Media Tables:

An extensible method for developing multi-user media interaction platforms for shared spaces

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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
at the
Massachusetts Institute of Technology

September 2005

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Abstract

As digital entertainment applications evolve, there is a need for new kinds of platforms that can support sociable media interactions for everyday consumers. This thesis demonstrates an extensible method and sensing framework for real-time tracking of multiple objects on an interactive table with an embedded display. This tabletop platform can support many different applications, and is designed to overcome the commercial obstacles of previous single purpose systems.

The approach is supported through the design and implementation of an acoustic-based sensing system that provides a means for managing large numbers of objects and applications across multiple platform instances. The design requires precise and dynamic positioning of multiple objects in order to enable real-time multi-user interactions with media applications. Technical analysis shows the approach to be robust, scalable to various sizes, and accurate to a within a few millimeters of tolerance. A qualitative user evaluation of the table within a real-world setting illustrates its usability in the consumer entertainment space for digital media browsing and game play. Our observations revealed different ways of mapping physical interaction objects to the media space, as either generic controls or fixed function devices, and highlighted the issue of directionality on visual displays that are viewable from different sides.

The thesis suggests that by providing a general purpose method for shared tabletop display platforms we give application designers the freedom to invent a broad range of media interactions and applications for everyday social environments, such as homes, classrooms and public spaces. Contributions of the thesis include: formulation of an extensible method for media table platforms; development of a novel sensing approach for dynamic object tracking on glass surfaces; a taxonomy of interface design considerations; and prototype designs for media content browsing, digital storytelling and game play applications.

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Acknowledgements

"The reasonable man adapts himself to the world. The unreasonable man persists in trying to adapt the world to himself. Therefore, all progress depends on the unreasonable man."

-- George Bernard Shaw

As this long journey comes to an end, I would like to take a moment to mention some of the many wonderful people who have provided support and inspiration along the way, and who in the long run have helped usher me out the doors of MIT and on to a new life ahead. In particular, I would like to thank the following people.

My advisor and mentor, Glorianna Davenport, for her guidance, vision and encouragement, and for providing me with all the resources – digital, physical and intellectual – that I could ever wish for in order to pursue my work.

My readers, Bill Mitchell and Joe Paradiso, for their invaluable insight and support along the way and for believing in my work from the very beginning.

My research team, for their incredible work, effort and imagination in solving even the hardest of problems under the craziest of deadlines. First and foremost, my collaborator and friend Matthew Reynolds, without whom this research would certainly never have been possible. Also my friend and post-doc, Wayne Hsiao, whose physical design sense and machine shop skills remain unparalleled. And of course the most talented and energetic group of UROPs that I have ever met, Carsten Jensen, Brandon Dell and Kim Ang.

Many other Media Lab faculty for their support and for all the truly inspiring discussions along the way, especially Walter Bender, Mike Bove, Hiroshii Ishii, Andy Lippman, Mitch Resnick, Deb Roy and Ted Selker.

My sponsors and friends at Samsung, without whose generous support the TViews tables would not exist today, especially Jay Lee, Seung-Hun Jeon, Hongsuk Choi and Yanglim Kim. Also the many other sponsors from TTT, CEL and DL that I have had the pleasure to interact with in my time at the Media Lab.

All the people in the Media Lab support staff who were always ready to help no matter how insane my requests seemed, especially Kevin Davis, John DiFrancesco, Will Glesnes, Kristin Hall and Cornelle King. And of course administrative staff Linda Peterson and Pat Solakoff who always made any bureaucratic absurdities I found myself facing at MIT disappear like magic.

All of my friends and colleagues in the Media Fabrics research group, Barbara Barry, Aisling Kelliher, Hyun-Yeul Lee, Paul Nemirovsky, Pengkai Pan, and Tracy Daniels. I will never forget all the intense brainstorming sessions that reshaped my world. As well as all my other friends, at the Media Lab, at MIT and everywhere else.

Galen Harris for all his love and support, and for being there whenever I needed it most. And for putting up with me through the many hectic months!

And most of all my parents, Bohumil and Dora Mazalek, for their love, support, and for always being there to help me think things through.

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Chapter 1

1. Introduction

Philosophers and scientists alike have long speculated that the way in which we understand the world is inherently shaped by the interfaces through which we perceive and act. Kant for instance, is well known for his belief that the world is objectively different from the way it appears. In his *Critique of Pure Reason*, Kant claims that knowledge of the world and the objects within it involves not just a passive capturing of sensual data, but a unification and synthesis of this data in the mind based on preconceived sensible forms such as space and time. An object is understood not as a thing-in-itself ("Ding an sich"), but only as it appears to us by means of these a priori forms. In other words if we apply the terminology of today, space and time for Kant are the filters or interfaces through which reality is perceived – they mediate and translate the knowledge of the world.

While still far from our current notions of interface, Kant's ideas have had a wide-reaching impact on human thought and have greatly influenced the way in which we perceive the physical world around us. The concept of interface can be widely applied to the translation of many different kinds of physical and sensory data. Examples of objects as interfaces include books, which mediate and disseminate knowledge, and musical instruments, which translate expressive gestures into audible music. Yet the term *interface* moved into common usage only in the 1960s, when it was appropriated by computer scientists to designate the planes of interaction within computing systems. These could include the interaction between different parts of a computer system, as well as the interaction between a computer and a person.

Today, the fact that our interactions with the digital world are necessarily mediated through different kinds of interfaces is part of mainstream knowledge. These interfaces often make use of physical-world metaphors that translate raw data into representations that we can easily understand and manipulate. The desktop metaphor currently used by most personal computers as a means of organizing interactions and information is an obvious example. It draws from the interactions we have with documents and filing systems at our physical desks to create familiar digital world analogues. Yet while digital information itself is inherently malleable, our interactions with this information are constrained by the interfaces presented to us by specific interactive environments and applications. The controls and displays of digital information shape the way we understand it and what we are able to do with it. As a result, the way in which we understand the computer as an appliance or tool or even as a social object is directly tied to the current state of digital interface technologies rather than to their full or future potential. Emerging technologies are the confrontation between what existing technologies present as feasible and the idea of what might eventually be possible, and as such technological progress constantly redefines the relationship between the two.

Since the mid-1990s, human-computer interaction researcher Bill Buxton has used two simple exercises to demonstrate the power of what users see and touch in shaping their mental model of an interactive system [Buxton 1996]. In the first exercise, he asks people to take 15 seconds to draw a computer. Most people draw a monitor and keyboard, many also draw a mouse, but very few people actually draw the box containing the CPU itself. In other words, people draw the input/output devices of the computer, not the computer itself. In the second exercise, he asks people to draw a computer imagining that they are in the year 1960. The results of this exercise tend to resemble large washing machines or refrigerators. A comparison between the two types of drawings (see Figure 1.1) shows us how we can change a user's mental model of a computer system simply by changing the input/output devices, and highlights the memorable quality of the things we use to interact with the system. Buxton argues that the current design of computing systems is hampered not so much by issues of speed and power, but rather by interfaces that are poorly matched to different users' skills and contexts and by the weakness of a "one size fits all" approach to computer interface design. Both work and leisure activities in our society are increasingly converging around desktop and laptop computers and employ the same tools and metaphors of graphical user interfaces. Yet the needs of different users vary greatly and necessarily depend on the particular tasks they wish to accomplish and the locations where they are typically performed.

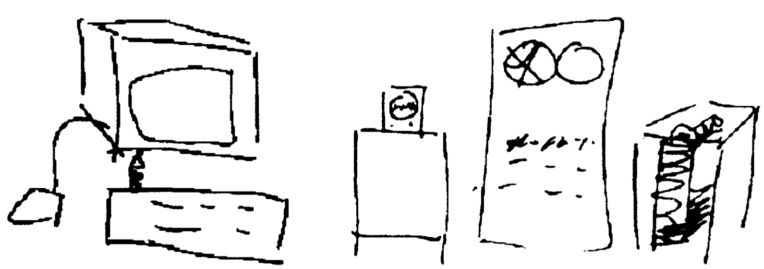


Figure 1.1: Computer interface sketches

Representative sketches of a computer today (left) and a computer in 1960 (right) [Buxton 1996].

To address the limitations of existing computer interfaces, the past decade of human-computer interaction research has shown a growing interest in emerging areas such as ubiquitous and pervasive computing, and tangible user interfaces [Weiser 1991, Ishii 1997]. Rather than moving more and more of our daily tasks out of the physical world into the limited interaction space provided by desktop computer interfaces, these domains seek to seamlessly integrate the digital and physical worlds in order to enable sensory-rich interactions with digital information within a broad range of contexts and environments. Tangible interfaces in particular, are characterized by the coupling of controls and representations of digital information within manipulable physical artifacts, surfaces and spaces [Ullmer 2002]. This interaction technique differs significantly from mainstream computer interfaces such as keyboards and mice, which act as input devices alone and are intended as controls for the visual representations of digital information provided by screen-based displays.

