

ORGANIC BOARD GAMES WITH TANGIBLE TILES:
INTERACTION METHODS FOR SMALL HEXAGONAL TILES

by

MICHAEL HOWARD ROOKE

A thesis submitted to the
School of Computing
in conformity with the requirements for
the degree of Master of Science

Queen's University
Kingston, Ontario, Canada

April 2009

Copyright © Michael Howard Rooke, 2009

Abstract

The keyboard and mouse have dominated human-computer interaction for over twenty years. Much effort has been made to break away from this paradigm by creating novel interaction systems and techniques. This thesis presents a system with small hexagonally shaped cardboard tiles called *Organic Board Games*, along with methods of interaction for these tiles. Tiles are used as a means for controlling and interfacing with abstract objects in a computer system. Particular attention is given to controlling games with the tiles, as some of the original motivation for the system was from the board game Settlers of Catan.

The many design considerations for Organic Board Games are discussed; prototype implementations that were constructed are presented and critiqued, and observations are made regarding these systems' applicability to interface design. Several proposals are presented for the system's evaluation and development beyond the example implementations.

Acknowledgments

I would like to acknowledge my thesis supervisor Dr. Roel Vertegaal for his guidance and mentoring during my time at the Human Media Lab. His original thinking inspired many of the ideas presented within, and without his help this thesis could not have been conceived. I would also like to thank the many individuals from the Human Media Lab and others who provided technical and creative help in my deliberation. In particular I would like to thank Adam, Eric and Julian for being patient soundboards and invaluable friends; to David, Tim and Anson for providing intelligence when I lacked it; and to Dr. Rappaport for hinting at some easy methods of grouping points. I must also thank Jamie and Mark for introducing me to the Human Media Lab, and to Chad, Dave and Robin for being excellent hosts. Finally, my family showed an incredible optimism and patience, and I must thank them profusely for their constant encouragement and support without which this thesis certainly would not have existed.

Table of Contents

Abstract	i
Acknowledgments	ii
Table of Contents	iii
List of Figures	vi
Chapter 1:	
Introduction	1
1.1 Introduction	1
1.2 Motivation	2
1.3 Objective	2
1.4 Contributions	3
1.5 Outline of Thesis	4
Chapter 2:	
Background	6
2.1 Human Computer Interaction	6
2.2 Ubiquitous Computing	10
2.3 Tangible User Interfaces	11

2.4	Technological Aspects of Organic Board Games	16
2.5	Pervasive Games and Collaborative Interfaces	18
2.6	Organic User Interfaces	19
2.7	Interfaces with Simulated Physics	21
2.8	Summary	23
 Chapter 3:		
	Tangible Tiles	24
3.1	Introduction	24
3.2	Prototype Apparatus	24
3.3	Settlers of Catan	32
3.4	Physical Movements	34
3.5	Interaction Styles	36
3.6	Summary	38
 Chapter 4:		
	Implementations	39
4.1	Introduction	39
4.2	Organic Board Games	40
4.3	Tangible Objects with Physics	48
4.4	Conclusion	50
 Chapter 5:		
	System Evaluation and Critique	51
5.1	Design and Observation	51
5.2	Discussion	55

Chapter 6:

Conclusions	57
6.1 Overview	57
6.2 Summary of Contributions	58
6.3 Future Work	59
6.4 Conclusion	61
Bibliography	62

Appendix A:

Computer Vision Algorithms	70
A.1 Finding Hexagons	70
A.2 Finding dots in a scene	74

List of Figures

2.1	Engelbart’s prototype mouse	9
2.2	Illuminating Clay by Piper et al. [33]	13
2.3	Agarawala and Balakrishnan’s <i>Bumptop</i> [1]	22
3.1	Tangible Tiles Apparatus	26
3.2	Hexagons with Reflectors	27
3.3	Software Diagram	28
3.4	Example Catan Layouts	33
3.5	Physical Movements: Touch	35
3.6	Physical Movements: Rotate	35
3.7	Physical Movements: Adjacent Placement	36
3.8	Physical Movements: Tilt	36
4.1	Context-Aware RTS Game Interactions	42
4.2	A Context-Aware Menu	46
A.1	Point-Finding Diagram	72

Chapter 1

Introduction

1.1 Introduction

This thesis describes work in Tangible User Interfaces (TUIs) and Organic User Interfaces (OUIs), both areas of Human Computer Interaction (HCI). It presents observations, implementations and design principles for the development of applications that provide information to the user via physical objects. Flat hexagonal cardboard tiles are used as input for various applications, most notably as a new method of playing the popular board game Settlers of Catan (the original motivation for the interface). The ideas from this original motivating genesis are extended to various other interface applications, and each extension is presented and critiqued. A summary of the technical implementation is included, showing how the original working prototypes were constructed, as well as how they were modified to suit particular scenarios. A description follows of how the tiles are used specifically to control existing games. Finally, a selection of technical descriptions is presented in the Appendix.

1.2 Motivation

For nearly 50 years the keyboard has been the dominant input device by which people communicate with computers. For the better part of those 50 years it has been sufficient and effective for manipulation of text for command-line interfaces. More recently, the mouse has gained dominance as the input device for windows, icons etc. in a Windows, Icons, Menu, Pointing (WIMP) interface. The WIMP interface gradually permeated the computer market when introduced almost 30 years ago; successful computer systems such as the Apple Macintosh and Microsoft's Windows operating system helped established the WIMP as the dominant paradigm. The consequence of this adoption is that interaction with general purpose computers is almost exclusively performed in such an environment. Interest in alternative input techniques, however, has existed ever since Bush [5] and others demanded more from the human-computer link; this trend continues today to attempt something better than just the keyboard and mouse, pillars as they are of HCI. Further pressure to interact seamlessly with computers has led to the development of Attentive User Interfaces (AUIs), Tangible User Interfaces (TUIs), and more recently Organic User Interfaces (OUIs) [18, 23, 45]. It is on these new pillars of research that the motivation for Organic Board Games stands, where its underlying goal is to further the ability for humans to use computers effectively, efficiently, and seamlessly.

1.3 Objective

The goal of this thesis was to design a computing device that facilitates input from, and output to, small hexagonal tiles. The intention of making a significantly atypical

design is to experiment with these small flat units, an attempt never before undertaken. The design demonstrates novel methods for interacting with these tiles in a three dimensional space with certain computer applications. The implementations shown are meant to give guidance on what applications are best suited to the design. Perhaps the strongest objective is to support and inspire future studies into similar systems involving thin objects with a display on them. New technologies are constantly being on the horizon is a tenet of the computer industry. As such, one of the key design objectives is to accommodate future display technologies and ensure that all the work done in this thesis is applicable beyond the limited prototype and applications presented.

1.4 Contributions

This thesis contributes to the field of Human Computer Interaction in a number of ways. First, it presents an exploration into how physical, tangible objects can be used to create an interface involving hexagonal tiles. A novel approach to prototyping a wireless tile-based system is presented with details of its design. Second, a proposal for interaction techniques for these tiles as well as situations involving the use of these interaction techniques is presented. Finally, several unique situations are specified where the use of these tiles has yet to be explored in the literature.

The main contribution is in the design and implementation of Organic Board Games. Organic Board Games is a platform for interacting with board games with small hexagonal tiles, most notably the board game Settlers of Catan. Organic Board Games is a novel scheme for computer and board game use, and can aid numerous interaction scenarios. With this prototype contribution, this thesis describes ideas

about how people can use computers for their benefit.

1.5 Outline of Thesis

This thesis is presented in six chapters. The second chapter discusses previous research motivating the investigation, forming a background for further discussion. Ubiquitous Computing, TUIs, Pervasive Games and OUIs are discussed with particular emphasis on motivating their extension with Organic Board Games.

The third chapter deals with the main principles around which the system was designed, referred to as *Tangible Tiles*. Design decisions are justified using ideas in the literature discussed in Chapter 2. The general concepts common to most of the individual implementations are presented, and a discussion of why these design decisions should make for a beneficial framework of operation is undertaken. The computer vision methods used to track the hexagons is also discussed.

The fourth chapter describes in detail the proposed applications of the hexagonal tile interaction system. The first and most prominent is Organic Board Games, an augmentation and improvement in the spirit of Settlers of Catan. This is divided into the many different styles of augmentation from very simple display tricks to entirely different game ideas. The second application explores the use of simulated physics with the game tiles, allowing for realistic manipulation of abstract objects. The final application is one employing a slightly different software technique for controlling a real-time strategy game.

The final two chapters deal with summarizing the observations and conclusions made while constructing the various systems presented. Suggestions are made for future work, following a discussion of the lessons learned while exploring this rather

unorthodox method of input and interaction.

Chapter 2

Background

In this chapter, a brief overview of Human-Computer Interaction (hereafter called HCI) is provided as well as a description of how this field of study led to the development of Ubiquitous Computing, Tangible User Interfaces (TUIs), and Pervasive Games (PGs). Emerging ideas in Organic User Interfaces (OUIs) are presented as motivation and direction for Organic Board Games's design. Various works related to these fields are discussed, with attention to prominent papers greatly affecting current research. In addition to these frameworks and examples, several systems similar in nature to Organic Board Games and its underlying technology are described.

2.1 Human Computer Interaction

The scientific study of digital electronic computers began in the 1920s. One goal was to develop computing machines that automate the work of human clerks, who would compute instructions sequentially. Early computer user interfaces were not interactive, and involved complex commands input manually with knobs, switches,

or punch cards. Computers designed in the 1950s were large and expensive, and required highly trained personnel. One computer would be used by many people, and thus its interface was designed for processing batch computing jobs.

It is interesting to note that the initial goal in developing computers was to replace the human clerk, but the aim soon became to extend the ability of humans through the use of computing power. In the article *As We May Think* written in 1945 by Vannevar Bush [5], the author discussed how the then-recent advances in electronic machinery and computing should be used to augment and aid human ability to process data. He proposed the *Memex*, a storage system using electromechanical controls and microfilm cameras for quick retrieval of documents, books, records and communications. Bush envisioned the storage system consisting of microfilm frames filed with code numbers. He also designed for adding information into the system through the use of a photographic mechanism that would allow the user to input hand-written notes, pictures and letters.

The key aspect was that the documents be linked and indexed for easy access, and for display of these documents on a desktop viewing panel. Bush realized that to aid humans in their data processing capabilities, systems should be designed around how humans handle data. Traditionally, information would be sorted either numerically or alphabetically, whereas the human mind searches via association. This led to the linking index of the Memex. Using the coded numbers on the microfilm storage, links were formed between disjoint frames. The sequence of links that emerged was known as a trail, and was the primary means of accessing data. It is worth pointing out that this system has strikingly similarities to the modern Hypertext Markup Language (HTML) in nature.

Douglas Engelbart, inspired by the ideas of Vannevar Bush, studied how humans could interact with computers, and was especially interested in the features that allow for efficient information representation. Engelbart helped to create the Graphical User Interface (GUI) to allow the computer user to interact visually with many different types of information simultaneously. One of the many key features demonstrated in a 1968 video presentation by Engelbart was the mouse (see Figure 2.1) which extended human interaction with a computer through a human's motor ability [12]. Engelbart also introduced the concepts of hypertext, object addressing, and dynamic file linking, as well as real-time networked collaboration with audio and video, where each user was able to share the contents on screen. The system he presented not only continued Bush's idea of the Memex, but it also laid many foundations for modern day computing.

After Engelbart's 1968 presentation, researchers began experimenting with graphical user interfaces. In these interfaces, a combination of a mouse and a keyboard were used to navigate around a virtual desktop that had Windows, Icons, Menus, and Pointing (WIMP), although this interface came in many flavors. Inspired by Bush, Ivan Sutherland introduced the Sketchpad system, a breakthrough system that allowed for manipulation of lines and shapes in contrast to the traditional approach of typing commands to a computer. In Sutherland's words, "The Sketchpad system, by eliminating typed statements (except for legends) in favor of line drawings, opens up a new area of man-machine communication" [41]. Similar research was being done by Allan Kay which was the genesis for work his done at the Xerox Palo Alto Research Center (PARC) on GUIs [26]. PARC, being famous for inventing the GUI, was not the only organization to research GUIs though many novel features did originate from

there, such as the concept of *overlapping* windows. EMACS at MIT, for example, could display multiple windows (which they called “buffers”), though a mouse was not used [39].

