardware required to establish a simple Responsive Layer includes a camera with high resolution, a depth camera, a projector with high brightness, and a laptop or computer. The high-resolution cameras should be placed as close as possible to the projector, facing the objects that will participate in the interaction with the user. The depth camera should be placed on the opposite side of the projector that closes to objects, facing the projector (Figure 3-3).

The ordinary camera is used for marker detection, objects localization, and hand gesture detection. To optimize the accuracy of computer vision detection and analysis, the camera is supposed to have a resolution no lower than 720p. The camera we used is a webcam that has a full 1080p resolution, H.264 video compression, and can work with a computer through the USB connection.

The depth camera is responsible for human body detection and depth detection. With the depth information of the captured human body, the system is able to calculate the distance between the depth camera and the human body. The Intel RealSense Depth Camera D435 is used during the experiments. It has up to 1280 x 720 active stereo depth resolution and up to 90 fps frame rate.

As for the projector, it is the core component of the entire system. The Responsive Layer relies on the projector to map digital images and information onto a variety of physical objects. Different from a plain screen, everyday objects usually have uneven surfaces and different colors on it. This requires the light bulb of the projector to be bright enough to avoid dim projection in daytime rooms or on dark surfaces. The projector used in the system is the ViewSonic M1 Portable Projector which has 250 LED Lumens.

The role of the computer in the system is the command center that connects every single component together and give commands to them. The software programs on the computer need to run continuously to maintain the normal operation of the Responsive Layer. In order to reduce the burden on the computer, we can also migrate the programs to a remote cloud.

3.7 Interaction Detection

The interaction detection module consists of two main detection tasks: user detection and object detection (Figure 3-4). The purpose of user detection is to identify and determine the presence of users, analyze user movement orientation, and detect hand gestures which are used to interact with the system. Object detection is used to localize objects with markers attached to them. Then get the unique ID of the object and retrieve the related dimensional information and other detailed information from the database. User detection and object detection together determine the status of interaction between the user and the responsive environment.

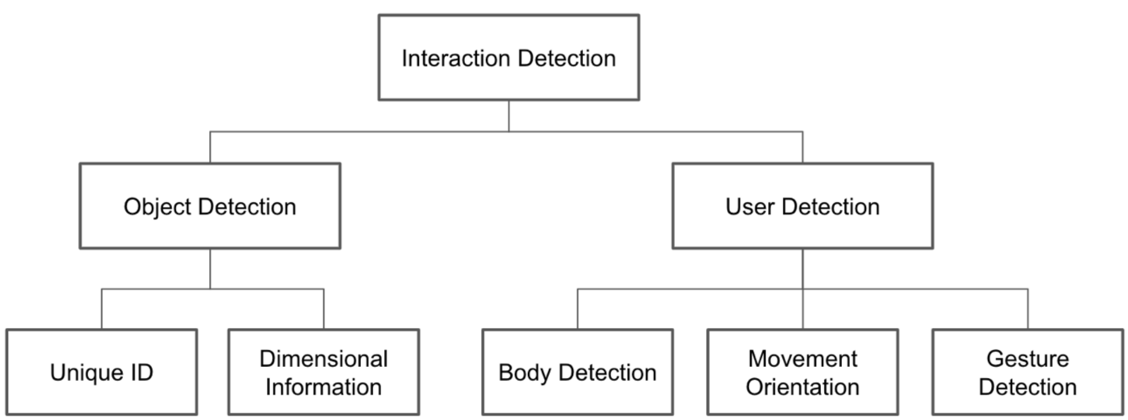

Figure 3-4 Interaction Detection Framework

3.7.1 User Detection

The user detection process consists of three main tasks: human body detection, movement orientation detection, and hand gesture detection. The whole process is based on the application of computer vision and image processing with the help of OpenCV.

Although it is possible to track the user's actions by wearing a sensor for the user, this method is not suitable for our daily life. In order to ensure continuous monitoring of the user's actions, the user needs to wear sensing devices at all times, which brings extra burden and inconvenience to the user. In addition, wearable sensing devices are not able to accurately perceive and recognize different gestures made by users, which is not feasible for the gesture detection of users. In contrast, computer vision technology has become more and more mature, and there are many algorithms for identifying people and objects (Xia, Chen, and Aggarwal 2011; Lin et al. 2013; Yao and Fei-Fei 2012). Recognizing users and gestures through cameras and computer vision algorithms can achieve user convenience and accurate recognition at the same time.

The general workflow of the detection process is given below:

1. First the system reads the real-time video captured by cameras and processes each frame one by one.
2. For each frame it tries to detect a human. If a human is detected it draws a marker or ID on it.
3. After completing step 2 it tries to detect human body components such as head, shoulder, and hands.
4. If the human body components are recognized, the system puts labels on the components, else it moves to step 2 again for the next frame.

Human Body Detection

Xia's research proposes a model-based approach for human body detection. This approach detects humans using a 2-D head contour model and a 3-D head surface model. A segmentation scheme is also provided to segment the human from the surroundings and extract the whole contours of the figure (Xia, Chen, and Aggarwal 2011). I used the depth camera and followed the guideline of this approach (Figure 3-5) to detect the human body and the body components.

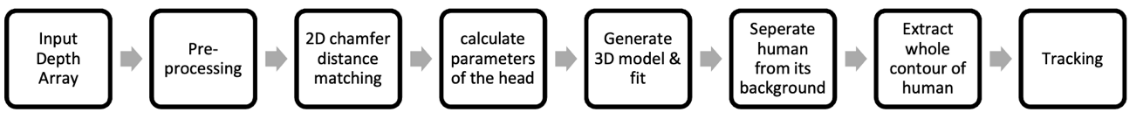

Figure 3-5 Overview of the human detection method (Xia, Chen, and Aggarwal 2011)

Movement Orientation Detection

As the aim of the system is to give intelligent and responsive action, it should be able to distinguish the status of the interaction between the user and the current environment. The underlying logic requires the system to react to the user's movement. Among various movements, the system needs to accurately recognize the movement of approaching. Since the system continuously processes captured image frames, by dynamic analyzing on the body scales the speed and orientation of the body can be calculated. This detection process is also in a feedback loop that informs other modules dynamically.

Gesture Detection

Hand gestures provide a natural and intuitive communication modality for human-computer interaction. Efficient human-computer interfaces have to be developed to allow computers to visually recognize in real-time hand gestures. Scale invariance feature transform (SIFT) features (Lowe 2004) and the concept of support vector machine (SVM) (Dardas and Georganas 2011) is adopted in this project for detecting a series of hand gestures. Hand gestures are used to allow users to directly communicate with the Responsive Layer to switch between different context information.

The system is able to tell the number of fingers of the user's hand gesture. These gestures can be combined with left and right movements to create more available gestures to let the user choose.