The research areas mentioned above provide a background and context for the doctoral research discussed here, which addresses the question of how these new types of interaction platforms can be generalized to function within different everyday physical contexts and to support a broad range of applications and user scenarios. To this end, the thesis presents a general purpose method for creating tabletop media interaction platforms for shared spaces in which the desktop metaphor may be inappropriate, such as social living spaces or classrooms. The following section discusses the specific problem space and challenges that are the focus of this thesis.

1.1 Problem Space

There are only a few metaphors that drive our interactions with digital information today. These interactions are largely dominated by the files and folders of the desktop interface and by the hyperlinked documents of cyberspace, which can all be accessed by a combination of mouse cursor and key input. Over time, these metaphors and devices have provided an as easy-to-learn and easy-to-use paradigm, inciting designers to retrofit every possible kind of application into the same kind of digital interaction space. And so even while the narrow bandwidth of existing input options limits the degrees of freedom by which designers can invent new applications and interactive environments, desktop computing platforms have nevertheless gained wide-spread acceptance in our society. But while it may be limiting in many respects, the "one size fits all" approach is also considered to be one of the greatest strengths of graphical interface platforms. The GUI model provides a means by which the same controllers and displays can be used to access hundreds and thousands of applications, and as a result designers have tried to fit everything into the particular interaction paradigm. It makes no difference what particular mouse (optical, trackball, etc.) a user plugs into their computer, nor whether they are using a small portable laptop or a powerful full-sized tower, as long as the pointing device and computer can understand and communicate with a shared protocol. Similarly, as long the application software that runs on the system can understand this same protocol, then the same pointing device can be used to operate applications as diverse as a 3D modeling tool and a spreadsheet. Consistency in the point-and-click interaction style and in basic interface elements such as menus and buttons allows users to move between different kinds of applications with relative ease. From a commercial and consumer-driven perspective, the advantage here is clear: desktop systems provide an extensible model for digital interactions that fosters wide-spread use and compatibility, encouraging users to continuously expand and upgrade their systems with the latest in available hardware and software technologies without having to re-learn the basics or throw away everything they have already built up.

Existing human-computer interfaces have been determined and designed in part based on notions of what users might need or want but do not currently have, and in part based on existing practices or on the availability of certain kinds of underlying technologies. While the former of these cases can at times lead to ideas and designs that are radical departures from existing approaches and fulfill user needs in novel and different ways, the latter case generally leads to designs that do not break the mould but rather move an existing method forward in incremental steps mostly through small technical refinements. As many interface designers acknowledge, the history of computer interface technologies is in this manner the result of a series of ad hoc decisions and implementations resulting from a dialectical relationship between technological innovations and the conceptions of their uses and users by their designers [Bardini 2000].

On the flip side, the history and evolution of new technologies is also heavily based on their acceptance by the user community. In general, new interaction technologies tend to acquire broad public appeal based on a variety of factors that are not always easily correlated to how good of an interaction approach they provide from a purely functional perspective, and their appropriation usually takes a certain amount of time. The mouse is a good example of this: it was invented in the 1960s by Douglas Engelbart, but did not become commercially available until 1981. Even when it did, the first two systems that provided mouse control and a graphical user interface, the Xerox Alto and the Apple Lisa, were big failures in the market due to a price-point that was too high for the user community of the time, one that was largely accustomed to low-priced hobbyist-geared self-assembly computer kits. The eventual acceptance of the graphical user interface and mouse interaction happened when the price came down. From that point forward, the approach became widespread thanks to its ease-of-use and to its flexibility that allowed it to adapt to all kinds of new software applications that were continually being developed.

At this point, we have many years of experience with the current configuration of mouse, keyboard and graphical windowing environment, and it has proved to be highly effective in the workplace environment. Yet as we have already mentioned, this is not the only paradigm that has been explored for human-computer interactions. Researchers have experimented with a large variety of interfaces in order to find natural ways for humans to communicate with computers. A couple of notable examples include the *Aspen Movie Map* [Lippman 1980] and *Put-That-There* [Bolt 1980], which illustrate the relationship between human input and content that is central to interface design. The former of these was an experiment in continuous surrogate visual travel through the streets of Aspen, developed by the Architecture Machine Group at MIT in the 1970s. In this case, the navigation controls were provided by a joystick located within the armrest of a chair, providing a "driver's seat" metaphor for the interaction. This kind of interaction paradigm is more or less limited to spatial navigation systems like driving or flight simulations, but could also be extended to the navigation of 3D virtual media environments even though they lack a physical counterpart. While it provides a natural means of navigation through a content space, the system does not extend easily to the manipulation of the content itself. In *Put-That-There* on the other hand, users could communicate with a graphical system via voice and gesture inputs. This is a challenging problem given that it is not easy to get computers to understand human language and that gestures are far from universal in meaning. In this case, the nuance of "that" and "there" augmented with a pointing gesture seemed to promise natural language understanding for computing platforms. However this was only one very particular case, and although the gestures here resolved the problem of spoken ambiguity, they did not necessarily present a solution that could generalize. As such, natural language input remains a difficult problem even today. While both systems provide seemingly natural ways of communicating user intention to a computing platform, neither one has become a universal standard. This is either because the technologies used are still too immature from the perspective of cost, scalability or robustness in order to support widespread use, or because the metaphors have not as yet come into their prime and gained the enthusiasm of a broad base of users.

In contrast to graphical interfaces platforms, tangible interfaces are a relatively new field and they have been restricted to a largely exploratory and conceptual level of research that has focused primarily on finding metaphors for physical-digital interactions with graspable objects. The world is a rich sensory space, providing a vast variety of possible interaction styles that can be applied to a broad range of application domains. For example, researchers have explored the use of block assemblies to simulate physical phenomena such as fluid-flows [Anagnostou 1989] and cellular automata [Frazer 1994]. Other researchers have used configurations of physical objects within the reference frame of an interactive surface in order to simulate physical-world spaces ranging from building rooms and assembly lines [Fjeld 1998] to entire urban environments [Underkoffler 1999]. While systems such as these provide interesting examples in tangible interaction design, each one has been built for a single purpose alone. The designers have generally not considered how these systems might extend to different application domains at the level of their physical construction, technical realization, or digital mappings. The problem can be summarized as follows: while the degrees of freedom in human physical-world interactions are extremely high, the forms of physical objects are rigid and fixed in a way that constrains each one to a small set of uses and applications. What if we could make a space that could recognize and track an almost infinite number of objects? Would making such a space lead us to a clutter of single purpose objects that are costly to manufacture and maintain? In order to reconcile the fixed form of physical objects with the malleable nature of digital contents, we need to think of ways in which the objects within this interaction space could be reused across different kinds of digital applications.

As Brygg Ullmer pointed out in his doctoral dissertation, most tangible platforms have made one-to-one mappings between interactive objects and physical world elements that have a clear geometrical representation [Ullmer 2002]. This creates a problem with respect to the scalability of such systems in terms of the physical/digital object mappings. If each physical object is used to represent only a specific digital media element (or perhaps a specific type of digital media element), creating a virtual space that has hundreds of different media elements would require just as many physical objects to control. Moreover, many kinds of digital information have no inherent physical or geometrical representation, making it difficult to map them to physical world objects. To address this, Ullmer took steps toward developing tangible systems that can be used to represent and manipulate large sets of digital information. In his systems, complex database queries can be accomplished through two-handed manipulation of physical tokens within the confines of rack-based structures called constraints. This work was perhaps the first attempt at tackling some of the scalability issues faced by tangible platforms. Nevertheless, the focus of the approach remained at the level of the physical/digital mappings and did not consider scalability across different platform instances or applications, or the identification, management or portability of large sets of physical tokens. In order for tangible interaction platforms to move beyond single-purpose custom prototypes, we need to consider the questions of scalability in a much broader sense, across both a variety of application domains and physical contexts. In particular, we need to create platforms that can scale in size and number, and we need to provide interactive objects and applications that can extend from one single platform to many separate and connected platform instances at once.

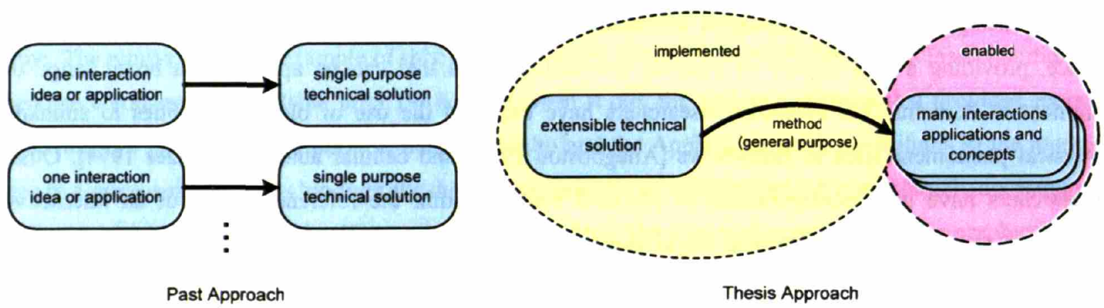


Figure 1.2: Thesis approach

The left side illustrates the past approach to the design of interactive tabletop displays. An interaction idea or application determined the selection of a particular single purpose technical solution. This thesis proposes an extensible technical solution and general purpose method that enables the creation of a large variety of interactive applications.