Commercial system that popularized the WIMP system were the Xerox Star and the Apple Lisa in the early 1980s. These interfaces allowed the user to access more information simultaneously through the use of windows and dialogue boxes. However, people were still using, and occasionally *preferring*, a command-line interface to a GUI in 1990 even after the GUI’s introduction, and this preference continues today [34]. The design challenge of making a truly universal, excellent human interface was still far from over, and Xerox’s PARC continued to be on the forefront of interface design with Ubiquitous Computing.



Figure 2.1: Douglas Engelbart’s prototype mouse design [12].

2.2 Ubiquitous Computing

Mark Weiser, a researcher at Xerox's PARC, realized that computers and their *interfaces* were becoming the focus of attention. Weiser suggested that, ideally, the interface should be transparent, allowing the user to use the computer as a tool [47]. With his introduction of Ubiquitous Computing, to quote Weiser, "the goal is to achieve the most effective kind of technology, that which is essentially invisible to the user." Ubiquitous Computers are essentially invisible devices, only providing the necessary functions required to perform the task. Rather than having one computer do many tasks, Weiser proposed that a large number of these specialized devices exist in our environment, and that they communicate together with sensing capabilities. Each device should be aware of its location as well as the presence and identity of the people interacting with the device. This knowledge of people and location would allow the computer to provide information that is context-aware and relevant to the user.

Ubiquitous Computing ushered in much creative work, and Weiser's landmark paper is still cited commonly today even though his vision of the future is almost two decades old. However, its importance in inspiring other works should be stressed; for example, the Digital Desk Calculator [49]. This early example of Ubiquitous Computing research has the image of a calculator projected onto a desk, and user gestures are translated to operate a virtual calculator. Wellner cites ideas the work of O'Shea et al. an early work in Ubiquitous Computing, as direction for the design of his system [32].

2.3 Tangible User Interfaces

Tangible User Interfaces (TUIs) became a popular idea after the introduction of Ubiquitous Computing. They typically involve the use of physical objects to represent abstract software objects. For example, using a real paintbrush as an input device to a computer that subsequently displays this input to a screen would be considered a TUI. Several authors have tried to create a suitable description of what exactly a TUI is and how TUIs provide a benefit to HCI, as the definition of what a TUI is has been debated since its inception. The following subsections introduce various examples of TUIs.

2.3.1 Tangible Bits

Following work done by Wellner and others, the study of TUIs began with work by George Fitzmaurice et al. as Graspable User Interfaces. Graspable “pucks” were the first attempt at a physical and virtual link to, “allow direct control of electronic or virtual objects through physical artifacts which act as handles for control” [14].

Hiroshi Ishii later extended this idea and proposed the goal to “fuse atoms with bits” [23]. Ishii’s work deals with trying to create interfaces out of physical objects, physical surroundings, and generally things not otherwise thought of at the time as methods of computer interaction. In a particularly important paper, Ishii and Ullmer outline their classification of TUIs describing three broad categories [23]:

1. *Interactive Surfaces*: Transformation of each surface within architectural space (e.g. , walls, desktops, ceilings, doors, windows) into an active interface between the physical and virtual worlds;

2. *Coupling of Bits and Atoms*: Seamless coupling of everyday graspable objects (e.g. , cards, books, models) with the digital information that pertains to them; and
3. *Ambient Media*: Use of ambient media such as sound, light, airflow, and water movement for background interfaces with cyberspace at the periphery of human perception.

All of these ideas draw on concepts from Ubiquitous Computing, e.g. a given surface, a certain object, etc. effectively acting as a computer fits into the Ubiquitous Computing idea of small computers being everywhere. Several notable examples of Ishii's vision of TUIs follow.

ambientROOM [24] In this paper, Ishii and Ullmer discuss a room augmented with various non-traditional input and output schemes. Things such as network traffic, amount of light in the room, and human movement change the various background displays in the ambientROOM, providing for an original sensory experience. There are two physical objects in the room, a clock and a bottle, that are both inputs and outputs controlling the surrounding displays. e.g. the bottle controls whether network traffic is displayed on the ceiling via a water-drop reflection projection.

metaDESK [44] The idea of metaDESK is that traditional GUI objects are mapped in various ways to real, physical objects on a desk. The mappings are as follows, from virtual object to physical:

- windows become lenses,
- icons become “phicons,”

- menus become trays,
- window handles become “phandles” (i.e. “physical handles”),
- sliders become (appropriately) real, physical sliders,

Illuminating Clay [33] Illuminating clay is a system that facilitates a link between a physical clay model and a computer model of the same shape. The system includes a large clay model which users can manipulate freely with their hands, while a computer tracks the shape via lasers in real-time and projects information onto the clay model via a projector. Figure 2.2 shows users interacting with the system.

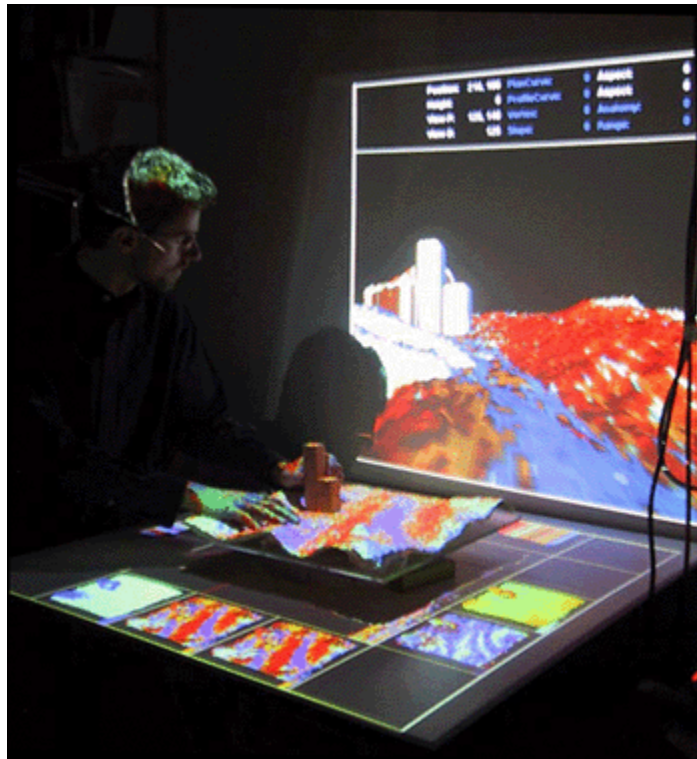


Figure 2.2: Illuminating Clay by Piper et al. [33]

These examples illustrate some of the first demonstrations of TUIs, and spurred a fruitful exploration into using computers integrated with various physical objects. Ishii's MIT Tangible group alone created over twenty projects, however they did not work alone or exclusively; other researchers collaborated and began investigating how these ideas should be interpreted and developed.

2.3.2 Other Visions for TUIs

Although Ishii and Ullmer were pioneers in shaping what people thought of as TUIs, others have attempted to go beyond simple classification in their treatment of the subject. Hornecker introduced a vision for TUI design enabling him to “address a larger design space and to integrate approaches from different disciplines” [21]. He presented four themes in the paper:

Tangible Manipulation refers to the material representations with distinct tactile qualities, which are typically physically manipulated in tangible interaction.

Spatial Interaction refers to the fact that tangible interaction is embedded in real space and interaction therefore occurs by movement in space.

Embodied Facilitation highlights how the configuration of material objects and spaces affects and directs emerging group behaviour with TUIs.

Expressive Representations focuses on the material and digital representations employed by tangible interaction systems, as well as their expressiveness and legibility.

Fernaesus et al. also composed four guidelines for evolving TUIs into better, more usable interfaces [13]. They offered careful attention to the many issues so that

these metaphors and analogies don't carry over unnecessarily, creating a confusing effect. Their idea was to take the TUI away from the dualist approach to HCI - e.g. knowledge and action, input and output - and debunk these many classic metaphors associated with GUIs, TUIs, and Ubiquitous Computing. Their four paradigm shifts are as follows:

- information-centric to action-centric,
- from properties-of-system to interaction-in-context,
- from individual to sharable,
- from objective to subjective interpretations

Note the statement that subjective interpretations should be introduced. It is argued that TUIs and Ubiquitous Computing usually develop specific designs not generally applicable to other computer interfaces. The idea is that a given design is eventually used *in practice*, and is not merely a theory on which few real systems truly adhere to. This issue was also raised by Greenberg and Buxton in a more general way, where they argued that user studies and evaluations are sometimes harmful [16]. This was a key consideration in the design of Organic Board Games, since it is hard to compare common desktop computer tasks to ones performed with cardboard tiles.

However, some specific experiments provide useful information with respect to tangibility and tabletop actions. Terrenghi et al. found that tangibility can provide subtle affordances not found in tabletop displays [42]. Their study used the Microsoft Surface for the manipulation of digital objects. Their experiment involved studying actions with some real objects (e.g. , pictures, maps, puzzle pieces) then comparing

them to actions with digital representations of these objects within their system. When discussing their experiment involving two-handed photo sorting, they noted,

Such [two-handed] interactions were much rarer in the digital case, suggesting a lack of tangibility and 3-dimensional space undermines the natural allocation of hands to these asymmetric roles.

Here, the “asymmetric roles” are actions performed. It is therefore important to realize that tangible systems, particularly new ones, can be rather hard to compare fairly, and may introduce benefits that are hard to quantify.

2.4 Technological Aspects of Organic Board Games

Advances in technology motivated many of the advances in interfaces discussed so far. It is necessary to gain a perspective on what future-looking technologies exist today, particularly for discussing a system involving thin, flat, individual display tiles. It is also important to notice what other researchers have accomplished with similar systems using varying technologies.

Although not yet widespread like LCD, plasma, or digital projectors, Organic Light-Emitting Diode (OLED) technology has garnered much attention in the literature [11, 40]. Like Field Emission Displays, it promises high resolution displays in very thin form factors [31]. Also of interest is digital ink (such as that from E-Ink Corporation), a technology more closely mimicking real paper in that it uses light *reflection*, and not direct emission of light, to be seen. Since these cheap, flat and lightweight technologies it is with these sorts of technologies in mind that the ideas in this thesis are based, and it is apparent that many researchers have this in mind

too with.

Organic Board Games’s simulation of these future-looking technologies was inspired by the Holman et al. PaperWindows system [19]. They project a computer display onto real pieces of paper, using computer vision techniques to obtain input such as the shape and orientation of the paper. Through gestures and motion capture, the system is able to provide information to the user through a visual representation projected on one or more pieces of paper. This information, such as webpages, digital photos etc. , is able to be manipulated and transferred between different pieces of paper. This enabled the study of futuristic OLED paper without the need to use laboratory- and research-grade technologies that would ultimately hamper the study of Paper Windows’ usefulness as an interface.

Schwesig et al. introduced novel interaction techniques for flexible, thin displays with Gummi, a simulation of a credit card-size flexible display [37]. In Gummi, surface deformations of the display provide intuitive zooming in and out of visual material (such as a map) on the flexible display surface. It is the flexible nature of OLED that could make this system a commercial possibility. This affordance can also be seen in interfaces such as ShapeTapeTM and its variations, proposed by Grossman et al. which were possible due to the introduction of the underlying technology [17]. However, ShapeTapeTM demonstrates only the possibilities for input, and lacks any direct output.

Waldener et al. and Rekimoto et al. investigated collaborative user spaces using a camera to track objects, and a projector to overlay information onto the users activity area [46, 35]. Their implementations required either visibly marked game pieces, or a rigid display surface that simulated projection. An example application of these

technologies is the Sony PlayStation®3 game *The Eye of Judgment*, where players use specially marked playing cards tracked by a camera to execute game actions. This is an example of how a static card game is augmented with an external video display to produce a unique experience. Integrating computers with traditional (i.e. non-computer) games has been extended in many ways beyond this as well.

2.5 Pervasive Games and Collaborative Interfaces

Pervasive games is an area of recent study which aims to augment many types of games (e.g. board games, puzzles, or the game of tag) with computer interfaces. It has become a diverse field, utilizing TUIs as well as other interface technologies. Many names have been given to this practice, such as Augmented Reality (AR), Hybrid Games (HGs), and Pervasive Games (PGs).

Organic Board Games is a digital extension of the game *Settlers of Catan*, and so follows the paradigm of pervasive games [29]. Augmenting tabletop games with digital information has been seen to have positive effects on usability and fun. For example, the *False Prophets* prototype introduces a computerized tabletop board game that includes small playing pieces, Personal Digital Assistants (PDAs) and audio in the game [30]. Not only did this framework provide flexibility for the authors in designing the game, but was also found to be highly enjoyable to play. Other research into this form of augmentation has been promising as well [4, 29].