3.7.2 Object Detection

Because there is no fixed placement of daily objects, in order to accurately overlay projection on object surfaces, the system must be able to locate the real-time position and rotation of objects. To solve this problem, I researched the state-of-the-art methods for object locating in the domain of computer vision. However, since the background in our daily life tends to be more cluttered than the background in experiments, it becomes a challenging task for the computer to successfully detect and locate the specific objects. Moreover, the entire detecting and locating process is time-consuming which is not suitable for daily use. The only feasible solution is to find a way for object to provide the mapping information itself.

There are possible solutions available already, with the most recognizable technologies being radio frequency identification (RFID) tags (Weinstein 2005), quick response (QR) codes, and barcodes (Woodland and Bernard 1952). Among the three options, QR codes and barcodes were designed for computer readability and only one code can be identified at a time. Besides, the readability decreases as distance increases which is not suitable for our scenario. RFID tags can communicate relevant information invisibly and be read simultaneously. However, RFID is relatively more costly and difficult to be recognized by cameras. Another possible solution is a visual identifier that serves the purpose of a QR code, initializing data to the system, and also cheap and easy to make. In the design of the Responsive Layer, I choose the pre-generated visual identifier to help the system localize and get the detailed information of objects (Figure 3-6).

The Responsive Layer system first locates the pre-generated markers that attached to objects, then gets their unique object IDs to retrieve data from the database. To get the coordinates and rotation of the object, the system algorithm keeps tracking the four corners of the marker. Once the corner is detected, the algorithm is able to detect the contour of the object using the prestored dimensional data. Depending on the shape and volume of the object, one or more markers can be attached to the boundary or center of the object. The user or designer needs to input the size information of the marker to each boundary of the object in the system.

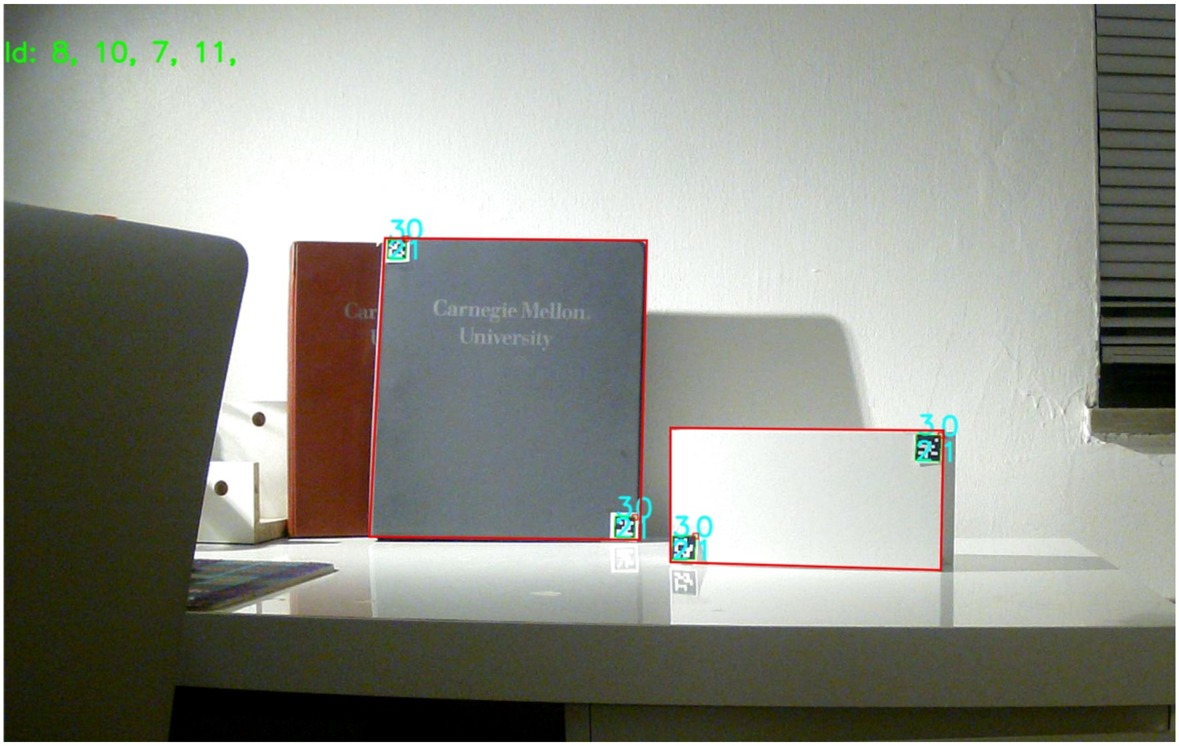

Figure 3-6 Localize objects by marker detection

3.8 Recording and Reconfiguration

The recording & reconfiguration module is the major module of the Responsive Layer which is for collecting and updating data, analyze data and interaction status, generate and modify the output to be sent to the real-time response module.

Data drives the work of the entire system. The data we care about here is mainly about context information of the physical environment, time, and movement during the interaction between the user and the system. The module has a feedback loop, which will obtain and update data in real-time, and adjust the system configuration according to the data and analysis results (Figure 3-7).

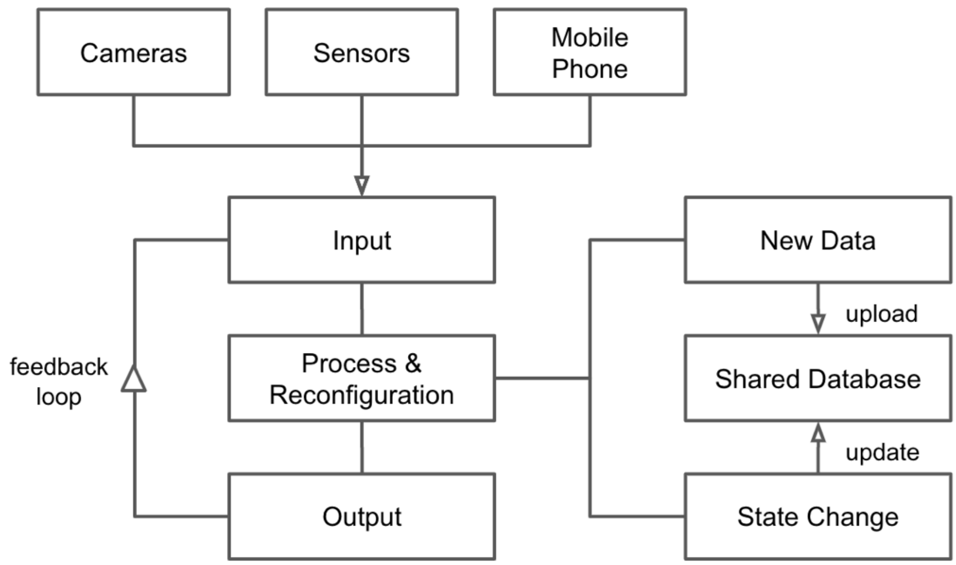

Figure 3-7 Data Collection and Update Workflow

3.8.1 Data Collection

The system supports two approaches to data collection. The first and major method is to rely on the system to actively utilize the camera and sensing devices to obtain context information. The context information to be recorded mainly includes time, objects, and users participating in the interaction, the duration of the interaction, the cumulative number of interactions, etc. Among them, the frequency and cumulative number of interactions are attained through analysis of time and interaction status.