In this thesis research, we address the scalability issues faced by tangible computing platforms through the formulation of an approach that enables the creation of extensible media interaction platforms for shared spaces. The platforms consist of a tabletop interactive display surface around which multiple people can engage with digital media applications through the use of tangible interactive objects. The approach considers how the combination of carefully coordinated object sensing, object identification and management, and visual display can form the integral elements for such a platform. If designed to work together, these elements can allow tabletop platforms to scale across many individual (and potentially connected) instances in different physical settings, and to support multi-user media interactions across a broad range of application domains. While we envision the technology to serve many different kinds of physical environments, the work has been realized as an everyday media table for the home. The diagram in Figure 1.2 contrasts the thesis approach with past work in the area of interactive tabletop display. The following section presents the thesis statement and claims that are evaluated by this doctoral research work.

1.2 Thesis Statement

A general purpose method for tabletop media interaction platforms needs to provide a self-contained means of input and output for multiple users that can generalize across diverse applications and physical contexts. The input for a tabletop platform should provide the ability to sense and locate an extensible set of uniquely identified wireless objects on the table's surface. These objects should be physically customizable in order to suit particular applications. The output for a tabletop platform should provide a coincident display mechanism embedded within the table. The platform should be scalable in size in order to suit different physical settings.

Two central claims can be generated from this hypothesis. These have been investigated during the design, development and testing of the extensible method for multi-user tabletop media platforms.

1st Claim

The following combination of elements enables the creation of an extensible solution for multi-user tabletop media interaction platforms:

(a) A scalable sensing mechanism contained within the table's surface that can dynamically identify and locate one or many tagged objects which are present on it.

(b) An extensible set of uniquely identified objects that can be customized by means of user activated input/output elements such as buttons, sensors or displays.

(c) A self-contained embedded display mechanism that can provide coincident visual output for the tracked objects.

2nd Claim

Using the method outlined above, tabletop media platforms can be generalized to enable:

(a) Multiple users to interact through multiple simultaneous points of control.

(b) Tables to be constructed at varying sizes.

(c) Multiple applications that can run on any interaction table or on many connected tables at once.

(d) A large number of interactive objects to be moved between tables and re-used across different applications or customized to suit a particular application's needs.

1.3 Thesis Contributions

In supporting the thesis statement and claims outlined above, this dissertation makes a number of specific contributions.

1. Identification of scalability parameters for media table platforms

A prototype platform for tabletop media interaction was first developed as a part of preliminary research for this doctoral dissertation. The prototype was used over the course of several workshops with user communities, allowing us to identify a series of technical and design parameters for the creation of general purpose tabletop media platforms, including size, number of objects and display. The thesis discusses the bounds of scalability from a technical perspective with respect to these different parameters. Together, the parameters point to a solution for media tables that ensures extensibility across different physical and social interaction spaces and across different kinds of media interaction and application domains.

2. Formulation of an extensible method for media table platforms

This thesis focuses in part on the formulation of an extensible method for media table platforms, as outlined in the thesis statement and claims above. The method proposes a combination of three core elements that work together to ensure scalability at the level of both hardware and software development. The critical aspects of the method include the sensing technology that enables real-time multi-object tracking on the surface of the table, an extensible and customizable set of interactive objects that can be transported between platforms, and the integration of a self-contained embedded display mechanism within the surface of the media table.

3. Development of an innovative sensing approach for dynamic object tracking on glass surfaces

A sensing technology for real-time multi-object tracking on a glass surface has been developed as a part of this thesis work. The approach is based on an acoustic ranging method for position detection. Transmitters placed at the corners of the glass tabletop transmit acoustic signals to the objects on its surface. The objects then respond with their time-of-flight measurements, allowing the table to determine their exact coordinates with respect to the embedded display. Since the coordinates are computed at the level of the table, interactive objects can be moved between tables of different sizes without the need for modification or recalibration. Two media table instances called the TViews table have been constructed using this sensing approach.

4. Development of an Application Programming Interface for media table development

An application programming interface called the TViews API has been developed for the TViews table, allowing developers to easily create new media applications for the platform. The API uses a simple event-based model that allows an application to register itself to receive information about the state of the interactive objects present on the table. The critical events communicated to the application-level software by the TViews API consist of notifications about when specific objects have been placed on or removed from the table, and real-time updates about each present object's (x,y) coordinates within the table's frame of reference. The API can be extended to include events from customized objects with add-ons such as buttons or dials. Finally, the API supports bidirectional communication which can allow events or messages to be transmitted from the table to one or more interactive objects. For instance, a message might make an object flash or cause a picture to be displayed on a small add-on screen.

5. A taxonomy of interface design considerations for media table applications

Based on observations of the media table in use and on past work on tabletop interactions, this thesis proposes a taxonomy of design considerations for applications developed for media table platforms. The taxonomy considers in particular problems that relate to the design of the interactive objects, the design of the interface and control, and the design of shared applications across networked tables. The taxonomy is intended to cover questions that are specific to media table application design, and as such it does not address application design issues that are covered by traditional human-computer interaction (HCI) research, such as consistency and coherency across the user interface or the visual organization of information. For a comprehensive look at graphical user interface design, the reader is referred to HCI literature such as [Baecker 1995, Laurel 1990, Schneiderman 1998].

6. Prototype designs for media content browsing, digital storytelling and game play applications

To complement the construction of the two media table instances and to illustrate the design considerations addressed by the taxonomy described above, the thesis presents prototype designs for several different media applications. On the preliminary platform, applications were developed for multi-viewpoint storytelling and spatial media browsing. On the TViews table, the applications developed include: a picture sorter, a spatial media browser that displays video and images on a geographical map, a digital version of a popular tabletop board game called Pente, and a game that engages multiple simultaneous users in improvisational play with dynamic visuals.

1.4 Thesis Overview

The following chapter considers the conceptual and technical foundations underlying the development of tabletop interaction platforms. The chapter begins with a look at the use of tables across history, and then provides a discussion of interactive media tables and the different technical approaches that have been used for their realization.

Chapter 3 presents specific research systems of relevance to this work and examines the primary object sensing and positioning technologies that have been used in these systems. The chapter begins by providing an overview of previous interactive table designs and systems, and then looks at the optical, electromagnetic and acoustic approaches by which these systems have been technically realized.

Chapter 4 presents the work leading up to the formulation of a general purpose method for media table platforms. The chapter begins with a look at the research prototype and sample media applications that were constructed at the beginning of this research, and then discusses several user workshops which helped to better understand how tabletop platforms can be used for shared media interactions and storytelling. The chapter concludes by identifying the requirements for the design of an extensible media table platform.

Chapter 5 presents an extensible method for tabletop platforms, demonstrated through the design and implementation of the TViews media table. In particular, the design of a novel acoustic-based sensing objects tracking method on glass surfaces is discussed. The chapter begins with an overview of the initial experiments that were conducted to determine the best configuration of sensors and parts, and the presents the development of the electronics, firmware, position estimation algorithm and application programming interface for the TViews table.

Chapter 6 provides a technical evaluation of the acoustic-based sensing approach designed for the TViews table. It looks at how the system performs in terms of object positioning accuracy, and with respect to background effects and object movement. It also discusses the technical extensibility of the sensing approach with respect to the number of objects and size of the interaction surface.

Chapter 7 provides a taxonomy of design considerations for shared tabletop media applications and discusses the design of prototype applications for media content browsing and game play and presents a taxonomy interface design considerations. The chapter also discusses the outcomes of a preliminary trial that was conducted of the TViews table in use within a real-world home. The chapter concludes by looking at the potential scope of the media table application space across different physical contexts.

Chapter 8 discusses design issues that were raised during the interaction sessions in a home environment. In particular, the chapter looks at how physical interactive objects can be mapped to a virtual media space and at different approaches for handling multiple viewing angles on a tabletop surface.

Finally, Chapter 9 concludes the thesis with a summary of the contributions and a discussion of future directions for the research.

Chapter 2

2. Conceptual Foundations

The research presented in this dissertation is focused on the development of an extensible, scaleable and economically feasible design for an interactive tabletop display. In this chapter, we examine the conceptual and technical foundations underlying the creation of this type of platform. We begin with a brief glimpse at the use of tables across human cultures and history. Next we focus on the concept of the interactive media table, concluding the chapter with an overview of common technical approaches for interactive tabletop displays and their limitations.

2.1 Tables across History

Tables are an ancient form of furniture, used to hold objects at a convenient or comfortable height from the ground. Across history, they have served various functional roles within different physical settings. In living rooms, dining rooms, or other social gathering spaces such as pubs and cafes, people sit around them to eat, play games, or simply engage in casual conversation. In settings such as kitchens or woodshops they are used as working surfaces or to deposit tools and utensils, while in libraries, studies and classrooms they are frequently used for reading and writing. In general, tables serve well for both individual and shared tasks that require having several objects at hand.