Collaboration is an inherent aspect of Organic Board Games, since it is used on a table large enough for many people to participate with it. A key benefit of TUIs, PGs, and OUIs is that they provide a collaborative environment almost automatically. Tse et al. observed that co-location in games provides many benefits not found in

traditional computer game environments [43]. They observed that “allowing people to monitor on the digital surface, the gestures, and speech acts of collaborators produces an engaging and visceral experience for all those involved.”

2.6 Organic User Interfaces

OUIs strive to create a tangible, flexible, potentially foldable display interface that draws inspiration from organic creations surrounding us everywhere. Holman and Vertegaal discuss this idea with an optimism about the increasing possibility to create input and output on any object intuitively. Their analysis is inspired by the organic architecture of Frank Lloyd Wright, who created a new paradigm in building design in much the same way that the designers of OUIs hope to shape interface design. Holman and Vertegaal’s description of an OUI is as follows:

“An Organic User Interface is a computer interface that uses a non-planar display as a primary means of output, as well as input. When flexible, OUIs have the ability to become the data on display through deformation, either via manipulation or actuation. Their fluid physics-based graphics are shaped through multi-touch and bi-manual gestures [18].”

They present three design principles for OUIs:

Input Equals Output When introduced, the GUI had a clear division of input and output. In these traditional GUI systems, the mouse and keyboard input actions from the user. Based on those actions, output is generated graphically on the screen. In contrast, with the OUI paradigm the input and output are nearly

indistinguishable from one another. This key feature of OUI means that a piece of OLED paper, or any potentially non-planar object for that matter, is meant to input actions from the user and also output them onto the same object. For example, with Illuminating Clay, users shape clay on a table that is subsequently tracked by a ceiling-mounted laser scanner. The change is immediately shown to the user with the use of a ceiling-mounted projector. Illuminating Clay therefore illustrates the synthesis of input and output and can be considered an early type of OUI. Other popular types of input hardware such as the stylus and multi-touch screens illustrate this facet as well.

Function Equals Form Holman and Vertegaal argue that the function and the form of OUI should not preclude one another, in much the same way Lloyd Wright argued this for building design. This means that the object or interface should be a physical representation of activities. For example, the Senspectra system offers direct manipulation augmented with visual feedback for an intuitive approach to physical real-time finite element analysis, particularly for organic forms [28]. The system's physical form does not constrain its function, but the system's function is designed with physical freedom in mind.

Form Follows Flow This principle states that it is of utmost necessity for OUIs to negotiate user actions based on context. One example of form following flow is the ubiquitous 'clamshell' phone, where incoming calls alter the phone's function when opening the phone during an incoming call. If the activity changes, so should the form; to better make use of size and space, the phone folds together when not talking. Similarly, clothing is a simple example of organic design. Its shape deforms according to the wearer, and can even act as a container to

transport objects. Thus, an object or interface should mould to the user's needs whenever possible to facilitate more intuitive and efficient interaction.

2.7 Interfaces with Simulated Physics

Until recently the computation required for minimally realistic motion and interaction of multiple objects in real time was too great to justify its benefit. Computer games, for example, have only recently begun integrating real-time computationally intensive physics calculations into 3D environments, partly due to increasing *parallel* computation ability in hardware. Interestingly, many of the earliest computers were devoted to simulating physics to predict artillery and other projectiles [3]. Therefore, the job of simulating realistic physical interaction of objects is well studied.

It was not until recently, however, that real-time physics simulations have been introduced into user interfaces. Studies such as Gonzalez's hint that fluidity and predictability of motion can be of great benefit to certain interfaces and actions [15]. He found that certain metaphores and movements are better understood and predicted under certain circumstances. Recently, Agarawala and Balakrishnan created *Bump-top*, a new desktop environment where each icon is able to move and interact with other icons in a realistic, physical manner[1]. Each text document, picture, video, etc. is able to be stacked and thrown in a virtual space, creating an environment quite similar to a real desk. The limited user study showed that this familiarity was quite welcome, as it allowed users to translate skills acquired in the real world to their computer environment. (See figure 2.3).

Simulated physics is appearing in mainstream GUIs as well [48]. Compiz, a graphical extension for the Linux desktop, can allow a window to behave as though it is a



Figure 2.3: Agarawala and Balakrishnan's *Bumktop*[1]

deformable piece of rubber, able to stretch and compress based on the user's movement of the window. To a lesser degree, Apple's Aqua interface incorporates some effects that could be described as physically inspired, such as various bounce actions for icons and windows. Additionally, real and simulated physics are mentioned repeatedly in the OUI literature as important in creating a good, effective organic interface [36, 18]. Needless to say, physics integration is become notably more prevalent and functional, due in part to the decreasing relative cost of computation compared to user productivity and enjoyability.

2.8 Summary

A brief background of HCI has been presented in this chapter, as well as notable inspiration for Organic Board Games from the literature. One of the key concepts developed was that of Tangible User Interfaces, a paradigm of HCI that investigates new methods of interaction with computers by means of physical, tangible things. This is in contrast to the more traditional WIMP systems involving manipulation of abstract, virtual objects indirectly with a pointing device.

An extension to the idea of TUIs is that of OUIs, where an attempt is made to have computer interaction mimic the organic world as much as possible through flexible, form-fitting displays on any type of object. The hope is through this emphasis on nature much inherent human experience can be utilized, essentially creating a more usable interface without any prior knowledge or training.

As computers continue to permeate every aspect of human existence, emphasis on non-standard UIs has become an important exploration into better interaction methods. With all these ideas under consideration, the following investigation and specification of Organic Board Games is presented.

Chapter 3

Tangible Tiles

3.1 Introduction

In this section, the physical aspect of Organic Board Games will be introduced to accompany the background principles presented in Chapter 2. These principles take shape in the next section with the presentation of the physical gestures and logical actions, hereafter referred to as Tangibles Tiles, that form the core of Organic Board Games and other applications that follow. To reiterate, Tangible Tiles is simply a name for the physical manifestation of Organic Board Games, like the mouse is to the WIMP interface. Design decisions are justified and referred to throughout the chapter.

3.2 Prototype Apparatus

First, the actual apparatus that was used in the design and eventual creation of Organic Board Games will be introduced. Projection onto interactive objects is well

researched as mentioned in Chapter 2 [19, 33, 49]. Computer vision using reflective markers has been used extensively for use in films and video games, typically with a VICONtm system. The combination of these systems engender the hardware and software system that will be termed “Tangible Tiles”.

3.2.1 Display Technologies

A discussion of the theoretical Tangible Tiles must include the discussion of practical display technology to be used. At its core, Organic Board Games is a new user interface featuring small hexagonal tiles, each of which has separate, distinct display capability (i.e. each tile may display something independent of all others). Ideally, each hexagonal tile would have a thin OLED or similar display to mimic the original Settlers of Catan tiles, together with an hidden wireless communication system; for example, a system similar but not limited to a wireless sensor network [6]. Movement and gestures would be tracked, and the images displayed on the tiles would change according to these movements. Small wireless display devices such as Hutterer’s have demonstrated such ability [22].

Lacking these future-looking technologies, a system was built using a digital projector to display on the tiles, and an infra-red camera to track their movements. See Figure 3.1 for an overview of the system.

3.2.2 Camera and Tiles

In the prototype system, each hexagonal piece is outfitted with small infra-red reflectors approximately 1mm square, pictured in Figure 3.2. In both the board game and the prototype, the hexagonal tiles are 5.2cm on each side, with the Tangible

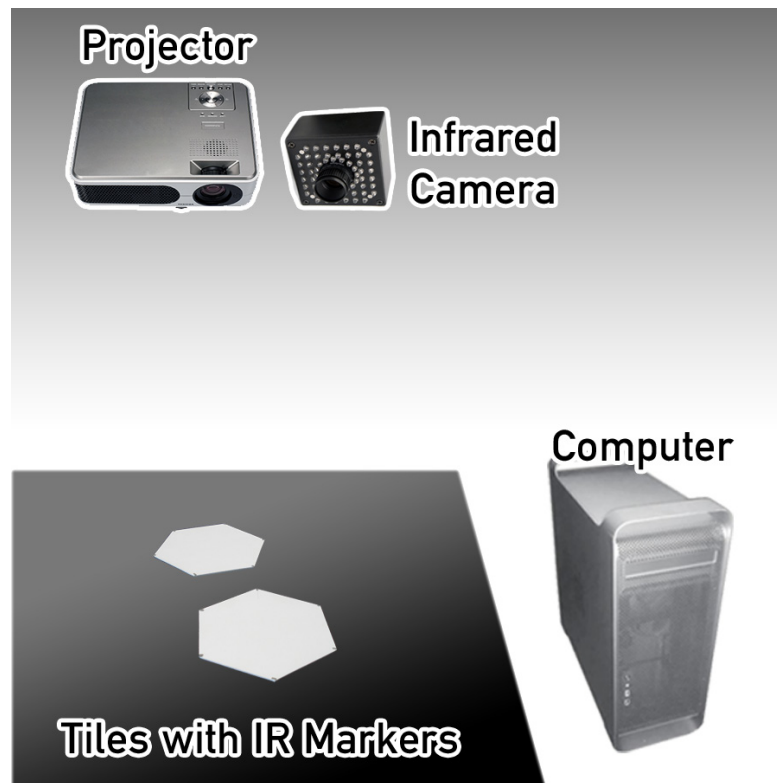


Figure 3.1: The apparatus used to implement Tangible Tiles, the basis of Organic Board Games

Tiles having completely white surfaces, compared to the board game tiles with static images on them.

A Xuuk Eyebox2 Eye Contact Sensor (ECS) is used as the infra-red camera, connected to a computer via the Universal Serial Bus [8]. This particular camera is used principally as an eye-tracking device [38, 20, 2]; however, its behaviour was modified to facilitate the requirements for tracking points as opposed to eyes. In the case of Tangible Tiles, the original eye-tracking system is simplified considerably. With the gathered image data, a software model can be made of how the hexagons are arranged on a tabletop. Specifically, points are arranged into groups of 6 vertices representing a hexagonal tile. This information is fed to a game model that interprets

the movement and orientation of the tiles in order to trigger game logic (e.g. events, animations, etc. - see Appendix A). Simple image rendering is performed to generate an image using the Open Graphics Language (OpenGL), and this is then displayed on the digital projector that is aimed and calibrated to shine on the tiles.

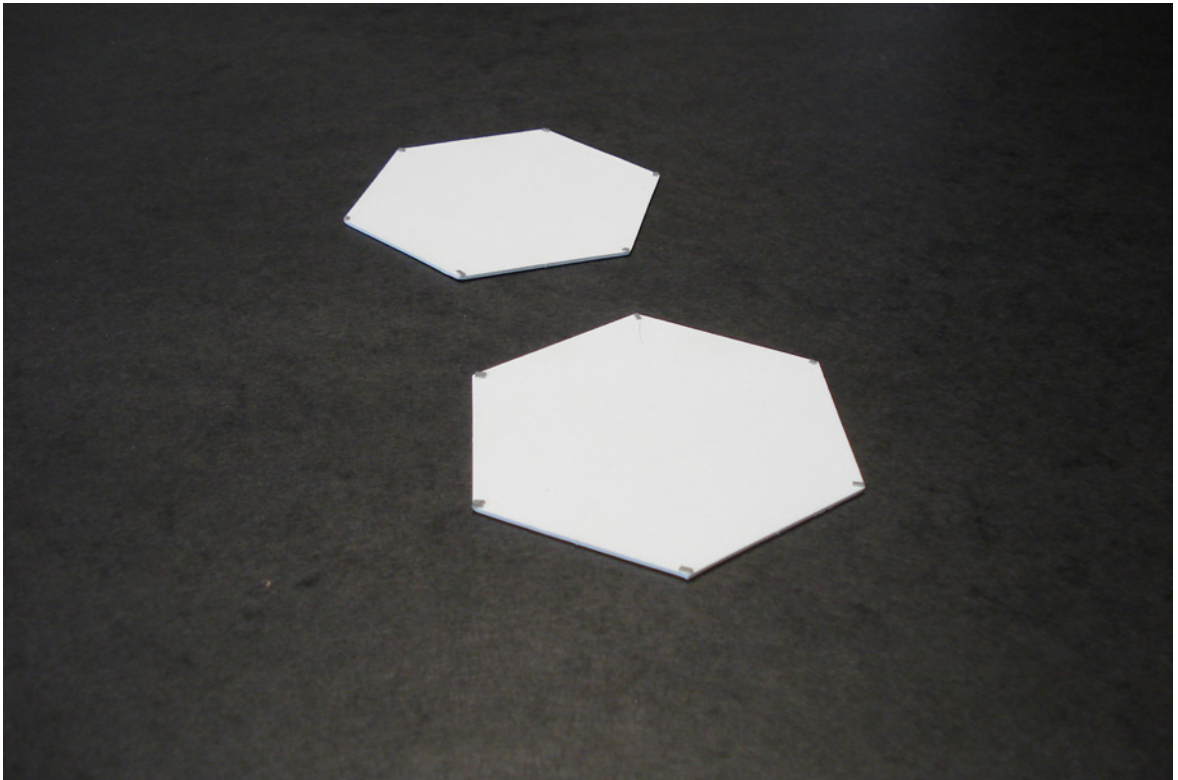


Figure 3.2: Tiles used in the Tangible Tiles prototype, augmented with small reflective dots used to track each tile.