The second approach is for the user to manually upload data via a mobile phone. Every marker code stores a link to its corresponding simple user interface for data transmission by the user (Figure 3-8). The user can choose to upload a photo or text to record any information about the object and express their own emotions. The image and text data then be sent as the form of a URL request to the system. The system will use the unique object id to store and index the data in the database.

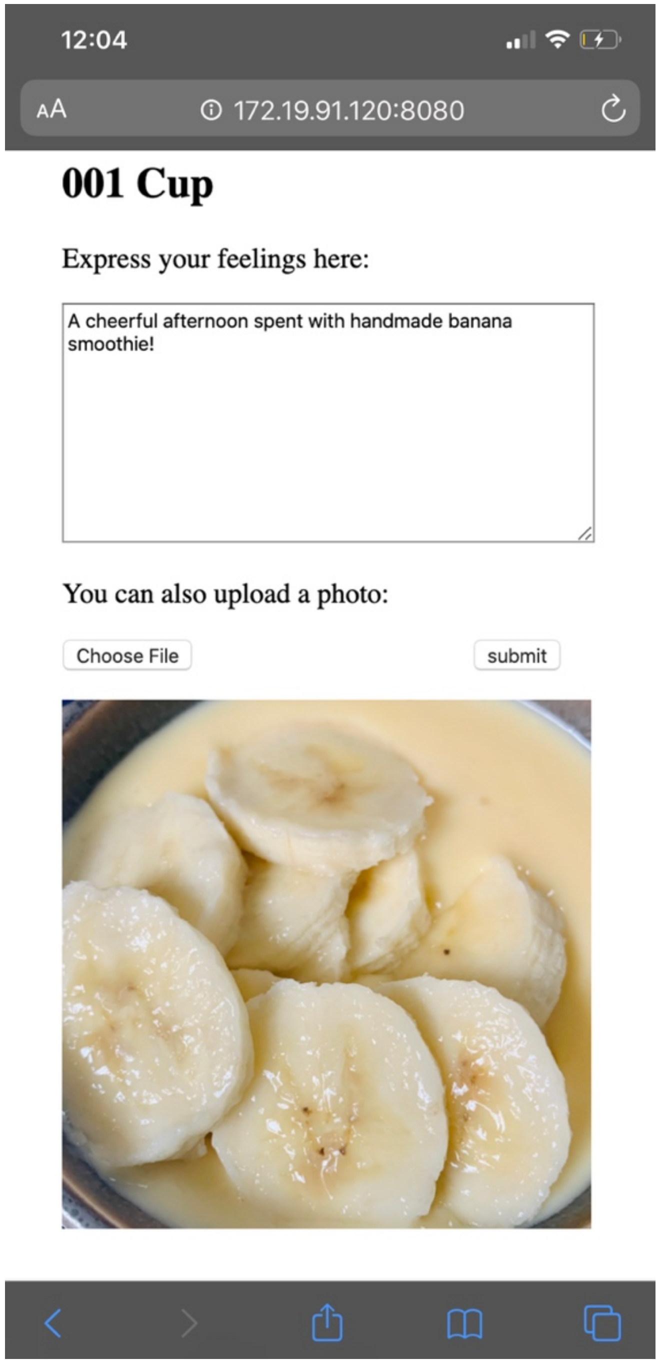

Figure 3-8 Screenshot of the User Interface on Mobile

3.8.2 Data Update

In order to achieve the timeliness of the Responsive Layer and its accuracy of the output content, the feedback loop of the system needs to constantly detect the real-time status, update and analyze the stored data while collecting new data. The following pseudocode shows the main logic and some of the detailed implementation of the feedback loop. The feedback loop is nested in the photo capture loop and is only triggered when the presence of a person in a specific space is successfully detected. The algorithm loops through every object that captured by cameras using their ID.

Inside the feedback loop, there are three conditions need to be checked: 1. Check whether the user is within the preset distance range of the object; 2. Check if one of the default hand gestures is detected; 3. Check the movement status of the marker. The distance range is used to trigger projection mapping, and once the distance from the object to the user is within this range, the Responsive Layer will be displayed. Users can customize the distance range for different objects.

Figure 3-9 shows the detailed workflow of the recording & reconfiguration process. The system first iterates through photo frames captured by cameras. Then the algorithm for human body detection is called to check the presence and movement of the human body. If the human body is detected, the system will evoke the process of object detection to localize objects that are currently registered in the system. After determining the interaction status between the user and the responsive environment, the system begins to iterate through the object IDs which are obtained from the markers. The system needs to check whether the user is within the object's distance range which is customized previously. If so, the system will retrieve data from the database to get the previous experience of the user and render the projection with the context information. The system continues to check if a predefined hand gesture is detected. If one of the hand gestures is detected, it will get the corresponding command of the gesture from, reconfigure the projection content, and update the context information in the database in the meanwhile. In order to make a correct judgment about when to stop the projection, the system also needs to continuously check the movement of markers which suggests the movement of the object. Once the object is moved by the user, the system will abort the current projection and update the current data. Then the system will go back to step 1 to process the next photo frame. The pseudocode of the algorithm is presented in Figure 3-10.