Most early tables dating from Egyptian and Greek times were small and low, and were used as temporary stands to hold food or objects [Hayward 1965]. For this reason they were often pushed under a couch or bench outside of mealtimes. Ancient oriental cultures also used low tables, typically kneeling or sitting around them on woven mats. Late in the Roman period, larger tables came into use in a more permanent manner as pieces of dining room furniture. The aesthetic style of tables, including their shape and size, has varied greatly over time and with changes in social customs in different eras. From the plainer surfaces of

Greek and Roman times and the simplistic functional versions used in medieval households, tables have been transformed into heavy and ornate pieces during the Renaissance and eventually to modern and efficient styles common today [Huntley 2004]. The materials used for table construction have also varied greatly, ranging across combinations of wood, stone such as granite or marble, metals such as bronze, iron, or aluminum, and an assortment of modern synthetic materials such as plastics.

Certain tables have taken on a symbolic meaning within our culture, such as the circular table from the legend of King Arthur and his knights. In medieval times, rectangular tables were typically used at feasts and the seating assignment reflected the feudal hierarchy. In contrast, King Arthur's knights sat at a round table with no head position, which was a symbol of their equality. Since then, the term "round table" has been adopted in common language to signify a meeting or discussion that has no leading voice.

What should be noted from this brief overview of tables throughout human history is that their use is wide-spread across different cultures, in both public and private spaces alike, and for both leisure and work-related activities. The physical form of the table creates a natural space for people to interact with physical objects, and for face-to-face interactions amongst small groups of people. The following paragraphs describe several specific examples that illustrate how collections of physical objects have been used in conjunction with tabletop surfaces for the purpose of game play or to organize and navigate information spaces.

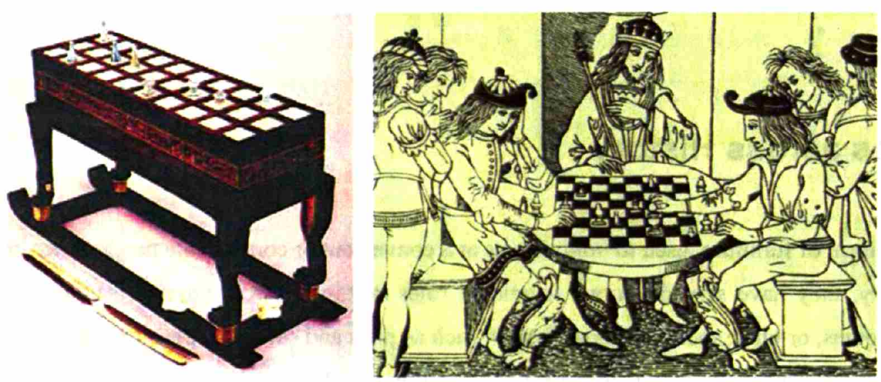


Figure 2.1: Table games

Senet game table from the tomb of Tutankhamun (left) and 15th century woodcutting that depicts a tabletop chess game (right).

The broad category of tabletop gaming including traditional board and card games provides a particularly relevant example of structured object interactions on the surface of a table. Early games date back to Ancient Egypt and China, many of which are still played today. The left side of Figure 2.1 shows an ebony and ivory gaming board and stand that was excavated from the tomb of King Tutankhamun (1336-1327 BC) and now resides in the Egyptian Museum in Cairo. In this case, the gaming board is double-sided: the top face serves as a board for the game of Senet, while the reverse bears a game called Tjaw [Piccione 1980]. Senet is thought to be an ancestor of modern Backgammon, and may be the oldest board game in the world [Bell 1960]. The right side of Figure 2.1 shows a game of chess amongst nobles that has attracted a small group of spectators. This particular illustration was printed in a 15th Century Italian Treatise on

Chess [Cessolis 1493]. Over the centuries, inventors have also created various kinds of mechanically instrumented tables for entertainment purposes, such as music tables with dancing figurines. An interesting example is the chess-playing automaton built by Hungarian inventor Wolfgang von Kempelen in 1769 [Standage 2002]. Known as the Turk, the machine was built in the form of a life-size man who sat in front of a large table and was able to play chess against a human opponent. The machine toured Europe and America in the 18th and 19th centuries and was eventually revealed to be an elaborate hoax, since its movements were controlled by a human operator concealed within the table (see Figure 2.2).

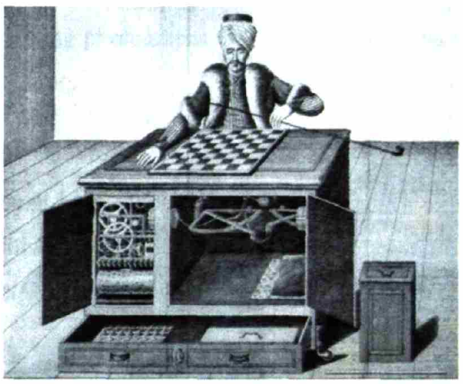


Figure 2.2: The Turk chess automaton

Invented by Wolfgang von Kempelen in 1769, the automaton known as the Turk was supposedly able to play chess against a human opponent.

Tabletops also provide an ideal surface for spreading out large maps that groups of people can examine together when planning or visualizing geographical spaces. For instance, architects and urban planners construct tabletop models of buildings and city streets in order to visualize construction projects. In military war rooms, large situation maps are used to plan the movements of ships and planes during a battle. Figure 2.3 shows a British command and control center from World War II. Croupiers use long wooden sticks to move pieces around the map, aligning them with incoming radar positions and simulating possible battle scenarios and strategies. Despite all the technological progress in desktop computing platforms since then, even modern aircraft carrier commanders manipulate small models of airplanes around a table surface in order to visualize and coordinate the movements of real airplanes on the flight deck.

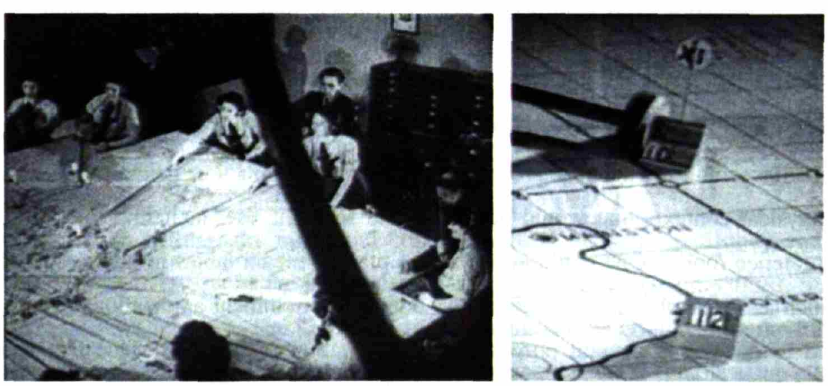


Figure 2.3: Military map tables

Tabletop situation map from a WWII British command and control room.

These examples demonstrate that tabletops have long provided an ideal interaction space for groups of people to share and engage with different collections of physical and informational objects. With the advent and rapid evolution of digital technology, we now also have affordable computing systems for managing and manipulating large collections of media and information in a digital form. A natural step forward in human-computer interaction is to intersect these two worlds in order to provide easy to use physical platforms for jointly engaging with our digital media collections. The following section looks at the concept of media tables, which are designed to do exactly this.

2.2 Media Tables

Interactive tabletop display surfaces have been around for quite a long time. The approaches used have evolved from touch-sensitive surfaces to prototypes of multi-object tracking platforms coupled with overhead projected displays. The most notable systems will be examined in the following chapter of this dissertation. In this section, we look at the definition and characteristics of tabletop media platforms.

A media table, occasionally referred to as an interactive workbench within work-related contexts, is a horizontal surface upon which the spatial configuration of tagged objects is computationally interpreted and then augmented with coincident visual output. The visuals are usually provided by rear or front projection. While some interactive table displays make use of touch as a means of input rather than object tracking, the concept is generally the same. The additional benefit provided by object tracking is the ability to identify and associate unique physical artifacts to different elements or functions within the application space. In particular, these physical artifacts can take on a form that is representative of their digital functionality. In this way, some of the information within the interactive environment can be off-loaded from a purely graphical form to a physical-world representation. This is an important characteristic of tangible interfaces that is noted by Ullmer and Ishii in [Ullmer 2000]. The graspable artifacts of tangible platforms are seen as physically embodying digital information, and they act as both *representations* and *controls* within the interactive environment.

As demonstrated by their everyday use and widespread appropriation across history and different cultures, tables provide an ideal space for people to engage shared and sociable interactions. For media tables, this implies a broad range of physical contexts that would be well-suited for their use, including the home, school classrooms, and conference rooms. One could also imagine placing media tables in public spaces and social environments, such as cafes, shops, or museums. As digital entertainment applications evolve, there is an increasing need to develop a general purpose interactive tabletop display surface that can support a diverse range of applications for these types of spaces, including media asset management, story construction, digital game play, and multimedia learning.