Most of the systems described in Chapter 4 use OpenGL to facilitate image manipulation and eventual projection onto the tiles via the digital projector. In addition, Apple Computer's Quartz system was employed for more complex integration of the tile system with so-called Real-Time Strategy (RTS) computer games, also discussed in Chapter 4.

A rough outline of the software system involved for this is seen in Figure 3.3.

Although emphasis is made throughout this thesis on the abstracted Organic Board Games interface, the substantial work for this thesis was in constructing Tangible Tiles prototype software system and physical apparatus for realization of various Organic Board Games.

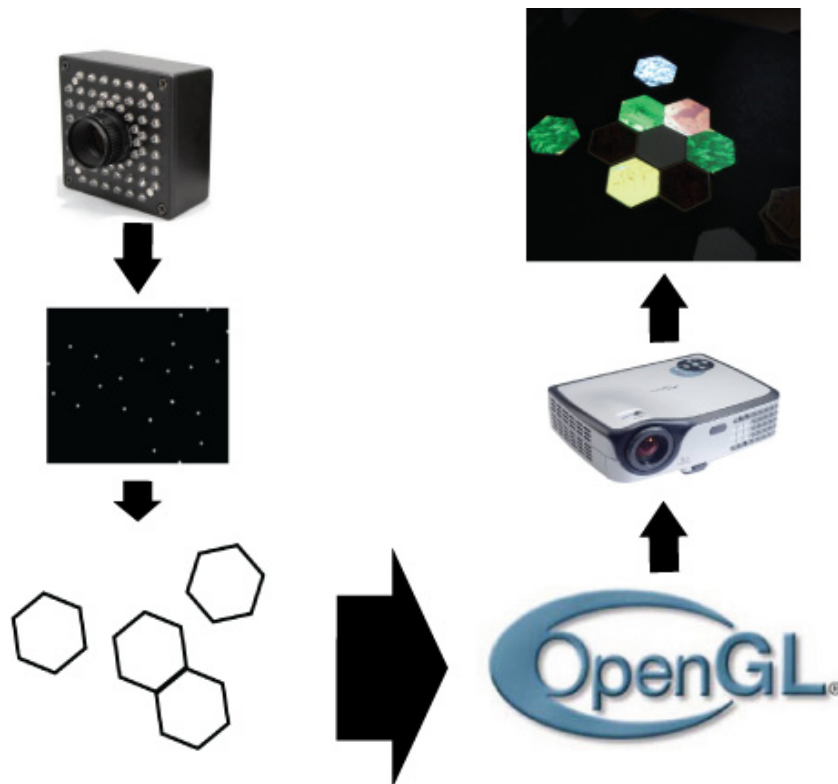


Figure 3.3: A rough software system diagram for Organic Board Games. The infrared camera takes a picture of what it sees. This picture is then processed to produce a model of hexagons. After this is complete, images are drawn in OpenGL based on this model and output to the display device, a digital projector.

3.2.3 Frame Memory

In some instances it is necessary to remember (i.e. record to the computer) states of the hexagons for some period of time; sometimes for a single frame, or sometimes

for longer. This is implementation specific as it relies on the context in which the tiles are being used. For example, if no additional game functionality is added to Settlers of Catan, and one simply wants to make game set-up faster, there is no need for memory in the system. However, when gestures and context-specific actions need to be tracked, a separate system is required to retain temporal information, similar to a finite state machine.

In every system that was constructed involving Tangible Tiles there is a need to detect when a tile is rotated. Otherwise a tile rotated by 30° will appear identical to a tile rotated by 0° due to its hexagonal shape. To combat this, a single-frame memory is in place to infer what the true orientation of the tile is. That is, the most recent frame of information is combined with the previous frame to produce a current position datum. The peril of this design is that movement of more than 30° in a single frame (i.e. in less than a fifteenth of a second) will be inaccurate.

3.2.4 Projector and physical space

The digital projector and Eyebox2 camera are mounted above a physical playing space 1.5m above a desk and connected to a computer as can be inferred from Figure 3.1. After the computer processes the data from the camera in the manner described above, it can display information via the digital projector onto the tiles. The image projected onto the tiles is without borders, meaning that when two tiles are adjacent there is no gap in the display. The two tiles could be considered fused, acting as a single tile depending on the application.

This approach requires basic calibration achievable by hand by adjusting the camera field of view, projection area, and projected image size of the tiles appropriately.

It is notable that the resting surface for the tiles can be anything, easily providing the opportunity for multiple participants and users to engage in a given application of Tangible Tiles. An advantage of this is that unlike conventional interfaces, users of Tangible Tiles can easily grasp a single object or many objects without the need for any special arrangements or data about orientation. Many touchscreens suffer from an inability to touch multiple objects, though this is becoming less of a problem with new systems [10, 25]. The collaborative aspect of Tangible Tiles is therefore inherent to the system.

3.2.5 System Limitations

It is important to realize what the limitations and drawbacks of an interaction system are in order to surmise its applicability in different situations or with potentially superior technologies; e.g. in the case of Tangible Tiles, a system using OLED displays with a wireless communication system might be a suitable replacement. Two main problems exist with Tangible Tiles that cause errors to occur in operation.

The system described above suffers from three main problems:

Object Occlusion The Tangible Tiles prototype suffers from the problem of object occlusion. When an opaque object such as a user's hand or another tile blocks the camera's view of just a single reflector, one tile will no longer be detectable using the methods described above. It is therefore necessary to implement another component that deals with this imperfect collection of data. For this system to achieve maximum robustness, this would be necessary; subjectively speaking, however, it did not present much difficulty and in fact allows for the touch gesture to be implemented easily using occlusion, as noted in section 3.4.

A hypothetical OLED system using wireless sensor-network detection does not have this problem as the tile itself would contain the display, negating the need for detection of its location for the display to work or to be seen properly.

System Latency The camera in use has an input maximum of 15 frames of useful data per second which adds noticeable delay in the production of a projected image. For example, if a given image is projected accurately when a tile is not moving, when a user moves the tile to the side at a constant speed the image will lag the tile, clearly depending on how fast the movement is. This problem can be overcome by either adding better, faster hardware, e.g. a camera with a faster frame rate, but like occlusion this problem does not exist when the display *is* the tile, as in the OLED example.

Limited View The usable area of control when using Tangible Tiles is limited by the camera and projector's field of view. Thus, if part of a tile is outside this field of view, it can no longer be detected and therefore cannot be projected upon properly. This view can be controlled by varying the distance of the camera and projector; however, if too far away from the camera accuracy of detection is lost

Tile Limit Due to the limited practical area of the prototype, there is a maximum number of tiles that can be detected using the system in the manner described above. This limit is the effective field of view of the camera divided by the area of a single tile. In practice, this was approximately 30 tiles.

Limited Tilt Angle Finally, because the camera is fixed above the user's desktop

space, the tile cannot be tilted beyond the angle at which light is no longer reflected by the markers on each tile. This limit was observed to be approximately 50 degrees to the horizontal.

Generally errors in detection and projection can largely be ignored because they are either short-lived, as in the case of occlusion, or they are inherently part of the system in the case of low frame rates, so can safely be ignored. In the implementation of Organic Board Games and other applications, some special considerations for imperfections in the system are accounted for and are discussed in each case.

3.3 Settlers of Catan

With the physical prototype described, motivation and presentation of how a user interacts with this system. Settlers of Catan, an early motivation of Organic Board Game's conception, is a turn-based board game, invented by Klaus Teuber, where players attempt to settle on the island of Catan faster than all other players. Game play consists of collecting and trading resources, and spending these resources on further resources such as settlements, roads, or specialized cards. The game is played on a board that can be modified; it is composed of 38 hexagonal tiles, and can be arranged randomly to produce a slightly different board every game (See 3.4 for an example board layout). However, this freedom comes at a cost: tiles and other game pieces get lost, scattered, and disorganized, the game takes a long time to set up, and much of the customizable nature of the tiles is lost due to the game's fixed playing style, requiring expensive expansions to introduce new methods of play. Settlers of Catan was chosen as inspiration due to the already organic nature. The entire board

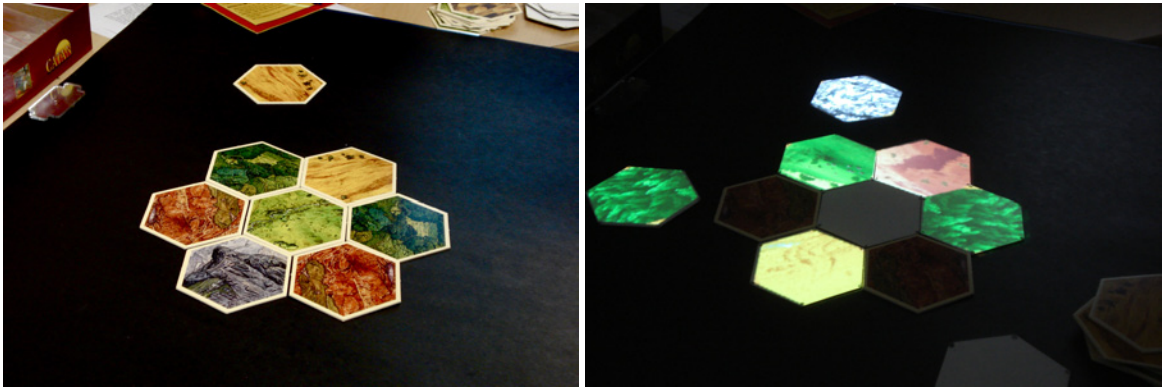


Figure 3.4: Left: an example layout of seven tiles from the board game Settlers of Catan. Right: an example layout of Organic Board Games showing tiles projected upon, augmented with reflective dots, lying together with some original tiles from Settlers of Catan

is movable and interchangeable, unlike most board games. Inspired by this freedom to modify the game board, Organic Board Games is designed firstly as an extension to the original board game. Its purpose is to enhance the game with physical interactions that augment the game's mechanics and make the game more immersive and fun. This original motivation led to other applications based on the same physical system, but in every example system that follows in Chapter 4 the goals remains similar:

To have an interactive display of hexagonal tiles

To have a system that responds to physical movements

To have a system that plays electronic games

In this way, the hope is to highlight how several small tiles with unique displays provide further interactivity to an already rich board game.

3.4 Physical Movements

The design of Tangible Tiles incorporates physical movements unique in scope and simplicity. They were created with simplicity and the limits of the technology in mind. However, applicability to possible future technologies still exists; the actions might be more or less diverse than they would be if using a different technology, but they remain useful. For example, if using OLED technology it might be quite easy to display on both sides of a tile.

The physical movement of a mouse can be considered as an analogy to the physical movements presented below. A mouse is able to move around in a planar space, and has a single button as input. Taken out of context (the context of a WIMP environment, for example) the cursor of a mouse on a screen is nothing of particular interest. Within the context of an application, however, it becomes exceedingly useful, since it is a tool that facilitates the manipulation of meaningful data such as files, windows, etc. Similarly, the four movements presented below, though seemingly narrow in variety, have been chosen for their simplicity and distinctiveness. This means that each gesture should be able to be interpreted clearly within the context of the application, in line with the third principle of OUI - “Form Follows Flow”. This also means the movements should not easily be confused with one another when combined together physically. Thus, they are designed to form a type of orthogonality. In the context of Organic Board Games and other uses of the tiles, these movements provide significant variation necessary for useful tasks.

These basic movements provide a foundation for all the interaction techniques in Organic Board Games. They are presented in Figures 3.5 through 3.8.

Touch A user can touch a tile by placing a hand or finger on the tile.