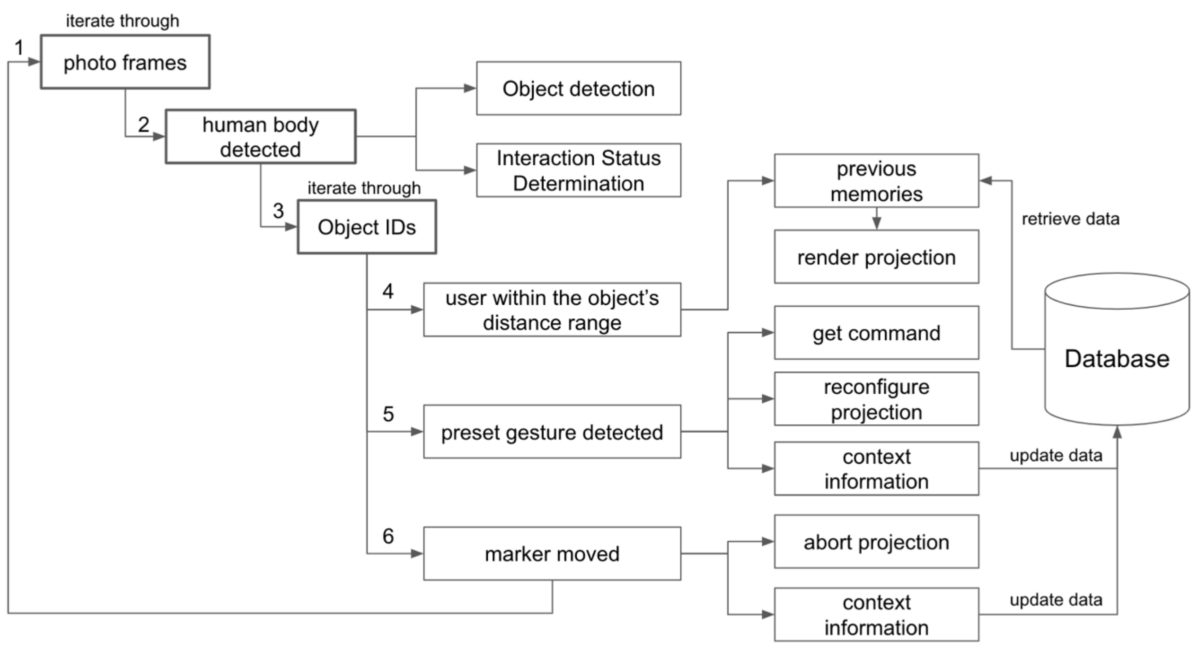

Figure 3-9 Recording & Reconfiguration Workflow

```
Step 1: Open cameras for marker and human detection.
BEGIN LOOP
    Step 2: Get the current photo captured by cameras.
    Step 3: Detect human body:
        IF a human body is detected
            Step 4: Run algorithm for extract objects information
                and locate them with marker detection.
            Step 5: Detect status of human-object interaction
                Record the current time and current distance
                from objects to the human body.
            BEGIN LOOP BY OBJECT ID
                IF the user is within the preset distance range
                of the object
                    IF the object if NOT being projected
                        Extract data from the database
                        by the object ID.
                        Render the image and send it to
                        the projector.
                    END IF
                END IF
                IF one of the preset hand gestures is detected
                    Get the corresponding command of the gesture.
                    Update the context information in the database.
                    Reconfigure the image to be displayed.
                END IF
                IF the marker is moved
                    Abort current projection.
                    Update data in the database.
                    Return to Step 3.
                END IF
            END LOOP
        END IF
```

Figure 3-10 Pseudocode for the feedback loop of the system

3.8.3 Database Schema

The underlying database of the Responsive Layer is designed to share among objects in the same space. Object ID and user ID together as the composite primary key to make access to the database and index the related data. The database I use here is MySQL for its high performance and on-demand scalability, which ensures the efficiency and effectiveness of the system. Figure 3-11 shows the general database schema.

In the process of interaction between user and objects, the system will continuously record new data and update in the database. The context information senses and captured by the Responsive Layer are mainly about the what, why, how of the interaction and transform the information into readable data.

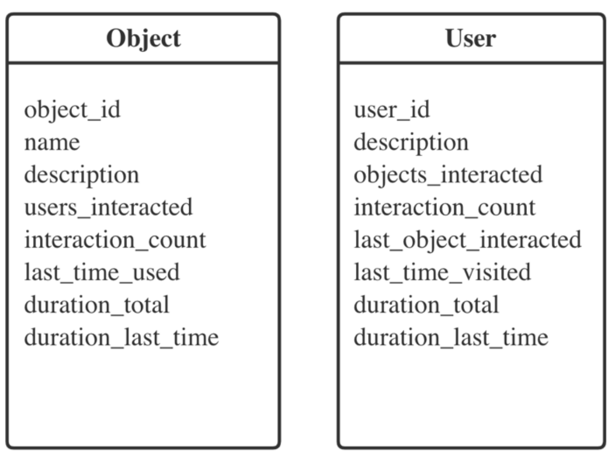

Figure 3-11 Database Schema

3.9 Real-time Response

The real-time response of the response layer is achieved by the projection of the projector on the surface of the object. There are two main forms of projected digital information: images and text. The content of the projection is generated by the recording & reconfiguration module. As described in Chapter 2, projection is used as a real-time response method because it is suitable for various object surfaces and is easy to operate.

The mapping of the digital information used for projection to the target object is determined by the camera's recognition of the markers. As a matter of fact, the accomplishment of the response process still needs the support of object detection.

The duration and modification of real-time response content are determined by the interaction between the user and the Responsive Layer and the detection of the surrounding environment by the system. These commands are translated into computer-executable instructions in the system, which in turn control the projection content of the projector. The real-time response process is inseparable from the detection of interaction status and analysis of the interaction data.

3.10 Usability

After a thorough illustration of the system modules and the workflow, this section will give a quick guide for end-users on how to use the system.

First, you need to follow the instructions in section 3.6 to prepare and set up the required equipment. Then you need to adjust the positions and the angles of the cameras and the projector to make sure they covered the area where you are going to interact with objects.

Secondly, you can use the ArUco library of OpenCV to generate markers with preset IDs and attach the markers on the surfaces of objects. According to the different shapes of surfaces, the positions of the markers can be the corners or the center of the object. More details in section 3.7. The dimensional information of objects should be stored with the objects' IDs in the database or a configuration file for later data retrieval.

After the preparation of the hardware and markers, you can now follow the steps of user detection and object detection in section 3.7. Users should predefine the gestures and their corresponding commands for the system.

To this point, the system is ready for some basic detections and responses. You can improve the settings and algorithms by interacting with objects. The default response function is to project a color block to the surface of the object when the system detects the user. You can customize different ways of responses and contents of digital information. More details and examples will be explained in the next chapter.

The system automatically senses context information about interaction status such as date and time. The information will be further analyzed to determine the frequency and duration of the interaction. Users can upload customized information about their experience through the user interfaces on their mobile phones, which is demonstrated in section 3.8.1.

The next chapter demonstrates some use cases of the system. The details of the implementation and observation results are also included.

Chapter 4

Use Case Prototypes and Observation

This chapter introduces the application of the Responsive Layer in various scenarios through the design and development of a series of prototypes. Through the observation of the experiments and the actual use of the prototypes, the advantages and limitations were evaluated. Mug cup and folder were selected as the subjects of the experiment because they are the common objects that we use a lot in daily life. The prototypes reflect the design that makes different kinds of responses based on the characteristics of different objects through the Responsive Layer. The system is further applied in a larger architectural space to explore more application possibilities.

4.1 Perception of User Proximity

The first prototype was developed to test whether the system can successfully detect the interaction status between the user and the object. This prototype simulated the interaction between the user and a folder. The reason why we chose a folder in the experiment is because the folder has regular shape and is common in daily life.