The particular focus of this thesis is the shared living space found in most homes, which provides a natural arena for sociable interactions around tables. Relevant uses in this physical context fit broadly within the domain of arts and entertainment, including specific applications such as game play, storytelling, and media browsing and organization. A media table for the living room needs to provide at least the size and scale of a typical game-board, and should support multiple points of control and multiple applications while ergonomically accommodating several users engaged in sociable interactions from different sides. In particular, a media table for the home might take the form of the low table which is often a living room's center-piece, and serves as a surface for depositing readings materials, playing games, assembling puzzles, sorting photographs and other shared activities. Figure 2.4 depicts a media table in a typical living room setting.

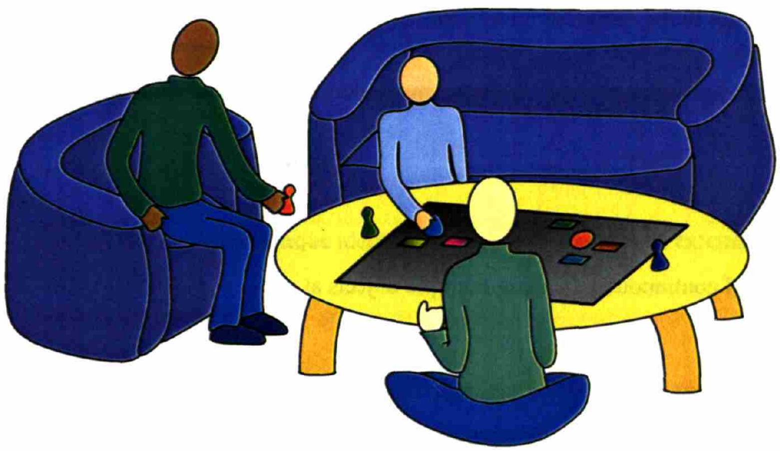


Figure 2.4: Media table in the living room
Sketch depicting a media table in a home context.

2.3 Technical Approaches

While the need for tabletop display surfaces seems to have been recognized by a number of researchers who have explored various interactive applications on tabletops, none of the early attempts point to a general purpose, economically viable tabletop display and interaction platform. In particular, existing examples have not succeeded in providing an extensible architecture that can support a diverse range of applications that would be required for everyday use by many people.

This section outlines the functional criteria required for tabletop display and interactions platforms and provides an overview of the past technical approaches and their limitations. Specific example systems are discussed in Chapter 3. The functional requirements can be grouped into the following three categories: (1) object sensing, (2) object management and identification, and (3) table setup and display. These correspond to framework for extensible tabletop media platforms that is outlined by the first thesis claim in Section 1.2.

(1) Object Sensing

While the technologies to track objects on a global scale such as the satellite-based Global Positioning System (GPS) become increasingly accurate and reliable, precisely locating objects on the surface of a table remains a difficult technical problem. A variety of different approaches have been tried, using techniques ranging across optical, acoustic or radio-frequency sensing. It should be noted that many optical or acoustic approaches that are done through the air can pose problems of occlusion if one or more objects are blocking the view of a receiver or transmitter. In these cases, it becomes difficult to support multiple continuously interactive objects. Another problem that often arises is the scalability of the interactive surface in terms of size or shape. In approaches that use antenna grids rather than a small set of fixed receivers or transmitters generally require tiling in order to scale in size which can be costly and generally results in an extra level of complexity in the design of the electronics.

The important considerations for object sensing on an interactive media surface that provides multiple points of control are as follows:

- ***Supports multiple objects:***

  The sensing surface is capable of continuously tracking multiple objects at once.

- ***Avoids interference and occlusion:***

  Multiple sensed objects do not interfere with one another. Hands or external objects placed in the interaction area do not affect the sensing mechanism.

- ***Scalable in size:***

  The sensing surface can be easily scaled to different sizes and aspect ratios.

(2) Object Management & Identification

Interactive tables face the problem of dealing with large numbers of physical objects across many different applications and platforms. While unique identifiers and an extensible namespace are common within the digital realm, getting computers to uniquely identify objects in the physical world is a difficult problem. Technical solutions such as barcodes and Radio Frequency Identification (known as RFID tags) give physical objects a unique identity that can be understood by a computer. This unique identity is retained regardless of where you move the object in the physical space.

On a media table, different interactive objects might have different physical properties or shapes depending on their application and use. For this reason, the objects need to be uniquely and digitally identifiable, and the means of object identification must be able to function together with the table's position sensing technology. Moreover, users might want to move their interactive objects from one table to another, meaning that all tables need to have a shared understanding of how objects are identified. Finally, if different types of objects are to serve unique purposes within different application environments, an interactive table should ideally provide a means for application designers to customize or tailor interactive objects to their particular applications in terms of physical form or functionality.

Past approaches to interactive tables have not been able to provide adequate systems for object identification and management. Optical-based systems have generally not been able to provide an easily extensible set of interactive objects, and customizations are difficult to manage or scale. Approaches that use actuated RFID tags typically provide only a small set of interactive objects. For example Wacom's pen tablets provide only two pens, while Zowie's interactive toys provide nine tags which are the same for every toy.

The important considerations for object management and identification are as follows:

- ***Global and extensible object IDs:***

  Each object is given a unique identifier that is global across an extensible namespace.

- ***Objects are portable:***

  The tagged objects can be moved from one interactive surface to another and retain their unique identity when moved.

- ***Objects are customizable:***

  The functionality of the tagged object can be easily expanded by adding user input and output elements such as sensors or displays on the objects themselves. The physical shape and form of objects can be customized.

(3) Table Setup & Display

Many of the technical approaches to interactive tables have required a large amount of external infrastructure, such as sensors placed around the room or overhead projection systems to provide a visual display on the table's surface. While these systems work reasonably well for prototyping or demonstration purposes within a research laboratory, they are not viable options for a media table that is designed for use within a home or other real-world settings. For these cases, both the sensing and display technologies need to be encased within the interactive table itself. Ideally, the table should be a single integrated unit that is not encumbered by too many wires or external connections and can be easily moved around typical living room.

The important considerations for table setup and display are as follows:

- ***Self-contained sensing:***

  The sensing mechanism can be fully contained within the table, requiring no external infrastructure such as cameras or separate antennas.

- ***Self-contained display:***

  A display mechanism can be integrated inside the table with the interaction surface, requiring no external infrastructure such as an overhead projector.

Functionality		**Technologies for Interactive Tables**					
		Optical	**Electromagnetic**		**Acoustic**		
		Vision-based object tracking	Actuated RFID tagged objects	Multiple touch sensing systems	Through-air ultrasonic triangulation	Through-glass tap tracking	Through-glass object tracking
Object Sensing	Supports multiple objects	✓	(Limited)	(Touch Only)	✓		✓
	Avoids interference and occlusion		✓				✓
	Scalable in size	✓	(Difficult)	(Difficult)	✓	✓	✓
Object Management & Identification	Global and extensible object IDs	(Difficult)					✓
	Objects are portable	✓					✓
	Objects are customizable	(Difficult)	(Limited)				✓
Table Setup & Display	Self-contained sensing		✓		✓	✓	✓
	Self-contained display				✓	✓	✓

Figure 2.5: Technologies for media tables

To summarize, past technical approaches to tabletop displays suffer from a number of significant shortcomings; specifically, the inability to incorporate an embedded display within the sensing surface, the difficulty of extending the sensing surface to various shapes, sizes and aspect ratios, and the difficulty of exchanging objects between platforms. In particular, computer vision technologies typically require external camera setups that are difficult to integrate into a compact tabletop platform, while antenna and tag based systems employ an opaque sensing surface that requires overhead projection of the display and is difficult to scale by means other than the tiling of antenna grids. The object identification and sensing method developed as part of this doctoral research enables the development of self-contained tabletop interaction platforms that provide an embedded display, are scalable to different sizes, and support an extensible set of tracked objects that are portable from one platform to another.

The table in Figure 2.5 provides an overview of the most commonly used technologies for interactive tables and shows the specific functionality enabled by each approach with respect to object sensing, object management and identification, and table setup and display. The last column indicates the sensing approach that was developed in order to demonstrate the extensible method for media interaction tables described in this thesis. Examples of interactive tables that have been implemented using the other approaches are discussed in the following chapter.

Chapter 3

3. Related Work

The previous chapter looked at the use of tables across history and discussed the concept of an interactive media table as a platform for shared user interactions with digital media applications. Several technical and functional criteria were identified for the successful realization of interactive tables. These were considered within the context of past technical approaches.

In this chapter, we look at the particularly relevant and notable interactive tabletop systems that have emerged over the past several decades, as well as at some other kinds of interactive surfaces that have been developed. We also provide a more detailed explanation of the principal object positioning technologies that are in use today.