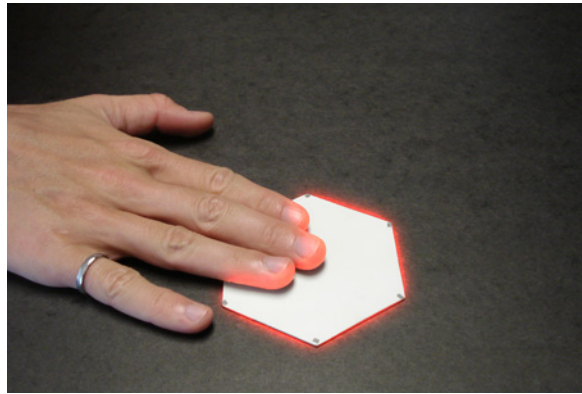


Figure 3.5: Touch

Rotate A tile can be rotated about its centre. This gesture can be used to simply get a better view of the object, or to initiate context-specific actions.

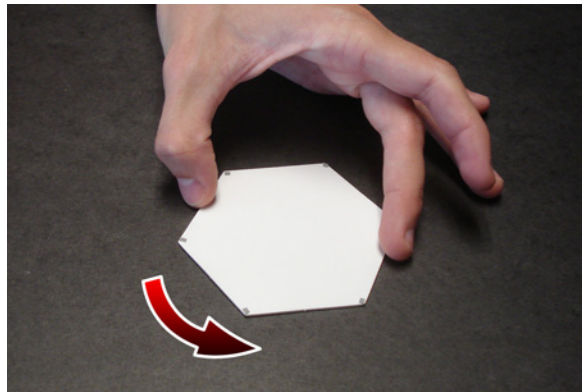


Figure 3.6: Rotate

Adjacent placement Two tiles can be placed adjacent to each other to connect them physically. By virtue of its shape, a given tile can have six adjacent tiles.

Tilt Picking a tile up and tilting it so that it is at an angle to the horizontal playing surface (typically between about 0° and 30° to horizontal).

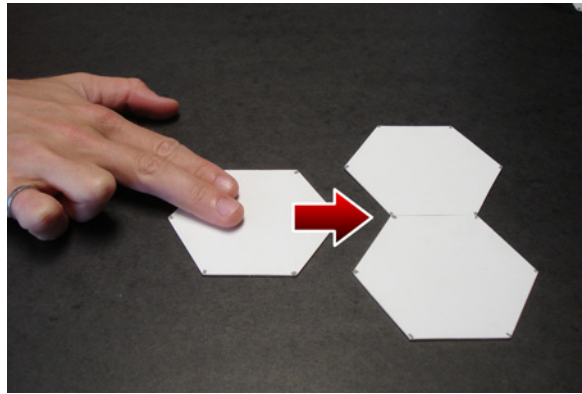


Figure 3.7: Adjacent Placement

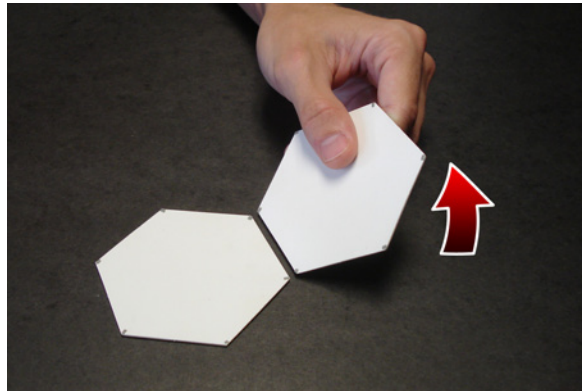


Figure 3.8: Tilt

Through these actions many interactions are possible, especially considering that more than one tile can be manipulated at once. These movements can also be combined to form multi-step interactions, described by specific key examples below.

3.5 Interaction Styles

These input gestures can be combined to allow the following interaction styles within the prototype game environment:

Connect In the prototype, the adjacent placement of tiles conveys information depending on how other tiles are arranged. Adjacent placement of two tiles causes a physical and logical link between the tiles. For example, adjacent placement can connect a piece of farmland with a piece of woodland. This technique is required for tiles to be able to be ‘poured’ into each other.

Pour Pouring is an interaction technique involving two adjacent tiles. After the physical movement of adjacent placement has taken place, tiles can be tilted. The direction of the tilt, as well as the amount of tilt, can be tracked. In the Catan prototype this action leads to the movement of a tile’s resource from the tilted tile to the flat tile, effectively “pouring” the resource from one tile to the other. In the above example this could produce a mixed farm and woodland on the destination tile, limiting the production of each resource per tile, something not possible in the original board game.

Select Although all game pieces are actively displaying, and can be moved at any time, some actions require a single tile to be the focus of the user, much like icon selection in GUIs. This is done in the prototype by touching or occluding a single marker on a game piece for one second. The tile then shows it is selected by displaying a fade-in/out animation. Multiple tiles can be selected in sequence or at once to facilitate certain actions. For example, three tiles can be selected to indicate where a new game “settlement” is to be projected.

Position At any time, a game piece can be moved around in the playing area. Just as a real game piece has no restrictions on the number of players who can move or touch it, our prototype facilitates multi-touch, multi-user interaction exactly

as a real board game would, since each piece is a real, physical object. No restriction is ever placed on a tile's movement, and the game engine keeps track of all movements automatically.

Throw If a hypothetical digital object (such as a rock) resides on a tile, it can be possible to move the object as though it were a real physical object resting on the tile, similar to BumpTop [1]. This ability is facilitated if using simulated physics within the system. Using a quick slide gesture, the object is able to fly through the simulated game space and land on another tile. Alternatively, the rock could be gently poured onto another adjacent tile. This comes as a result of the system augmented with simulated physics described in Section 4.3.

3.6 Summary

The Tangible Tiles system was presented as the foundation on which Organic Board Games is based on. This system of gestures and interactions provides a rich set of possibilities taken in the context of a game or other application. With the prototype described, investigations into several systems were made and are presented in the next chapter.

Chapter 4

Implementations

4.1 Introduction

Tangible Tiles is a useful and distinctive hardware and software construction, so it is important to consider how else it might be used. In this chapter some uses of Tangible Tiles are presented in detail. The Tangible Tiles prototype along with Settlers of Catan created a foundation on which the concept of Organic Board Games was to be developed. During this development, many different ideas were created regarding how Tangible Tiles could be used as an interface. The possibilities for creating more than a board game extension became clear through continued interaction, and it was therefore determined that each of the systems described below deserved special attention. Stated another way, Organic Board Games became one of several variations on a theme. These themes became valid interaction schemes in their own right, and hence they are presented in detail. Discussions and observations follow in the next chapter.

4.2 Organic Board Games

The design for Organic Board Games came from a desire to further improve the board game *Settlers of Catan*, as mentioned earlier. The flexibility that hexagons with dynamic displays provides means that game set-up is quick, expandability is trivial, and new, creative game design is possible. The original game can be adhered to, or creative extensions to the rules can be added. A modest extension to the original game is presented that highlights the interaction mechanisms presented using tiles with dynamic displays. This extension is designed with the following question in mind: “What can be done with dynamic display tiles that cannot be done with static displays?” Though the possibilities are unbounded, the principles of OUIs, outlined in section 2.6, are used extensively as guiding principles.

For example, the pour technique could be used to take adjacent tiles and mix them together. The result, with regards to the principles of OUI, could be that an output (an animation on a tile) is shown for the user’s input (the tilt of the tile), following which a resource is gradually transferred from one tile to the other. Form will follow flow, and the two resources would be mixed or transferred. The speed at which this happens could be based on the tilt applied to the tile. Although all these principles could be implemented inside a desktop application to some degree, their implications would lack the unique physical interface provided by *Tangible Tiles*, and thus would not provide any insight into interface design.

Several increasingly ambitious extensions to *Settlers of Catan* follow. The prominent system that was developed involved replacing the OpenGL subsystem with the Quartz Composer (itself an OpenGL application) to deal with imaging. This proved

fruitful for dealing with a large number of media for display on tiles, and was eventually used as a method for controlling the RTS games *Age of Empires* and the open-source *Glest*. This capability to control existing RTSs was deemed a useful demonstration of the general framework of Organic Board Games.

This interesting fusion of board games with RTS games deserves some historical consideration. The original motivation and inspiration for the first modern RTS games (such as *Warcraft* and *Dune II*) were rooted in board games, notably the strategy table-top game *Warhammer* in the case of *Warcraft*. This quasi-reversal of history is not accidental; the decision to emulate computer games with board games and *vice versa* is intentional.

Three methods of control were implemented:

Tilt Movement The tilt/pour movement acts in two ways. It acts to move land units to an adjacent tile. It also acts to move naval units, as well as triggering any land units contained in the naval unit to disembark onto land. For the latter to happen, it is required that the naval unit be poured onto an adjacent tile which is not water but land. The mimicked action is *pouring* the boat's contents onto shore.

Slide Movement The slide movement triggers many potential actions depending on the context. Slides triggered movement of units if there is nothing in the adjacent tile, and triggers an attack if the adjacent tiles contain enemy units. It might also prompt a unit to build, repair, or heal certain other units or features.

Rotation Movement Rotation of the tile simply changes the perspective displayed on the tile. That is, the virtual view of the objects displayed is modified much

like a drawing program's 'orbit' manipulation. This can be useful to gain a better perspective or to orient a particular building, unit, etc.

Context-Aware Menus Figure 4.2 shows a user directing a unit to move to the specified tile in the RTS implementation. In this case only three tiles are shown for simplicity. A touch triggers a context menu to be shown depending on what is on the surrounding tiles (if anything). The user is then restricted to complete the action by touching one of the highlighted tiles.

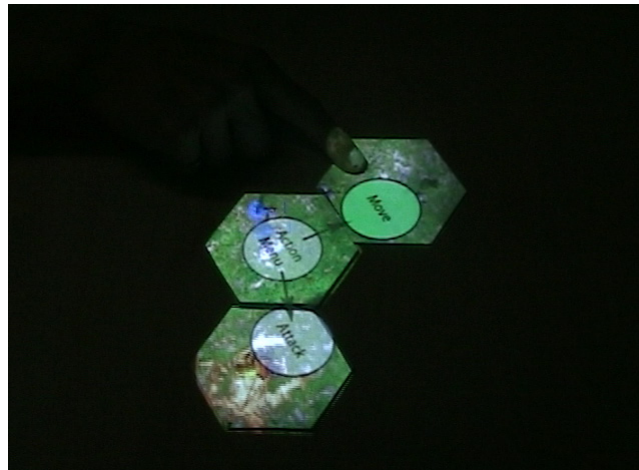


Figure 4.1: The context-aware RTS game interactions allow for a 'move' command to be issued

This example illustrates culminating levels of design. In the next sections, several increasingly complex additions to the original Settlers of Catan are outlined.

4.2.1 Static Displays and Cosmetic Extensions

Simply replacing each tile in Settlers of Catan with a computer-controlled display tile creates a surprising number of benefits. The first and most obvious is that orienting the tiles for game play is faster, and is also less prone to error. In the original

board game 19 tiles are oriented in a circular pattern much like in Figure 3.4. The pattern of these tiles is random, so there is no advantage in using static tiles in this sense. However, another 24 tiles must be placed around the 19 in a very particular orientation. Small coin-sized markers must be placed on top of the inner 19 tiles as well. This entire set up can be done in a single gesture using Tangible Tiles (in the actual implementation it was the act of turning on the system that did this). Further benefit is gained when one considers costly expansions to the board game. These expansions require further tiles and game pieces. The flexibility afforded to Organic Board Games by Tangible Tiles means that almost any retooling of rules or images is possible, while using inexpensive cardboard with inexpensive reflective tape to expand the number of tiles. Therefore the flexibility in design and art provided by computers is extended to Settlers of Catan.

The system implementation for this extension was trivial. Taking information provided by Tangible Tiles and a set of images representing each resource in Settlers of Catan, the images were projected onto each tile and remained there for the duration of the computer program. No use of Tangible Tiles' interaction methods was needed to execute this, though this extension naturally uses the physical movements of *touch*, *rotate*, and *adjacent placement* without them actually triggering anything special.

Another simple but effective possibility for the game is adding animated images for each tile. This was performed by a rather straightforward implementation. Instead of adding a static image, a brief animation or video that fits on the tile was displayed instead. For example, a forest tile was represented with a lumber worker felling a tree. Another demonstration that was created involved a tile *glowing*, i.e. fading into black and back again, when the tile was selected by a user. Needless to say, one can

introduce quite a bit of artistic creativity with such a system, provided sufficiently simple tools exist to add these media.