Figure 4-1 Once the system detects the approaching of the user, a color block will be projected to the folder.

4.1.1 Design and Implementation

We first imitated the way the user interact with everyday objects. The user entered the scene multiple times at different time stamps, used the folder, and changed its location. The system continuously captures the image of the scene and tries to detect the human body. Once the user was detected, it started the process of object detection. We used two markers for object detection and localization. The size information about the folder surface has been encoded along with its object ID. Once the system detects the markers, it can compute and identify the boundary of the folder with the size information.

This prototype attempts to attract the user attention with the projected color block on the folder. Due to the projected color and brightness, the user was attracted to the folder and stayed. Then the user can choose whether to interact with the object through the Responsive Layer or by direct touch.

4.1.2 Observation and Reflection

Figure 4-1 suggests that the system has successfully detected the user, triggered the object localization process, and mapped the yellow color block to the folder precisely. Although the user has moved the folder multiple times, as long as the relative position of the markers corresponding to the folder has not been changed, the system can quickly and accurately identify the folder. However, for objects with irregular shapes, it is difficult to select the position for the markers and make the system determine the boundary of the object, which will further affect the projection mapping.

On the other hand, the application scenarios of methods that attract users 'attention through color are limited. In this experiment, we only tested the attraction of a single folder to a single user. However, in real life, there are often multiple objects interacting with a user in a same space. If this method of intriguing the user is applied to multiple objects in the same space, the user may feel confused and overwhelmed instead of being attracted.

4.2 To understand the importance of an object in our life

The design intention of this prototype is to allow the user to intuitively understand the relationship with everyday objects. By recording, analyzing, and displaying the context information of interaction behaviors, the importance of these objects in our daily life can be indicated by the Responsive Layer.

Figure 4-2 The user chose to control the display of the interactions count by clenching her fist

4.2.1 Design and Implementation

The design of the prototype is inspired by Spotify’s annual end-of-year Wrapped feature (Pasarow 2019). Recently, many music apps have introduced user data statistics features that analyze the data of users listening to songs in the past year, which are designed to help users review their listening preference and moods at that time. These statistics usually select the user's own annual top songs and preference by listening count and frequency. In this way, the music apps can help us find the songs and stories about the past that have a great impact on us but are gradually forgotten.

Such design ideas also can be applied to real life. Many everyday objects are of great significance to us but are easily overlooked. We hope that through the recording and analysis of interactions, the Responsive Layer can make users understand the participation and importance of these ordinary objects in daily life and remind users to reflect on the relationship with objects.

Based on previous interactions, the system was able to record and store the context information about the time and frequency of previous interactions. The user's interaction with the Responsive Layer is mainly achieved through computer vision algorithms. So, the user was asked to preselect the gestures and the corresponding instructions to be used instead of directly touching objects.

In this prototype, the user chose to control the display of the interaction count by clenching her fist (Figure 4-2) and browse the date of the last use through the open palm (Figure 4-3). We also tried to manipulate the display of context information of two objects at the same time (Figure 4-4).

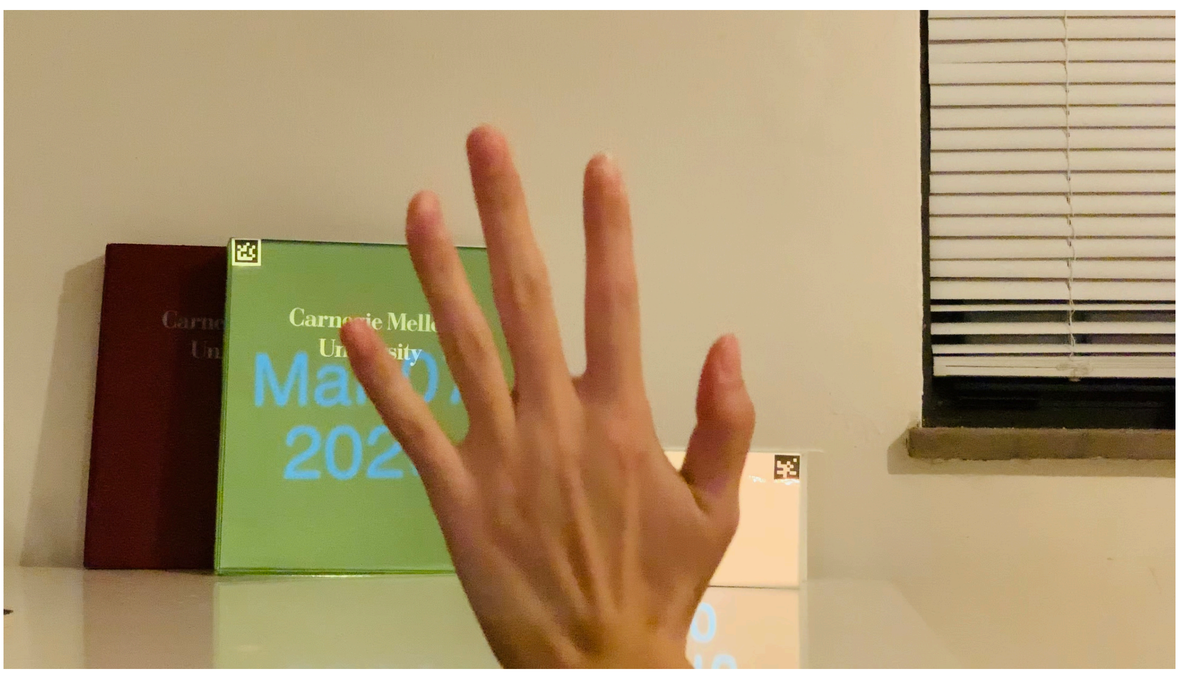

Figure 4-3 The user browsed the date of the last use through her open palm.

Figure 4-4 Manipulating the display of context information of two objects at the same time

4.2.2 Observation and Reflection

This prototype suggests that the Responsive Layer was able to record and analyze the data of the interaction between the user and the objects, demonstrates a feasible way to display the statistical data to the user, and shows how the user manipulate the display of the information and interact with the system.

In this experiment, the display of the statistical data of previous interactions was achieved by numbers and text projected directly on the objects' surfaces. The user can easily understand the information that the system wanted to convey and control the display of the information by hand gestures. As long as the gestures can be captured by the camera, the control of the Responsive Layer is basically not limited by position.

Although the display of the statistical data by the prototype is simple and straightforward, it still requires the user to be familiar with the operations and different gestures. Since the hand gestures used in the Responsive Layer are quite different from the gestures that the user used to directly interact with everyday objects, it is necessary for the system to provide corresponding prompt information about gesture manipulation to the user.

Another limitation is that when the user interacted with multiple objects through the Responsive Layer, by default, the system will overlay the context information related to the user on all objects within the camera lens range. At present, it is impossible for the system to tell which object the user intended to interact with.