3.1 Interactive Table Systems

Early work on interactive tables began with research prototypes such as the Digital Desk built by Pierre Wellner at Xerox EuroPARC and the ActiveDesk work at the University of Toronto. The Digital Desk made use of an ordinary physical desk with a video camera mounted above that could track the movements of an LED tipped pen to determine where the user was pointing [Wellner 1993]. Later versions included overhead digital projection of electronic objects onto regular paper documents. The ActiveDesk allowed two-handed input through physical artifacts called "bricks" and was used with a drawing application called GraspDraw [Fitzmaurice 1995].

The next major steps in interactive tabletops took place at the MIT Media Lab, with the metaDesk and I/O Bulb projects [Ullmer 1997, Underkoffler 1999]. These systems differed from the Digital Desk and

ActiveDesk systems in that they were designed for collaborative use. Applications included geographical visualization, simulation of holographic setups, and urban planning. In both systems, the tracking of multiple objects was achieved through computer vision, and the display was accomplished with projected graphics from the rear (metaDesk) or the front (I/O Bulb).

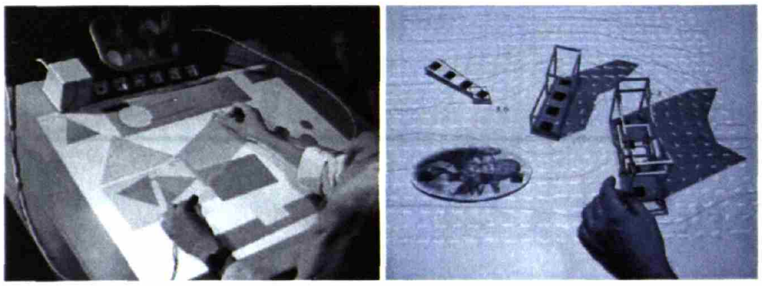


Figure 3.1: Interactive desks and tables

The left side shows single user two-handed interaction on the ActiveDesk. The right side shows an urban planning application running on the I/O Bulb system which can support multiple simultaneous users.

At this point, interactive tables are being explored by an increasing number of researchers for different applications in a variety of physical contexts. The Sensetable project at the MIT Media Lab has been used for applications in a number of areas, including supply-chain visualization and musical performance [Patten 2001, 2002]. The DiamondTouch table from MERL allows multiple users to interact simultaneously via touch, and has been used for applications such as a multi-user map viewer [Dietz 2001]. Other tables that are being developed at research labs within universities include the iTable from Stanford which has been used for information organization [Grant 2002], the reacTable* from the University of Pompeu Fabra which is used as a musical instrument [Jordà 2003], and the Planar Manipulator Display from NYU which has been used for simulating the furniture layouts in an interior space [Rosenfeld 2003]. In the latter of these, the interactive objects are equipped with motors and their movements can be not only sensed but also controlled by the computer. As a final example, researchers at the Viktoria Institute and Lancaster University are developing a Weight Table concept based on their Smart-Its platform [Holmquist 2004]. Smart-Its allows embedded devices to be attached to everyday objects in order to augment them with sensing, perception, computation and communication. In the case of the Weight Table, load cells are added to the corners to enable the detection of position and weight of the different objects that are placed on or removed from the table. While the Sensetable, iTable and reacTable projects all focus mostly on the exploration of new application or interaction concepts, the DiamondTouch, Planar Manipulator Display, and Weight Table projects focus also on the development of new sensing and actuation technologies.

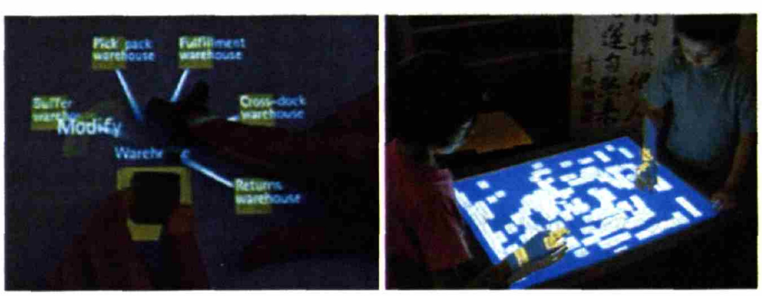


Figure 3.2: Prior interactive table systems

The left side shows the Sensetable object-tracking table used for supply chain visualization. The right side shows a poetry application on the DiamondTouch multi-touch table.

Continuing with the research on digitally augmented physical desktops, researchers at the Ars Electronica Futurelab are developing a Future Office Table that can accommodate a group of up to six people on site and also makes it possible to link up participants at remote locations via videoconferencing [Futurelab 2005]. The prototype features personal workspaces for individual users as well as a shared space for exchanging and jointly organizing documents. This idea of territory-based interaction techniques for tabletop workspaces has been explored from the perspective of co-located collaboration by Stacey Scott in her Doctoral Dissertation research at the University of Calgary [Scott 2005].

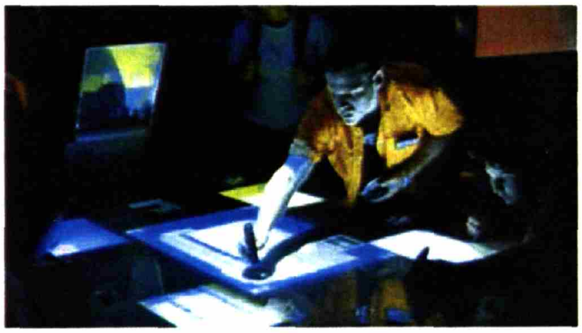


Figure 3.3: *Future office table*

The Future Office Table developed by researchers at the Ars Electronica Futurelab provides individual and shared workspaces for up to six co-located users.

Interactive tables have also been used within interactive art projects, such as the sensor table developed by Post and collaborators from the MIT Media Lab for an installation at the Museum of Modern Art in New York. The sensing surface in this case was a pixilated capacitive matrix that could detect and track bare hands through capacitive loading [Omojola 2000]. Another example is the Dialog Table which was commissioned by the Walker Art Center as a permanent installation that promotes social interactions among visitors and provides access to the museum's multidisciplinary collections [Walczak 2003]. Finally, the Flights of Fantasy installation at the Decordova Museum in 2001 presented a video construction table that resembled a giant version of a child's sliding-block pocket puzzle where each block contained a story-related icon [Davenport 2001]. By sliding the blocks around in the tabletop, visitors could collaborate with the machine to form short story fragments based on characters and places that were contained in the system's media database.

Figure 3.4: Flights of fantasy

The video construction table created for the Flights of Fantasy installation resembled a giant version of a child's sliding-block pocket puzzle.

It is important to note here that none of the tables which use multiple object tracking have been realized in a manner that can scale beyond a research prototype or single-platform project in order to gain widespread and possibly commercial use. Nevertheless, the idea of an interactive table is gradually making its way into the consumer market, and Hitachi has announced the development of a touch-sensitive tabletop display which they plan to commercialize within the coming year, starting at a price of $20,000 US [Hitachi 2004]!

3.2 Other Interactive Surfaces

In addition to the table, there has been research on a variety of other interactive surfaces, ranging from small tablets, to whiteboards, windows, walls and floors. In this section we provide some example technologies and applications from both research institutions and industry contexts. While this is not an exhaustive list, it should give a sense of the breadth and scope of the research space.

Tablet and pen input devices have been around since the 1960s, when the RAND Corporation in Santa Monica created a pen-like position input mechanism that could sense electrical pulses relayed through a grid of wires contained within a small horizontal tablet pad [Davis 1965]. Since then, pen tablets have been used as an alternate to the mouse for controlling digital desktop applications. One of the best known current examples is the line of Wacom pen tablets, the most recent of which provides an embedded display within the tablet's surface [Murakami 1986]. Canon also holds patents on an acoustic-based pen and tablet input device that is described in the following section [Kobayashi 1990, Yoshimura 1992]. There are also many tablets that are designed to track finger touches rather than specially designed pen devices. While most of these tablets can only track a single touch at a time, a number of systems have been developed for multi-touch tracking. An early example is a multi-touch tablet created at the University of Toronto in the mid-80s that was used as a musical control device [Lee 1985]. Other examples in the commercial realm include the Tactex smart fabric technology [Tactex 2005] and JazzMutant's Lemur [JazzMutant 2005].

Figure 3.5: Tablet input devices

The RAND Tablet (left) was an early pen tablet input device. The JazzMutant Lemur (right) is a current multi-touch musical controller.