However, almost all of these benefits can be had with a traditional computer game version of Settlers of Catan, e.g. a game played with a keyboard and mouse. This idea is therefore too limited in scope. The only novelty is that the user gets to actually experience the *physical board* of the board game.

4.2.2 Context-Aware Actions

Context awareness is a key component to many common interfaces, including most flavours of Ubiquitous Computing and TUIs. It provides organization for actions the user wants to perform, as well as restricting the user from performing unwanted or inappropriate tasks. Context-aware interfaces are particularly popular with mobile and ubiquitous computing since the available interactions are quite simple, so actions must be sufficiently focused based on context.

The ability to sense where tiles are in relation to each other is an important ability that arises from Tangible Tiles as well as most other systems that mimic it, e.g. the wireless system suggested in Section 3.2.1. This ability lends to inferring what can and should be done in the game. Several possibilities exist for implementing this strategy based on what kind of rules are considered. The fundamental reason for dynamic displays in the game is to justify game state change and create a dynamic, potentially real-time version of Catan. This might introduce a skill aspect of the game, or continue its strategy based roots. In either case, a defined set of rules is a matter for a game designer and not an interaction designer, though the two can and should be closely linked for a case such as this. Several categories for context-aware

augmentation for Organic Board Games are as follows:

Context-aware menus In Section 3.4 the touch gesture was presented, and it was noted that this gesture could be detected using either occlusion or by placing a reflector on the finger. When this touch is detected, a menu can shown as in Figure 4.2. This menu shows the possible actions a user can take on the adjacent tiles based on the current state of the game.

Action-aware reactions What happens when a user moves or takes one of the 33 tiles away from an ongoing game? Usually nothing would happen, the user would replace the tile, and the game would continue. With Tangible Tiles, this does not need to be the case as it is clear when the tile would no longer be adjacent to the others in the model constructed by Tangible Tiles. When a tile does leave the playing area, actions such as immediate or gradual switching of adjacent tiles to some other resource could take place. The detection of adjacency is also useful to determine what kind of contextual menu might appear. e.g. ‘Pause game?’, ‘Flood land?’, or ‘Place tile here’ may be suitable.

Restricting game actions Having context-aware menus pop up constantly, or having tiles mix with each other if moved around may not be necessary or wanted. It is therefore important to restrict all interaction to the absolute minimum number possible, below which certain functionality is impossible. This means not every potential action should necessarily have an effect. For example, occluding a tile to select it may be unnecessary most of the time. If operating in a turn-based fashion, it may only make sense to perform this at the beginning of a player’s turn. The action of selection, however, changes depending on the level of modification.

Context-aware menus, specifically, take a form similar to *marking menus* since they effectively present several choices when a user selects or moves a tile. The maximum number of choices for the particular implementation created in Organic Board Games is six, since this is the maximum number of tiles any given tile can be adjacent to. This is well under the threshold of where users begin to make many mistakes or take too long to choose [27].



Figure 4.2: A Context-Aware Menu

4.2.3 Fundamental Game Modification

Adding the *pour* interaction style to Organic Board Games represents a radical shift from the original board game. Moving, rotating and pouring tiles while the game

progresses requires a complete rethink of standard rules, therefore it engenders an entirely different game. This is interesting considering nothing is physically changed in the game other than how one moves things around. For this mechanism to be introduced an awareness of the temporal nature of the game is necessary. This criterion is mainly a choice between a continuous and a turn-based passage of time. The original Settlers of Catan is turn based, whereas continuous time in this context means something akin to a real-time strategy game introduced above.

Tilting introduces a new possibility involving context-aware actions. Adjacent tiles might be mixed, transferred completely, or temporarily disturbed depending on what the two or more adjacent tiles represent. This illustrates a OUI's ability to allow for fairly flexible creative interaction mechanisms *as long as they can be detected*. Two example concepts can be introduced using the pour gesture.

Position-aware game pieces Having knowledge of all the tiles' positions generates the capacity to decide how a pour effects the display on the tiles and the subsequent game mechanics. A water tile adjacent to a pasture tile may allow for bonus production on the pasture; pouring water onto the pasture may render it useless for several turns or seconds, again depending on whether the game is conducted with the normal turn based mechanism or a real-time environment.

Real-time game actions If a real-time game is being played, potential for spontaneous user action (i.e. an action not prompted by a turn change or direct user stimulation) is possible. A user may tilt a tile to initiate a mixing of resources so that production of the resources is divided equally among them. It could also trigger destruction or flourishing of the resources, again depending on adjacency conditions. For example, pouring a desert tile onto a pasture may turn

the pasture into a desert, but pouring water on a desert may transform it into a pasture. This could potentially lead to frantic pouring by users in an attempt to gain advantage of the benefits of pouring while capitalizing on the penalties to opponents.

4.3 Tangible Objects with Physics

The addition of simulated physics has been shown to improve immersion, user feedback, and generally improves a user's impression of interactive systems as mentioned in Section 2.7. It is worth repeating that simulated physics has been anticipated as an important addition to video game development due its ability to create a more believable, immersive environment. This experience can encourage beneficial design of interfaces by allowing everyone's experience with actual objects to be utilized. With this in mind, the pairing of simulated physics and Tangible Tiles was undertaken.

The system built was one where each tile corresponded with a similarly shaped object (i.e. a flat, thin, hexagonal, closed polygon) within a simulated environment. In the implemented system the objects that the tiles interact with are typically simple shapes like spheres, cubes and rectangular prisms. In this environment, each simulated object can interact with every other simulated object as if it has momentum, shape, etc. Physics environments such as this are typically simple, simulating Newtonian forces, forgoing inter-object gravitational and microscopic forces; however can vary. Typical physics simulation for real-time applications (e.g. games or interactive systems) is done approximately, without the need to be exact since the goal is to *appear* real. Unless gross errors occur, these errors are not detectable by the user or gamer so go unnoticed. Other applications (e.g. biology or weather simulations)

have different concerns, and accuracy might be paramount. Describing a simulated physics system completely, however, is beyond the scope of this thesis.

To aid in the development of such a system, the PhysX commercial physics simulation Application Programming Interface (API) was used [7]. It provided a relatively straightforward software environment in which to experiment with, being originally intended for real-time applications, specifically 3D games. Roughly three steps are involved in adding physics to Tangible Tiles: gather a model of the *real* physical environment using Tangible Tiles, link the objects in this model to *simulated* physical objects using the PhysX package, and display this environment back onto the real physical tiles again using Tangible Tiles via the projector system described in Section 3.2.4. An obvious problem arises with respect to how the real physical objects are described in the simulated environment since the cardboard tiles cannot be moved directly or indirectly by simulated objects. Achieving this would require some separate system to move the tiles synthetically with some system of actuation. It becomes necessary that the simulated objects corresponding to the real objects be given zero inertia, i.e. they become immovable objects within the simulated space only able to move with a direct manipulation of their position vector. Therefore, when a user moves a tile, the position of its corresponding virtual tile is moved. The PhysX package did all background calculations; all that was necessary was to link each tile's position with that of their corresponding PhysX software object.

One interesting side-effect of adding physics is that the pour gesture from section 3.5 is added without the need to specifically add it as a feature. In other words, no direct detection of a tilt event was necessary since this was effectively being updated

every time the physics simulation was updated (roughly 30 times per second). Simulated fluid allowed for ‘water’ to be poured over tiles for a user to eventually pour it off. An important point here is that all the loose virtual objects (i.e. ones not tied to a tile) are being controlled directly or indirectly by the objects the user is gripping with his hands, and the output of this is usually being seen directly on the tile it is occurring on. This is in contrast to Agarawala and Balakrishnan’s Bumptop, where objects are being indirectly controlled by the mouse.

4.4 Conclusion

This chapter presented several example applications of Tangible Tiles, most notably the idea of Organic Board Games. It can be seen that the invention of tiles with displays on them can generate much variety in application to things other than the board game Settlers of Catan. It is mainly the tile’s tangibility that allows for this to be so, though it is also the hexagonal and flat nature that determines their applicability to the demonstrations discussed in this chapter. Some descriptions are purposely left abstract as only specific examples could be demonstrated without delving into very detailed and focused software. It should be clear that although these demonstrations are rather varied, the same set of movements and gestures are present in all of them, indicating the interesting nature of Tangible Tiles as a basic method of input. Further observations are presented in the next chapter.

Chapter 5

System Evaluation and Critique

In this chapter, the systems proposed in Chapter 4 are evaluated. The observations are very encouraging and it is believed that they validate the use of small tangible tiles for interacting in various ways with a computer. A list of design critiques and observations that were made during construction and use of Tangible Tiles are presented, and the chapter is concluded with some initial user experience comments. Users consisted of the author and members of the Human Media Lab including four males and one female.

5.1 Design and Observation

The design of Organic Board Games started as an attempt to bring aspects of Organic User Interfaces to the board game of Settlers of Catan. Its design deviated slightly from the original idea of creating a marketable game due to the constraints of technology and time, but several principles continued to be adhered to. The principles of OUI played a strong part in shaping almost all decisions involved in Organic

Board Games. The following description notes how these principles ended up being manifested.

Input Equals Output Obviously Organic Board Games follows this design principle by displaying the results of user interaction to the input mechanisms, i.e. the tiles.

Function Equals Form Each tile in Settlers of Catan is a place holder for some resource or entity. Each tile in Organic Board Games continues this function, and adds to that the ability to display even more information about various game actions. The tiles therefore continue their functions that focus around being a representation of a single resource or object, and to act as something that can easily be view and identified.

Form Follows Flow Many context-specific actions are able to take place in Organic Board Games due to the fact that the tiles are being tracked at all times. As such, the form of the apparatus and the objects within has an effect on Organic Board Games's flow of game play.

The principles of OUI as placed into and observed in the design of Organic Board Games were not the only results from the study of Tangible Tiles. Many ideas not related to games or potential application of interaction techniques to future interfaces were conceived and observed. Notable observations are presented below.

5.1.1 Observation 1: Tangibility is Key

OUIs provide a new way of interacting with computerized objects, and Organic Board Games accomplishes this by controlling a board game. It is impossible to accomplish

the identical interaction methods of Organic Board Games with a mouse or most other forms of computer input. From a purely objective view there are many faster techniques that would accomplish the same or similar tasks to those proposed in this thesis using a mouse (or something even faster, such as the eyes [9]). However, one could argue that any board game could be played with a pencil and paper, and could forgo the physical game pieces. This overlooks the importance of the ability to pick up and hold each tile, and to view them together on the board collaboratively with other people. The tangibility and the natural presentation of actions of Organic Board Games and Tangible Tiles is therefore a key strength to be noted.

5.1.2 Observation 2: Tracking Technologies Affect Immersion

Experience with Organic Board Games indicates that an extremely important element of its use is the latent period between game actions and display updates. Natural items change their ‘display’ effectively at the speed of light. Conversely, the Tangible Tiles system was restricted to about 15 frames per second, well below a normal person’s perception of what is smooth (approximately sixty frames per second). This gap does not restrict much *per se*, but is usually one of the first things to be noticed about the system (almost every user commented on this). The illusion that a tile from Organic Board Games is simply a normal tile from Settlers of Catan but with a changing display is therefore not complete. This illusion exists in specific cases, for example when the tiles are not moving or when someone is viewing the tiles from a distance, but cannot be achieved with such obvious lag in image projection.

5.1.3 Observation 3: Tiles Are Best for Imprecise Tasks

Although the tiles proved quite flexible for applications, the most obvious drawback is that pointing and movement tasks tend to be rather blunt. Transferring some objects from one tile to the other is quite easy and intuitive, much like dragging objects with a mouse is an intuitive action within a WIMP environment. However, as noted with the RTS demonstration, actions were restricted to tile-level granularity. That is, everything must be done in terms of one tile to another, and rarely involves intra-tile manipulations; in fact this intra-tiles manipulation was restricted to the physics system of Section 4.3. The tiles are therefore suitable for the many tasks presented, but would not fit many traditional desktop applications needing detailed and complex interfaces.

5.1.4 Observation 4: Physics-Enabled Interfaces are Relatively Unstudied As Interaction Aids

The growing popularity and acceptance of various injections of simulated physics into interfaces of all shapes and forms is a positive sign. The prototype system of Section 4.3 attempts to create a flavour of physics-based interaction. The results of such a system were positive overall. Moving objects around by bumping and directing them is quite intuitive, allowing for motions used in real life to be used. For example, shoveling many smaller objects around with the tiles feels quite visceral. The brain is provided with a vivid sensory perception that objects *exist*, being pushed around, poured and so on. A skilled user could conceivably juggle three objects using two tiles as ‘hands,’ although the 2-dimensional nature of the display made this difficult.