4.3 It's fun to relive the past

Another purpose of the Responsive Layer is to help us relive the past precious moment with the object. We use everyday objects to perceive the happiness they bring. When an object fully realizes its intention in our lives, this experience becomes a precious moment between us. The following prototype is designed to explore the possibility of establishing an emotional connection between the user and the physical world through an interesting review of the past.

4.3.1 Design and Implementation

Although the Responsive Layer is designed to be applicable to various objects and scenes, it is still necessary to design different methods and contents according to the characteristics of different objects. In the design of this prototype, we fully considered the daily functions of the folder and the ways of user interaction with the folder.

The main function of the folder is to collect files and allow users to replace and change the order of the files at any time. When designing the folder with the function that reminds people about the past, we use the items inside the folder as a witness of the past and display them in the form of digital images. The selection of gestures also mimicked the actual interaction with the folder.

The folder first aroused the user's interest through a dialogue “Want a throwback?” (Figure 4-5). The inanimate objects started to talk to people, which surprised the user and make the user wonder what kind of interaction would happen next.

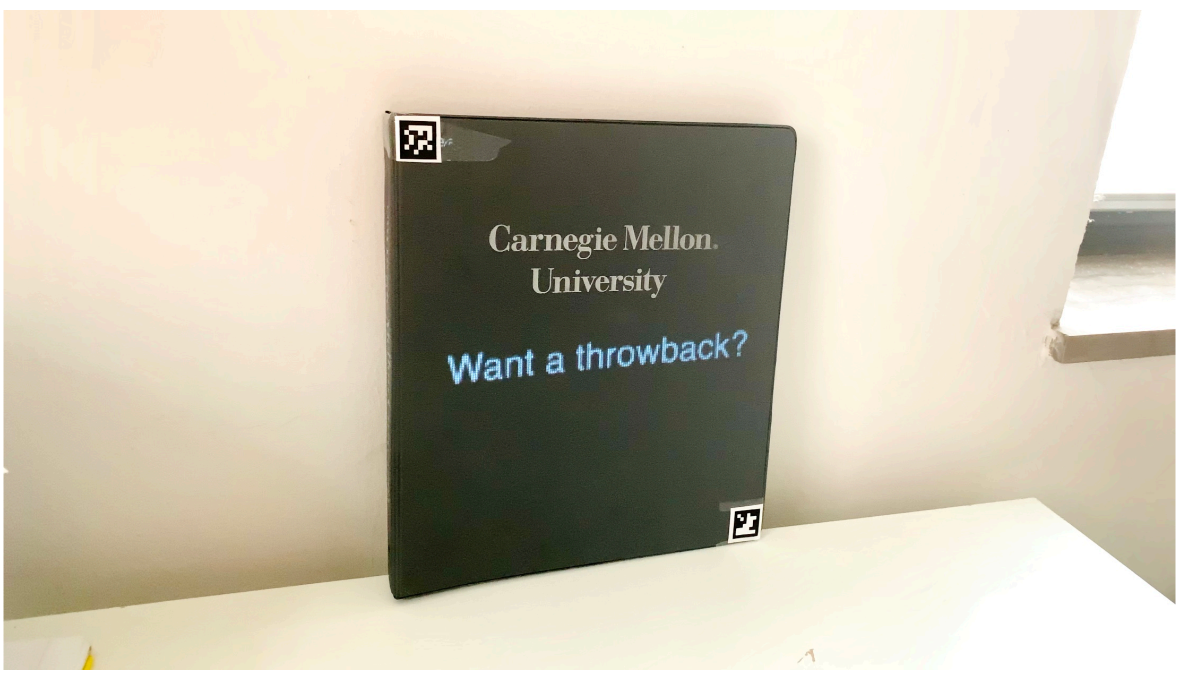

Figure 4-5 The folder talked to the user like an old friend.

Then, the user used a gesture with the meaning of "open" to give permission to the folder to let it take her to relive the precious moments between her and the folder (Figure 4-6). The user slid her finger left and right to review the pieces of old stories that were stored in the folder like flipping through old photos (Figure 4-7; Figure 4-8). Those photos that have been uploaded because of their special meaning have come alive through interactive display, reminding the user of her feeling at that moment.

Figure 4-6 User uses gesture to authorize the Responsive Layer.

Figure 4-7 Swipe the finger to the right to discover next photo.

Figure 4-8 Swipe the finger to the left to review the previous photo

4.3.2 Observation and Reflection

The prototype demonstrates the playful feature of the Responsive Layer in helping people recall and relive the past. By simulating the conversation between people and projecting past files inside the folder, the system enables the folder to communicate with the user and review the past stories together. Even if the files in the folder have been replaced many times, users can still review the old files with special significance through the Responsive Layer.

The limitation of this prototype is that the system cannot automatically filter and record files with special meanings. Taking photos and uploading these files requires users to take the initiative. On the other hand, manually uploading photos and text provides the user with more flexibility. Unlike the plain text in the previous prototype, the photos and texts uploaded by users have more personality. In a sense, the user recorded the story between her and the folder through the Responsive Layer, and the system will tell the diary to the user through the folder in the future.

Regarding the attraction of this prototype to users, the interaction process between the user and the folder in the experiment reflects a certain amount of fun, but more user experience experiments are still needed to evaluate and improve its playability.

4.4 How a cup act as a reminder

Because people tend to forget small things in their daily life, we often set many alarm clocks and memos to remind ourselves. Taking drinking water as an example, the elders always say that drinking more water is good for our health, but we just fail to remember to drink water. Are you going to take out your phone and set up a couple of alarm clocks under this condition? Now it's time to consider the cup itself as a reminder. This prototype discusses the potential of the Responsive Layer to extend the function of daily objects to take the role of reminders.

4.4.1 Design and Implementation

This prototype is designed to use the nature of the cup to remind the user to drink water. The drop-shaped pattern projected on the cup represents water and reflects the function of the cup itself to contain water. The digital water drop conveys the message of drinking water to the user (Figure 4-9; Figure 4-10; Figure 4-11). The position of the projection is confined by the dimensional information encoded in the marker. The system can remind the user by analyzing the routine of the user's use of the cup or by the user's customized time setting.

The prototype also tested the ability of the Responsive Layer to judge the interaction status. Once the system detects the movement of the cup which is reflected by the movement of the marker, it will stop the projection and reminder function (Figure 4-11).

Figure 4-9 The cup reminds the user to drink water through a symbolic digital graphic

Figure 4-10 The user noticed the digital cup and grasped the cup

Figure 4-11 The projection and reminder function was stopped once the cup is moved

4.4.2 Observation and Reflection

This experiment shows the practical function of the Responsive Layer as a reminder in daily life. With the help of the sensing and projection of the system, the cup successfully realized the function of a reminder for the user through digital graphics and stopped the reminder function in time when sensing the user interaction with the cup.