There has also been range of research on technologies and applications for much larger interactive surfaces, such as whiteboards, windows, walls and floors. An example of an electronic whiteboard is Mimio, a capture system developed by Virtual Ink that can record the writing made on a regular whiteboard fitted with special tracking technology [Chery 2000]. Some examples of research on interactive walls and windows include the Laser Wall and the Tap Window projects from the Responsive Environments group at the MIT Media Lab. The Laser Wall was a gestural interface that used a laser rangefinder to track hands in front of a large projected wall display and was used for musical performance [Strickon 1999, Paradiso 2000]. The Tap Window project (discussed in the following section) turned an ordinary window pane into an input device for applications such as interactive store displays [Paradiso 2002, Paradiso 2005]. Finally, there has been a variety of work on interactive floors. An early example is the prototype MIDI dance floor based on an array of force sensitive resistors developed by the University of Texas and used for musical dance performances during the Columbia Interactive Arts Festival in 1999 [Pinkston 1995]. Other examples of interactive floors include the Magic Carpet from the MIT Media Lab [Paradiso 1997] and the Smart Floor from the Georgia Institute of Technology [Orr 2000]. The Magic Carpet was developed as part of the touring musical installation from the MIT Media Lab called the Brain Opera, and used piezoelectric sensors to create a space where the position and pressure of a performer's feet could be measured together with upper-body and hand motion to generate expressive sound. The same device was also used to develop the CINEMAT Dream Weaver, an interactive installation that premiered at the 27th International Film Festival in Rotterdam, and allowed audience members to actively control the selection and play-out of associative narrative streams by standing, stepping and stomping on the carpet [Davenport 2000]. The Smart Floor prototype is built using force measuring load cells and is able to identify different people walking on the floor based on their footstep profiles.

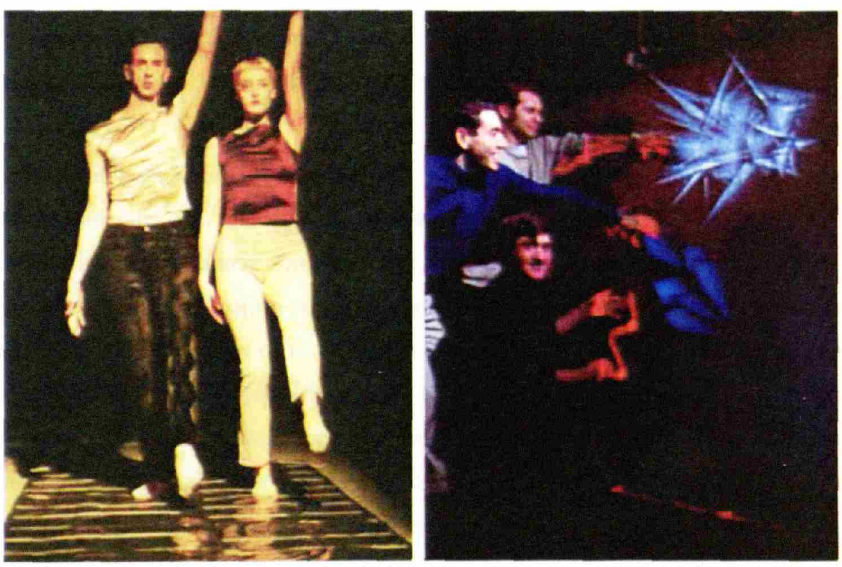


Figure 3.6: Interactive floors and walls

The left side shows a MIDI dance floors from the University of Texas. The right side shows a gestural wall for musical performance called the Laser Wall developed at the MIT Media Lab.

3.3 Object Positioning Technologies

The previous sections looked at a variety of past and current research on interactive surfaces primarily from a user interaction or application perspective. This section looks at the main approaches that have been used for positioning of objects on relatively small-scale horizontal surfaces, such as tabletops or single-room floors. For the most part, these fit into three broad categories: optical, electromagnetic and acoustic.

3.3.1 Optical

Objects can be tracked on a horizontal surface using computer vision algorithms, as in the metaDesk and I/O Bulb systems [Ullmer 1997, Underkoffler 1999]. Optoelectronic triangulation systems are widely used for tracking mobile robots. These typically involve a scanning mechanism that operates in conjunction with fixed-location receivers placed in the operating environment [Everett 1995]. For example, the CONAC system made by MTI Research, Inc. employs a vehicle-mounted rapidly rotating and vertically spread laser beam that sequentially contacts fixed networked detectors in the space [Borenstein 1996]. In the Planar Manipulator Display, two infrared LEDs are mounted on each mobile object and outputs of their sequential pulses generate position-dependent current when imaged onto a position sensing device inside the table [Rosenfeld 2003].

3.3.2 Electromagnetic

Other approaches to object tracking use electromagnetically actuable tags. The Sensetable project mentioned above [Patten 2001] is based on Wacom's tablet and pen technology that uses an antenna grid within the sensor board to track pens containing coil-and-capacitor resonant circuits [Murakami 1986]. While a typical Wacom tablet can track only two pens at a time, the Sensetable project modified the system using a duty cycling approach in order to allow a greater number of objects to be tracked at once. Another example of an electromagnetic position detection system was developed by Scientific Generics and licensed by Zowie Intertainment for use in a couple of children's toys [Piernot 2002]. This technology was used in the first prototype of the tabletop media interaction platform described in Secion 4.2 and by later versions of Patten's Sensetable work. Since electromagnetic systems require sensors to be embedded within the interaction surface, coincident display of graphics must be projected from overhead.

3.3.3 Acoustic

Objects can be located using an acoustic approach by embedding ultrasonic transmitters inside the tracked objects. Ultrasonic receivers placed around the sensing area pick up the short acoustic signals emitted by the objects and triangulate the object's location based on the time-of-flight of the signal from the transmitter to each receiver. The acoustic signal is typically transmitted through the air, which can result in errors if there are objects in the way between a transmitter and receiver. This approach has been used to locate performers on a stage [Reynolds 2001] as well as in a number of electronic whiteboard systems such as Mimio by Virtual Ink, in which an ultrasonic tracking array is positioned along the upper left edge of the board, and the acoustic signals are transmitted from special sleeves that hold the whiteboard markers [Chery 2000]. In another system from the MIT Media Lab, ultrasonic positioning has been used to track knocks or taps on large glass surfaces [Paradiso 2002, 2005]. In this case, the receivers are affixed to the back of the glass panel and the acoustic signal travels through the glass rather than through the air, which eliminates potential problems of occlusion. This method provided the inspiration for the approach used in TViews (described in Section 4.3), but differs in that the TViews system places the receivers in the objects in order to allow the system to scale to larger numbers of tracked objects. In the commercial realm, two companies from France, Intelligent Vibrations [Devige 2003] and Sensitive Object [Ing 1998], have both developed systems for tracking taps on large flat surfaces such as windows and tables, and their approaches are similar to the work by Paradiso described above. Intelligent Vibrations has designed an "Internet Table" with an embedded display that is designed for bars and internet cafes. Users interact by tapping on the table surface with their fingers or other objects such as pens and cutlery. Finally, Canon has developed a similar approach for tracking a vibrating stylus on the surface of a display tablet using the acoustic propagation time of the signal through a glass plate placed above the display surface [Kobayashi 1990, Yoshimura 1992].

Chapter 4

4. Research Prototype

This chapter presents the work leading up to the development of the general purpose media table design that is described in Chapter 5. The research approach followed an iterative design process, beginning with the development of a research prototype and several media applications. The goal of this preliminary work was to better understand how tabletop platforms can be used for shared media story interactions.

The research prototype, which takes the form of a small tabletop interaction platform, was first constructed as part of the author's MS research work in the MIT Media Lab's Tangible Media group, under the supervision of Professor Hiroshi Ishii [Mazalek 2001]. Two narrative-based applications were constructed as part of the doctoral research discussed in this thesis, and focus on multiple viewpoint and spatial storytelling. Each application was used as part of a storytelling workshop that served as a test-bed for identifying the limitations of the prototype platform and the design principles for the final design.

The research prototype and media applications are presented in sections 4.1 and 4.2 below. The two user studies and relevant results are discussed towards the end of the chapter, in sections 4.3 and 4.4.

4.1 Implementation

The research prototype is a tangible display platform that supports interactive story navigation through the manipulation of graspable pawns and other tangible tools on a sensing surface. This section provides an overview of the physical interface design, and describes the software architecture that enables developers to create simple narrative and media-related applications for the system.

4.1.1 Physical Design

The research prototype was constructed using a commercially available inductive sensing technology that was licensed by Zowie Intertainment for use in a couple of digitally enhanced children's toys [Piernot]. The Zowie system provides nine electromagnetically actuable tags and a sensing surface in the form of a loosely wound grid of antenna wires. Since each individual antenna pad is quite small, two pads were tiled together to provide a larger sensing area. The tags were embedded in the base of the interactive objects, which for the purposes of the storytelling applications consisted of small chess-like pawns, as well as selection and rotation tools.

The coincident display of graphics on the horizontal interaction surface was provided by overhead projection. Instead of hanging the projector from the ceiling, a special stand was constructed to hold it in place behind the platform, and a mirror was used to direct the image onto the interaction surface. In this way, the entire system could be transported to different locations for the purpose of user testing. In addition to the horizontal interaction surface, a vertical display and speakers could be used to playback content clips in audio-visual form or to give additional media information, such titles or textual descriptions. Figure 4.1 illustrates the physical setup of the platform. A more detailed description of the platform design is provided in [Mazalek 2001].