Several drawbacks existed that limited the system to a prototype in its presented

form. The 15 frames-per-second frame rate of Tangible Tiles hampered sweeping motions, thus most movements were small (less than 10cm). This is similar to Observation 3, but introduced an even more awkward disconnect since the delay caused physical inaccuracies as well - a large, fast movement was able to produce a disproportionately large force. It is possible to overcome this with various forms of interpolation and averaging of forces or position, however.

The system could potentially exist with small OLED tiles in a slightly modified way. Objects could reside on a small object (similar but not restricted to a tile), and their movement would be constricted to inside the tile. For example, an invisible box could contain whatever objects reside on the tile. When tiles are close enough a transfer on the tiles might take place. In the example, the invisible box would open on one side to let objects pass freely to the other tile, given that appropriate momentum is applied. Simulating physics, however, would prove a practical hurdle for small tiles with embedded processors.

5.2 Discussion

Organic Board Games is an exploration of new interaction methods with a computer, and as such it has many excellent features as well as glaring drawbacks. However, with respect to moving abstract objects around in some kind of very flexible environment it does show promise for applicability and further work.

Future study must be done to investigate how seamless, cheap, very thin displays (OLED or otherwise) might enable interesting systems such as Organic Board Games. A key to this is that each tile is cheap. This exists with Tangible Tiles insofar as each tile is basically just a piece of cardboard. However, digital projectors are relatively

expensive compared to the marginal cost of cardboard tiles produced for board games. Thus it is hard to see the mass adoption of a projector-based system to play a board game with.

Never before have small, thin, cheap, disposable, physically robust things (hexagonal or otherwise) that can display and change colour images at high resolution existed in the past. An interface such as this is not easily comparable to many indirect methods of input (such as the pointer-based WIMP interface), nor is it necessarily comparable to other TUIs intrinsically since most TUIs don't have embedded displays.

The observations presented provide encouraging evidence for the applicability and importance of tangible extensions to traditional board games as well as to similar systems. In the next chapter, we will summarize these four identified observations for the development of a system of small, flat, thin display tiles. The next chapter also contains more future directions of study and the conclusion of the work presented in this thesis.

Chapter 6

Conclusions

This chapter deals with summaries and conclusions of the work done as well as suggesting areas for further research involving small display tiles. The main concepts throughout the thesis are touched on, and observations deemed important to deciding the usefulness of Organic Board Games and Tangible Tiles are presented.

6.1 Overview

The proposed system of Organic Board Games generally suggest that the novel interaction techniques allowed for reasonable affordances for Organic Board Games. This section discusses some of the benefits and shortfalls of this system, using the observations from Chapter 5 as a guideline.

Much recent scientific study has been done to improve people's ability to harness the power of computers. A wide variety of research is conducted with end users as the primary concern, with interfaces once thought computationally wasteful or impossible, such as the GUI, now being standard. The path to mouse ubiquity is

quite long and complicated, starting first as a simple extension to a track ball, then being strengthened by a suitable interface in the form of the WIMP interface.

In this light, OUIs offer interesting potential. Many professional fields such as architecture, engineering and art still require tangibility for development, but also take advantage of computers. OUIs provide a useful marriage of tangible experience with the increasingly ingenious uses of computer science people have become reliant upon. OUIs take this a step further, and strive to make an interface not only tangible, but *natural*.

Organic Board Games is an interface that was developed with the principles of OUI in mind, while keeping the spirit of its genesis, Settlers of Catan. The investigations in this thesis provided a look at how such an application can be developed and executed.

6.2 Summary of Contributions

Organic Board Games is a hardware and software framework built to explore how physical, tangible hexagonal tiles can be used to create an interface. The field of Human Computer Interaction is dense with new unique interaction mechanisms including multi-touch screens, spatial finger gestures using volumetric displays, and various others. As such, it may seem difficult to justify yet another interface with a seemingly narrow application domain. However, it has been shown that through the proper design of projector-based display mechanism mimicking a wireless, tile-based prototype, various applications can benefit from the distinctive approach to the interactions presented.

The main contribution to the field of HCI is the combination of a hardware prototype and several applications found to be intuitive for its use. Organic Board Games,

physics-based interaction, and interfacing with RTS games show how this kind of system is potentially beneficial, at least subjectively. The following four observations serve to highlight the lessons learned in this endeavour.

- Tangibility is Key
- Tracking Technologies Effect Immersion
- Tiles Are Best for Imprecise Tasks
- Physics-Enabled Interfaces are Important

6.3 Future Work

It should be clear that the most pressing area for future research would be into conducting experiments involving small display tiles. Several proposals for experimentation are as follows:

Questionnaire Gauge user acceptance of the system based on a brief questionnaire.

Timing Experiments Compare several variations of the system and see which is the fastest.

Comparison Experiments Using objective measures or subjective questions, seek to compare Organic Board Games to a similar system, such as Rekimoto et al.'s Datatiles.

These experiments give some rough ideas for experimentation for the theory that Tangible Tiles provide some kind of beneficial interface. However, it is important to

realize the answer to this question is highly subjective, as with many TUIs discussed in Chapter 2. The results of one experiment might easily be meaningless when considered with another application, or with different hardware. They might also provide great insight into how further refinements should be made for a system such as this to become popular and useful. The decision to judge which of these two groups the results of an experiment will lie in is extremely important.

In addition to experimentation, alternate approaches to developing something similar to Tangible Tiles and Organic Board Games has been alluded to throughout this thesis (e.g. in Section 3.2.1). It is therefore obvious that these approaches would be a prudent direction for future study. Seamless, thin, light and small objects that have a display capability are not tied to something like Organic Board Games, so would offer fruitful potential for investigation.

Finally, the physics metaphor shows great potential to make computers easier and more intuitive to use. After all, the use of metaphors in HCI is prevalent, e.g. the idea of a “window” in the WIMP interface, or a “file” inside a computer file folder. When introducing realistic physical movements of objects, a given metaphor may strengthen, providing benefits to existing interfaces. This is by no means universal, however, since much of the benefit of abstracting real file folders to their digital counterparts is that most of their drawbacks are eliminated. There is no mess, sorting is trivial, and the space consumed by digital information continues to shrink; caution should be taken in adding physics without thought to common interfaces.

6.4 Conclusion

Organic Board Games has been presented as a prototype with a novel interaction scheme that extends the board game Settlers of Catan by introducing dynamic displays for each hexagonal playing piece. First, Tangible Tiles, a hardware and software combination to implement these small hexagonal displays, was specified. Novel interaction methods were introduced using these displays, including physical movements which result in various types of feedback such as triggering animations. Organic Board Games was the original motivation for the work done with Tangible Tiles, but other applications were deemed useful to demonstrate the tiles' ability. Physics-based interaction provided an intuitive way of moving around objects in a simulated physical environment. Tangible Tiles also proved useful for controlling a real-time strategy computer game with a limited set of commands. It is believed that a set of small, flat dynamic displays presents a promising interaction mechanism for future work, and it was found that the tiles are indeed an encouraging method of interfacing with computers in various ways.

Bibliography

- [1] Anand Agarawala and Ravin Balakrishnan. Keepin' it real: pushing the desktop metaphor with physics, piles and the pen. In *CHI '06: Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 1283–1292, New York, NY, USA, 2006. ACM.
- [2] Mark Altosaar, Roel Vertegaal, Changuk Sohn, and Daniel Cheng. Auraorb: social notification appliance. In *CHI '06: CHI '06 extended abstracts on Human factors in computing systems*, pages 381–386, New York, NY, USA, 2006. ACM.
- [3] S. Bennett and TW Berrie. A history of control engineering 1930-1955. *Computer*, 13068859:2.
- [4] J. Bohn. The Smart Jigsaw Puzzle Assistant: Using RFID Technology for Building Augmented Real-World Games. In *Workshop on Gaming Applications in Pervasive Computing Environments at Pervasive 2004*, 2004.
- [5] Vannevar Bush. As we may think. *interactions*, 3(2):35–46, 1996.
- [6] E.H. Callaway. *Wireless Sensor Networks: Architectures and Protocols*. CRC Press, 2004.

- [7] NVIDIA Corporation. Physx. http://www.nvidia.com/object/nvidia_physx.html.
- [8] Xuuk Corporation. The Xuuk Eyebox 2. <http://www.xuuk.com>.
- [9] Connor Dickie, Jamie Hart, Roel Vertegaal, and Alex Eiser. Lookpoint: an evaluation of eye input for hands-free switching of input devices between multiple computers. In *OZCHI '06: Proceedings of the 20th conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design: activities, artefacts and environments*, pages 119–126, New York, NY, USA, 2006. ACM.
- [10] Paul Dietz and Darren Leigh. Diamondtouch: a multi-user touch technology. In *UIST '01: Proceedings of the 14th annual ACM symposium on User interface software and technology*, pages 219–226, New York, NY, USA, 2001. ACM.
- [11] CD Dimitrakopoulos and DJ Mascaro. Organic thin-film transistors: A review of recent advances. *IBM Journal of Research and Development*, 45(1):11–28, 2001.
- [12] Douglas C. Engelbart. A research center for augmenting human intellect. pages 81–105, 1988.
- [13] Ylva Fernaeus, Jakob Tholander, and Martin Jonsson. Towards a new set of ideals: consequences of the practice turn in tangible interaction. In *TEI '08: Proceedings of the 2nd international conference on Tangible and embedded interaction*, pages 223–230, New York, NY, USA, 2008. ACM.
- [14] George W. Fitzmaurice, Hiroshi Ishii, and William A. S. Buxton. Bricks: laying the foundations for graspable user interfaces. In *CHI '95: Proceedings of the*

- SIGCHI conference on Human factors in computing systems*, pages 442–449, New York, NY, USA, 1995. ACM Press/Addison-Wesley Publishing Co.
- [15] Cleotilde Gonzalez. Does animation in user interfaces improve decision making? In *CHI '96: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 27–34, New York, NY, USA, 1996. ACM.
- [16] Saul Greenberg and Bill Buxton. Usability evaluation considered harmful (some of the time). In *CHI '08: Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems*, pages 111–120, New York, NY, USA, 2008. ACM.
- [17] Tovi Grossman, Ravin Balakrishnan, Gordon Kurtenbach, George Fitzmaurice, Azam Khan, and Bill Buxton. Creating principal 3d curves with digital tape drawing. In *CHI '02: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 121–128, New York, NY, USA, 2002. ACM.
- [18] David Holman and Roel Vertegaal. Organic user interfaces: designing computers in any way, shape, or form. *Commun. ACM*, 51(6):48–55, 2008.
- [19] David Holman, Roel Vertegaal, Mark Altosaar, Nikolaus Troje, and Derek Johns. Paper windows: interaction techniques for digital paper. In *CHI '05: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 591–599, New York, NY, USA, 2005. ACM.
- [20] David Holman, Roel Vertegaal, Changuk Sohn, and Daniel Cheng. Attentive display: paintings as attentive user interfaces. In *CHI '04: CHI '04 extended*

- abstracts on Human factors in computing systems*, pages 1127–1130, New York, NY, USA, 2004. ACM.
- [21] Eva Hornecker and Jacob Buur. Getting a grip on tangible interaction: a framework on physical space and social interaction. In *CHI '06: Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 437–446, New York, NY, USA, 2006. ACM.
- [22] Peter Hutterer, Mark T. Smith, Bruce H. Thomas, Wayne Piekarski, and John Ankcorn. Lightweight user interfaces for watch based displays. In *AUIC '05: Proceedings of the Sixth Australasian conference on User interface*, pages 89–98, Darlinghurst, Australia, Australia, 2005. Australian Computer Society, Inc.
- [23] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *CHI '97: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 234–241, New York, NY, USA, 1997. ACM.
- [24] Hiroshi Ishii, Craig Wisneski, Scott Brave, Andrew Dahley, Matt Gorbet, Brygg Ullmer, and Paul Yarin. ambientROOM: integrating ambient media with architectural space. In *CHI '98: CHI 98 conference summary on Human factors in computing systems*, pages 173–174, New York, NY, USA, 1998. ACM.
- [25] Shahram Izadi, Steve Hodges, Stuart Taylor, Dan Rosenfeld, Nicolas Villar, Alex Butler, and Jonathan Westhues. Going beyond the display: a surface technology with an electronically switchable diffuser. In *UIST '08: Proceedings of the 21st annual ACM symposium on User interface software and technology*, pages 269–278, New York, NY, USA, 2008. ACM.