On the other hand, this example shows us the broad platform that the Responsive Layer provides to designers. Designers can use the Responsive Layers to design objects in both functionality and appearance aspects.

One disadvantage of the system's reminder function is that, because the system currently only uses graphic projection, the reminder function can only be achieved within the user's visual range. From this perspective, the reminder function of the response layer is still flawed and needs to be combined with other forms of digital augmentation such as sound to complete together.

4.5 Tracing Movement in Architectural Space

Responsive Layer also has a wide use in large scale architectural space. User movement in architectural space can reveal a lot of information about interaction with the space such as user preference. The prototype aims to test the usability of the system in a larger space by simulating user interaction with an exhibition space.

4.5.1 Design and Implementation

Similar to the method of tracking the user’s footprint on the floor, this experiment uses a depth camera that was placed close to the wall to detect the interaction between the user’s palm and the wall. Unlike the interaction between people and daily objects, the interaction between people and large spaces is mainly reflected in the movement and stay. The Response Layer can continuously track and record the user’s movement through the sensing devices (Figure 4-12). By analyzing the user's actions, we can obtain information about the user's use and preference of the space.

Same as the method for detecting the user-object interaction state introduced in Chapter 3, the response layer determines the user's interaction with the wall by detecting the distance between the user and the depth camera. And when it is detected that the user is moving close to the previously visited location, the past movement information is displayed in the form of handprint graphics (Figure 4-13; Figure 4-14).

Figure 4-12 The system continuously records the movement of the user's hand

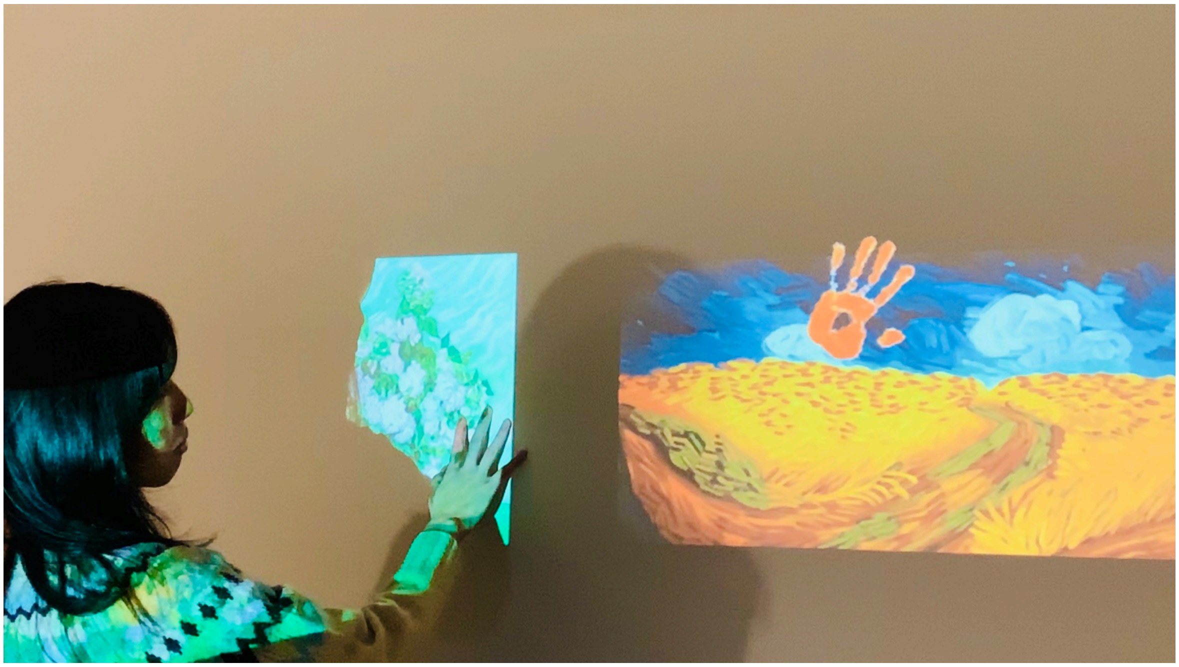

Figure 4-13 The previous movement was represented as fingerprint graphics on the wall

Figure 4-14 The projected fingerprint reminds the user of past visit.

4.5.2 Observation and Reflection

By tracing the user’s hand, the Responsive Layer was able to extract and analyze the context information between the user and the architectural space. The next time the user visited the space, previous traces were overlaid on the wall of the space to indicate the previous experience to the user. By this means, the system triggers an emotional connection between the user and the space to some extent.

Although the application of the Responsive Layer in the architectural space showed by this experiment is similar to the application on everyday objects, the user's movement information in large architectural spaces will be more complicated and difficult to filter and analyze. If all the traces recorded in the past are displayed to the user, it will confuse the user and hinder the review of the past activities. How to better apply the Responsive Layer to a larger space still needs more research and experiments.

Chapter 5

Conclusions and Future Work

The previous chapters introduce the design background, inspirational works, the design and implementation of the Responsive Layer system, and the use case prototypes used to observe and evaluate the system. This chapter summarizes the findings in the previous chapters, concludes the contributions of the Responsive Layer, articulates the limitations of current work, and introduces the plan of my future work.

So far, I developed an interactive system for users to overlay a digital information layer on everyday physical objects and spaces. This information layer can not only display context information about previous interactions but also sense the interaction status between users and objects and make responses. The five prototypes illustrated the current usability and functionality of the Responsive Layer. The Responsive Layer has successfully detected users and objects in the area captured by cameras and recorded context information and displayed them on the surfaces of objects. It can also act as a reminder to remind users and help users review the experience with a specific object. Moreover, the thesis also demonstrates the potential of the system to be applied in larger architectural space.

5.1 Contributions

Overall, this thesis answers the initial research questions and provides a feasible solution. The thesis demonstrates various use cases and broad application prospects of the Responsive Layer. The contributions of this thesis are reflected in the design value and the technical value.

Design Value

The novelty of this research lies in the special research perspective, unconventional design ideas, and the design for the universal system architecture.

First, the thesis focuses on commonly used objects in our daily life and discusses the possibility of making them convey information and respond to our actions. The design of the Responsive Layer preserves the original function and appearance of everyday objects and extends their functions with the consideration of the characteristics of each object.

Furthermore, in the trend that user interfaces tend to be embedded in objects, the thesis proposes the idea of adapting tangible interaction content to changing interfaces. Everyday objects act as agents for universal tangible user interfaces and interact with users with the assistance of digital augmentation and computer vision technology.

Technical Value

This thesis systematically introduces the working principle of the Responsive Layer, the composition and the configuration of the system, the logic and the implementation of each module, and the collaboration between the modules. The thesis satisfies the design criteria that the setup and the configuration of the system is easy to follow.