- [26] Alan Curtis Kay. *The reactive engine*. PhD thesis, 1969.
- [27] Gordon Kurtenbach and William Buxton. The limits of expert performance using hierarchic marking menus. In *INTERCHI '93: Proceedings of the INTERCHI '93 conference on Human factors in computing systems*, pages 482–487, Amsterdam, The Netherlands, The Netherlands, 1993. IOS Press.
- [28] Vincent LeClerc, Amanda Parkes, and Hiroshi Ishii. Senspectra: a computationally augmented physical modeling toolkit for sensing and visualization of structural strain. In *CHI '07: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 801–804, New York, NY, USA, 2007. ACM.
- [29] Carsten Magerkurth, Adrian David Cheok, Regan L. Mandryk, and Trond Nilsen. Pervasive games: bringing computer entertainment back to the real world. *Computing and Entertainment*, 3(3):4–4, 2005.
- [30] Regan L. Mandryk and Diego S. Maranan. False prophets: exploring hybrid board/video games. In *CHI '02: CHI '02 extended abstracts on Human factors in computing systems*, pages 640–641, New York, NY, USA, 2002. ACM.
- [31] M. Nakamoto. Advances in Field Emission Displays. In *Discharges and Electrical Insulation in Vacuum, 2006. ISDEIV'06. International Symposium on*, volume 2, 2006.
- [32] T. O'Shea, M. Lamming, M. Chalmers, N. Graube, R. Wellner, and G. Wlgmenton. Expectations and Perceptions of Ubiquitous Computing: Experiments with BirdDog. a prototype Person Locator. *BCS/IEE ITaP*, 91.

- [33] Ben Piper, Carlo Ratti, and Hiroshi Ishii. Illuminating clay: a 3-d tangible interface for landscape analysis. In *CHI '02: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 355–362, New York, NY, USA, 2002. ACM.
- [34] Larry Press. Personal computing: Windows, dos and the mac. *Commun. ACM*, 33(11):19–26, 1990.
- [35] Jun Rekimoto, Brygg Ullmer, and Haruo Oba. Datatiles: a modular platform for mixed physical and graphical interactions. In *CHI '01: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 269–276, New York, NY, USA, 2001. ACM.
- [36] Carsten Schwesig. What makes an interface feel organic? *Commun. ACM*, 51(6):67–69, 2008.
- [37] Carsten Schwesig, Ivan Poupyrev, and Eijiro Mori. Gummi: a bendable computer. In *CHI '04: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 263–270, New York, NY, USA, 2004. ACM.
- [38] Jeffrey S. Shell, Ted Selker, and Roel Vertegaal. Interacting with groups of computers. *Commun. ACM*, 46(3):40–46, 2003.
- [39] Richard M. Stallman. Emacs the extensible, customizable self-documenting display editor. *SIGPLAN Not.*, 16(6):147–156, 1981.
- [40] A. Sugimoto, H. Ochi, S. Fujimura, A. Yoshida, T. Miyadera, and M. Tsuchida. Flexible OLED displays using plastic substrates. *Selected Topics in Quantum Electronics, IEEE Journal of*, 10(1):107–114, 2004.

- [41] Ivan E. Sutherland. Sketchpad: a man-machine graphical communication system. In *AFIPS '63 (Spring): Proceedings of the May 21-23, 1963, spring joint computer conference*, pages 329–346, New York, NY, USA, 1963. ACM.
- [42] Lucia Terrenghi, David Kirk, Abigail Sellen, and Shahram Izadi. Affordances for manipulation of physical versus digital media on interactive surfaces. In *CHI '07: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1157–1166, New York, NY, USA, 2007. ACM.
- [43] Edward Tse, Saul Greenberg, Chia Shen, and Clifton Forlines. Multimodal multiplayer tabletop gaming. *Computing and Entertainment*, 5(2):12, 2007.
- [44] Brygg Ullmer and Hiroshi Ishii. The metadesk: models and prototypes for tangible user interfaces. In *UIST '97: Proceedings of the 10th annual ACM symposium on User interface software and technology*, pages 223–232, New York, NY, USA, 1997. ACM.
- [45] Roel Vertegaal. Introduction. *Commun. ACM*, 46(3):30–33, 2003.
- [46] Manuela Waldner, Jörg Hauber, Jürgen Zauner, Michael Haller, and Mark Billingham. Tangible tiles: design and evaluation of a tangible user interface in a collaborative tabletop setup. In *OZCHI '06: Proceedings of the 20th conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design: activities, artefacts and environments*, pages 151–158, New York, NY, USA, 2006. ACM.
- [47] M. Weiser. The Computer for the Twenty-First Century. *Scientific American*, 265(3):94–104, 1991.

- [48] Aaron Weiss. Desktops in 3d. *netWorker*, 11(1):26–33, 2007.
- [49] Pierre Wellner. The digitaldesk calculator: tangible manipulation on a desktop display. In *UIST '91: Proceedings of the 4th annual ACM symposium on User interface software and technology*, pages 27–33, New York, NY, USA, 1991. ACM.

Appendix A

Computer Vision Algorithms

A.1 Finding Hexagons

Here follows the algorithm, written in C++, to find a hexagonal shape assumed to be somewhere in a two-dimensional grid. The assumptions are that the vertices of the hexagons are a single pixel, that the hexagons are all the same shape (defined externally) and that the number of hexagons in the scene is sufficiently low as to allow the algorithm to run every 1/15th of a second.

All the gathered points are iterated through in a pair-wise $O(n^2)$ fashion. For each pair of two-dimensional points $A(x, y)$, $B(x, y)$, we determine if $distance(A(x, y), B(x, y))$ is approximately the diameter of the circle intersecting all six points of a hexagon we're looking for. This measurement, $2(radius)$, is found and defined globally elsewhere. If this condition is met, the list is stepped through again, looking for points approximately on the circle defined by $A(x, y)$ and $B(x, y)$. If four other points are found to lie on the circle defined by $A(x, y)$ and $B(x, y)$, this is probably a hexagon, so it is stored.

Note that we could optimize this by taking out the points we have found, since they are now included in a valid hex. However, a point may be included in more than one hex (up to three, in fact) so this optimization alters the desired functionality. There is one case that necessitates **not** doing this - the hexagon surrounded by six other hexagons. Assuming the use of the optimization, these points may all be removed from this central hexagon before we get around to trying to detect it.

Note also that this is not a terribly robust method of computer vision. To give an example degenerate case, twelve points lying on a circle of the appropriate radius creates undefined behaviour depending on how the points are arranged. In the implementation used, the six points with the lowest y-coordinate will qualify as a hexagon. The next hexagon to be found will include five points from the previously detected hexagon, as well as the

Notwithstanding the degenerate cases mentioned, this method of hexagon finding actually works a great majority of the time in normal circumstances, e.g. situations where tiles are not overlapping, are fully visible, and stable lighting is used, based on the author's extensive operation of the Tangible Tiles system.

The following definitions may be helpful with reference to Figure A.1. In the figure, $\text{point}[l]A$ is a point that *does* lie on the circle, while $\text{point}[l]B$ is one that does not.

dist1 is used as a preliminary distance check to determine if $\text{point}[j]$ and $\text{point}[k]$ are approximately a diameter's distance apart.

dist2 is the distance between the midpoint (of $\text{point}[j]$ and $\text{point}[k]$) and $\text{point}[l]$, less the radius. For example, in Figure A.1, the **dist2** calculation for $\text{point}[l]A$ is approximately zero, whereas for $\text{point}[l]B$ it is much greater than zero.

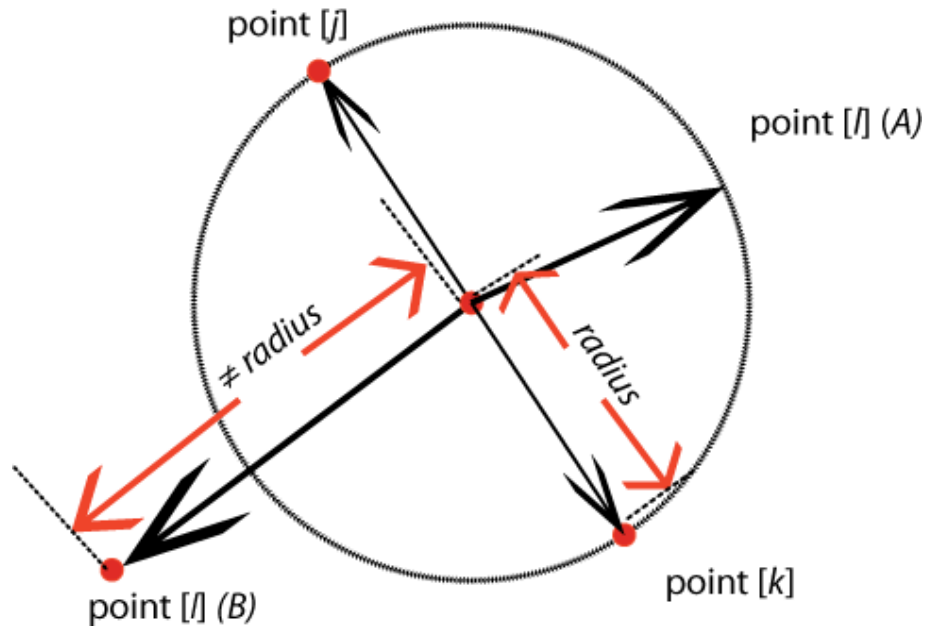


Figure A.1: An example arrangement of points found in a frame

jitter is used to counteract the random perturbations in the locations of points. It can be considered a noise threshold to counteract standard noise from camera image.

```
// Hex-finding algorithm
vector<CvPoint> point; // a list of all points (reflectors) in the scene
list<Hexset> hlist;    // empty linked list of all hexs (groups of 6 points)
float dist1 = 0, dist2 = 0;
int accum = 0;        // accumulates the number of hexs found
float jitter = 3.5;

unsigned int j = 0;
while(point.size()>0){

    for(unsigned int k = 0; k<point.size(); k++){

        dist1 = distance(point[j], point[k]);
        if(abs(dist1-2*radius)< jitter && dist1> 0.1){
```

```

hlist.push_front(Hexset(accum++));

for(unsigned int l = 0; l<point.size(); l++){

    CvPoint midPoint = mid(point[j], point[k]);
    dist2 = distance(midPoint, point[l])-radius;

    if(abs(dist2)<jitter){

        hlist.front().insertPoint(&point[l]);
    }// end 'if'
} // end 'for' iteration through ALL points
if(hlist.front().getSize()<6){ // a hexagon has 6 sides

    hlist.pop_front();
} // end 'if'
} // end distance-check 'if'
} // end 'for' loop and hex creation
point.erase(point.begin());
} // end 'while' loop

// delete duplicate hexagons
list<Hexset>::iterator m = hlist.begin();
list<Hexset>::iterator n = hlist.begin();
while(m!=hlist.end()){
    n=m;
    n++;
    while(n!=hlist.end()){
        if(n->equals(&(*m))){
            hlist.erase(n++);
        }
        else{n++;}
    }
    m++;
}

```


A.2 Finding dots in a scene

The following code demonstrates how points can be found from a raw video frame captured from an infra-red camera. It is a simplified but accurate approximation to what was used in practice. A frame can be assumed to be a gray-scale, 8-bit image. This method checks each pixel in the scene to determine if it is above a certain light threshold, then implements a linear search on all previously confirmed points to ensure that the bright pixel found is not part of the same physical reflector. Therefore, the distance threshold describes approximately the size of an IR reflector as seen by the camera. It is necessary to adjust these light and distance thresholds based on the lighting conditions, size of reflectors, camera field of view, camera aperture, and approximate distance of the tiles from the camera. These values are hard coded in this example for simplicity.

```
void findMarkers(IplImage* src){

    vector<CvPoint> points; //a container to hold dots we find
    BwImage imgA(src);      //an image container used for convenience
    int distThresh = 20;    //used as a minimum distances between points
    int lightThresh = 20;   //based on light conditions.

    for(int i = 1; i < cvGetSize(src).height; i++ )
    {
        for(int j = 0; j < cvGetSize(src).width; j++ )
        {
            if (imgA[i][j]>lightThresh)
            {
                bool close = false;
                for(unsigned int k = 0; k<points.size()&&points.size()>0; k++)
                {
                    if(sqrt(pow((float)(j- points[k].x), 2) +
                               pow((float)(i - points[k].y), 2) )<distThresh )
                        close = true;
                }
            }
        }
    }
}
```

```
    }
    if(!close)
    {
        points.push_back( cvPoint(j,i));
        j+=distThresh;
    }
}
}
}
```