Readers can not only understand the workflow and operation of the system through reading this thesis but can also follow each step to build and realize a simple Responsive Layer system on their own.

5.2 Limitations

Single User

The current system and prototypes have only been tested by a single user. Although in theory the system can support multiple users, this affordability has not been tested and proved. In addition, the multi-user mode is much more complicated than the single-user mode, so the system's logics and algorithms need to be improved further.

Limited View Area

The current system uses one camera and one IR-based camera for detecting and tracking. This setting limits the movement of users and objects within the visible area of the cameras. It also adopts only one projector to project context information on objects, which only covers the surfaces of physical objects that face the projector. By incorporating multiple cameras and projectors, the system could enlarge the covered area.

Latency

When users changed their gestures and locations, or when they moved physical objects, the projected digital information has some delay which creates unnatural scene motion and degrades the user experience.

Not Open Source

Currently, the thesis only provides the system architecture and the workflow of the modules. For end-users who want to use the system and get a quick start, they still need to do some coding and put the modules together. The underlying code of the system needs more work on integration and modification to be available to general purposes.

5.3 Future Work

The thesis shows the broad application of the Responsive Layer and indicates the potential develop directions in the future. We plan to improve and examine the system in four directions: many-to-many interaction, digital technology integration, construction of responsive environments, human memory.

5.3.1 Many-to-many Interaction

The current prototypes and experiments are mainly for one-to-one interaction between a single user and a single daily object. In future research, the Responsive Layer will be applied to scenarios where one user interacts with multiple objects and multiple users interact with multiple objects. Since the interaction between users and various objects is prone to conflicts, the detection and the configuration of the system need to be improved and logically adjusted to adapt to richer application scenarios.

The system will be able to analyze the characteristics of user groups by recording and analyzing the interaction of multiple users with objects or spaces. In order to test the stability and performance of the system, more user experience experiments are required.

5.3.2 Digital Technology Integration

This thesis mainly introduces the application of the projection mapping of digital images in the Responsive Layer system. In fact, digital augmentation technology also includes many other popular digital technologies such as Virtual Reality (VR), Augmented Reality (AR), and mixed reality combined with audios.

As mentioned in the observation and reflection part of the prototypes, the information conveyed through the visual digital graphics alone is limited. The function and application of the Response Layer can be sublimated through the integration of more digital technologies.

For the next step, we will first integrate audio and sound to the system to enhance user experience. By recording the sound of the environment and users, the system can provide users with more interesting experience of reliving the past. The reminder function of the system can also be improved with the help of sound.

5.3.3 Construction of the Responsive Environment

The setup of the Responsive Layer system introduced in this thesis is very simple, aiming to complete the most basic detection and response. The current hardware setup is not suitable for more complex interaction scenarios. To construct a responsive environment, we need to install more sensing devices, cameras, and projectors. In this way, the limitations we discussed before such as the difficulty to detect rotated objects can be solved. Moreover, more sensors and cameras can make the interaction detection process more accurate and faster.

5.3.4 Open Source

Currently, I am working on the code integration and the design of the application programming interfaces (API). I will also test its usability and stability by conducting user experiments. Once the code is fully tested, I will publish it on GitHub for people to download and contribute.

5.3.5 Human Memory

The thesis shows the use of the Responsive Layer to record the past interaction experience and enable users to relive the past. The study of human memory can better help us design the throwback function of the system. An in-depth study of human memory is needed for future research. Preliminary background study of memory and autobiographical memory is explained in the appendix section.

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Appendix

“In smaller, more familiar things, memory weaves her strongest enchantments.” — Freya Stark (Freya Stark 1948)

Memory has been a focus of research within discursive psychology (Edwards and Potter 1992; Locke and Edwards 2003), which in a challenge to traditional cognitive psychology, investigates memory as an interactional phenomenon rather than as just a cognitive process. The analysis on repeat calls shows new interactions are built off previous calls, and illustrates the importance of memory — claimed, displayed, and made manifest in interaction. In this sense, memory is the interactional achievement. One view of human episodic memory defines it not only as the knowledge about the what, where, and when of a past event, but rather as a conscious recollection and re-experiencing of a unique past experience, which involves autonoetic awareness and a sense of subjective time (Shaw and Kitzinger 2007).

The interactive memory between people and the physical world we studied is closer to autobiographical memory. Autobiographical memory refers to the recollection of past events experienced by individuals, often based on a combination of episodic memory (personal experiences and specific objects, people and events experienced at particular times and places) and semantic memory (general knowledge and facts about the world) (Tulving 2002). Autobiographical memory is constructed within a self-memory system (SMS) where knowledge of the self is stored. The self-memory system provides a person with information about lifetime periods, general events, and event-specific knowledge. The lifetime period consists of general knowledge about the distinguishable thematic time in an individual ’s life. Compared to the lifetime period, the general event is more specific and is a single representation of a repeated event or a series of related events. The vivid and detailed information about a single event is event-specific knowledge, usually in the form of visual images and sensory perception features (Conway and Pleydell-Pearce 2000). The memory mentioned in this thesis mainly refers to the general events information and event-specific knowledge in autobiographical memory.

Speaking of the memory processes in autobiographical memory, William F. Brewer compares two theories of personal memory: copy theory and reconstructive theory (Brewer 1986). Copy theories of memory have a long history in philosophy. Earle argued that personal memories were "a direct vision of the genuine past, and veridical to the extent it is clear" (Earle 1956). However, Brewer argues that there is little evidence to support the copy theories. Neisser's study found that the detail of personal memories is easy to be incorrect. On the other hand, reconstructive theory indicates that personal memories are experienced from the perspective of others who have also viewed the scene. This was also confirmed by the findings of Neisser (Neisser 1981). Brewer then outlines a partial reconstructive view of personal memory (Brewer 1986):

> Overall, the partially reconstructive position suggests that recent personal memories retain a relatively large amount of specific information from the original phenomenal experience (e.g., location, point of view) but that with time, or under strong schema-based processes, the original experience can be reconstructed to produce a new nonveridical personal memory that retains most of the phenomenal characteristics of other personal memories (e.g., strong visual imagery, strong belief value).

Daniela Petrelli and Steve Whittaker consider the family home as “a place of memories”, where the term memory mainly focuses on mementos: the objects that are kept as reminders of a person, place, or event (Petrelli 2010). Photos, as physical mementos, are usually considered as the memento prototype of personal reflection and sharing (Crabtree, Rodden, and Mariani 2004). Other physical mementos like everyday objects have greatly participated in our lives. Digital artifacts such as video clips and digital photos have also penetrated into daily life. A deeper understanding of the meaning of mementos and the reasons why mementos are chosen can help apply computational design ideas to designs related to autobiographical memory.