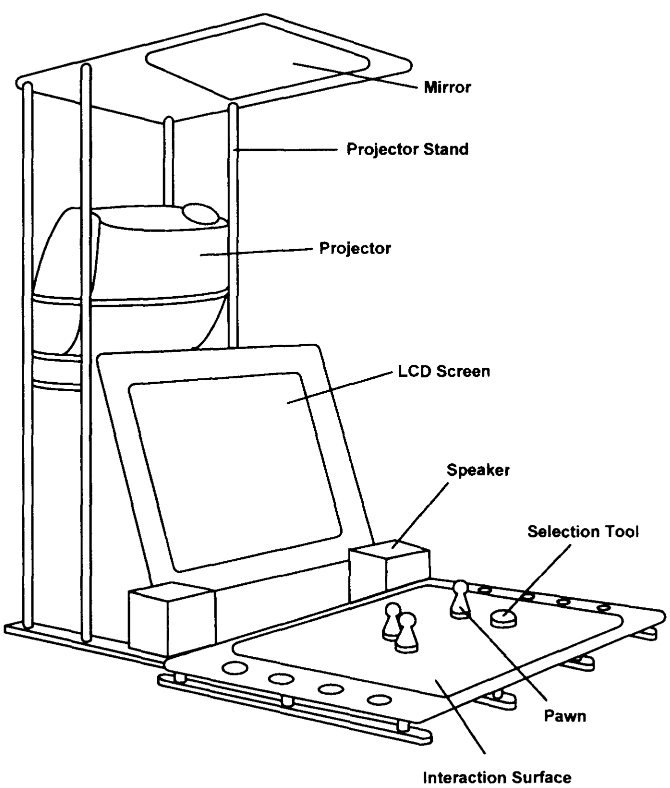


Figure 4.1: Physical setup of research prototype

The prototype interaction platform provides a horizontal interaction surface with several interactive objects and coincident display via overhead projection. A vertical display is used to play video clips or provide additional visual information during user interactions.

4.1.2 Modular Software Framework

A modular software framework was implemented for the platform in order to allow easy integration of multi-object tracking with the display of coincident graphics. This software framework provided the basis for the creation of exemplary multimedia storytelling applications.

The architecture consists of three independent modules, illustrated in the middle section of Figure 4.2. The position sensing module uses a polling mechanism to gather information about the tagged objects present on the interaction surface. The data is transmitted to a computer via the RS-232 protocol, where it is decoded into (x,y) positions for each object. The playback module is responsible for playing content clips in the form of video, audio, images or text via the on-screen display and speakers. The narrative engine module forms the core of the system's interactive functionality and determines how users will perceive and manipulate media content on the interaction surface. In consists of a computational media structure, which provides a means of organizing media information from a content database, and a graphical engine, which determines how the content will be visually represented through graphical projection. User interactions with media information through the tagged objects are reflected by dynamic changes in the projected graphics. By separating the narrative engine from the position sensing and content playback modules, the system becomes a flexible media platform that can be used to drive a variety of different applications.

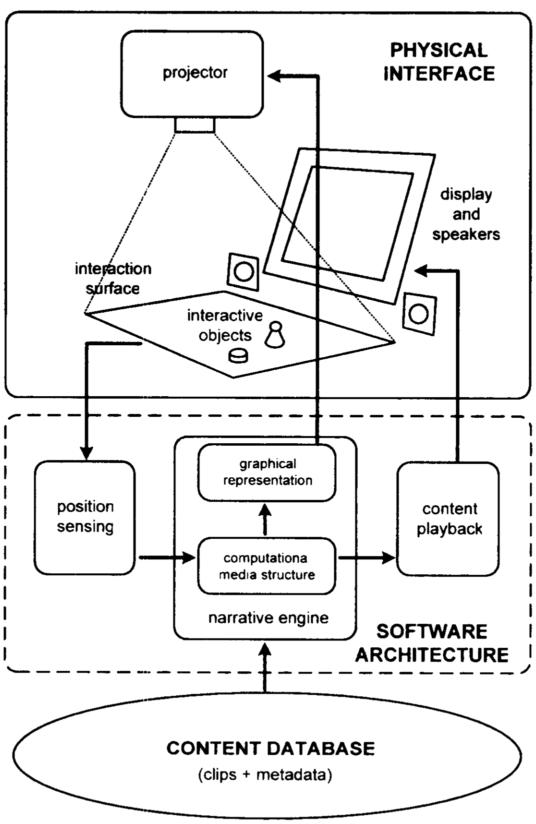


Figure 4.2: System diagram of research prototype
This diagram illustrates the software architecture and the way it communicates with the physical interface and the underlying content database.

4.2 Media Applications

The applications developed for the prototype platform described above included multi-viewpoint and spatial approaches to story revealing and media browsing. These applications have been described in [Mazalek 2002] and [Mazalek 2003].

4.2.1 Tangible Viewpoints

The *Tangible Viewpoints* application allows the audience to experience character-driven narratives. The content clips of a multi-viewpoint story are organized according to the character viewpoint they represent, and their place in the overall flow of the narrative. The physical pawns are used to represent the different character viewpoints in a story. When placed on the interaction surface, the story clips associated with its character viewpoints are projected around each pawn in the form of small thumbnails. Figure 4.3 shows the pawns on the interaction surface and the projected graphics.

Figure 4.3: Tangible Viewpoints

The left side shows the pawns on the interaction surface with content clips projected around them. The right side shows a screenshot of the graphics that are projected onto the interaction surface. The large colored circles represent pawns, and thumbnails that cluster around them are clips from the content database that provide different viewpoints on the story.

Users can explore the different viewpoints and story threads by activating the clips that cluster around the pawns using a small lens-shaped selection tool. This causes the narrative to advance and new clips to become available, drawing users forward through the multi-threaded story space. Activated clips are also sent to the playback module, and in turn to the on-screen display.

The narrative engine that guides the story forward as users interact makes use of a rule-based structure for controlling narrative progression, and a spreading activation network that ensures continuity and relevance as new content clips are revealed to the audience. The narrative engine provides breadth or depth of different character viewpoints based on user preferences that are revealed from the selections they make throughout a session of story exploration. The details of the narrative engine functionality are described in [Mazalek 2002].

4.2.2 Tangible Spatial Narratives

The *Tangible Spatial Narratives* application explores the notion that physical spaces become an arena for story construction and narrative development through the human actions, conversations and memory creation that unfold throughout them. The application recreates the physical space of a story on the tangible platform, allowing audience members to navigate on a story map, gradually reveal the many pieces of a complex spatially structured and co-constructed documentary.

Figure 4.4: Tangible Spatial Narratives

The left side shows the pawns placed on at different locations on the map with content clips projected around them. The right side shows a screenshot of the graphics that are projected onto the interaction surface, including the overall map of the story setting, the colored circles representing pawns, thumbnails representing content clips, and the time tool.

The content clips in the application are organized in the database according to location, character and time, and a visual landscape is projected onto the interaction surface to provide a spatial framework for browsing media content and for the many perspectives and narrative threads that emerge as it plays. Users associate pawns to the different people in the story, and move them around the map in order to discover content clips displayed around the pawns in the form of small thumbnails. These content clips are dynamically retrieved from the story database through character and location-based queries that are determined by the placement of pawns on the interaction surface. A clock tool can be used to retrieve clips using the additional parameter of time, allowing users to scroll forward and back through a chronologically ordered and spatially distributed set of story clips. Content clips can be played on the display screen by gliding a lens-shaped selection tool over top of the thumbnails on the interaction surface. Figure 4.4 shows pawns on the map and the projected graphics.

4.3 Exploratory Evaluations

The research prototype and applications provided a means for exploring questions of media table design and use: in particular, who might use such a platform and how? The applications described above allowed small groups of users to share multimedia stories created about their personal experiences in an informal and social setting. In this case, the tangible form of interaction enabled authors and audiences to jointly engage in a reflective learning process, re-examining their own experiences and relating them to the perspectives and experiences of others.

To explore this idea of sociable storytelling on a shared tabletop platform, the multi-viewpoint and spatial applications were used to support two different personalized storytelling experiences in which the community of story authors was also invited to become the audience members of their own stories. Through iteration between story creation and story engagement, participants were able to watch their own story grow and evolve, and as a result became engaged in an active process of story revealing and personal reflection. The following sections provide an overview of these two storytelling workshops and the lessons learned from each.

4.3.1 Computer Clubhouse Workshop

In November 2001 we conducted a 10-day storytelling workshop at the Boston Museum of Science Computer Clubhouse. This after school learning environment provides a safe space for young people from underserved communities to engage in creative activities and skill building through the use of technology [Resnick 1996]. Three teenage participants were selected to create personal stories to be displayed back in the *Tangible Viewpoints* system.

During initial brainstorming sessions, the participants worked together to develop a structure for their story. Their goal was to create a documentary piece that would chronicle one day in each of their lives in their East Boston community. They used digital still cameras to record images for their stories, and provided voice-overs and metadata information before adding their clips to the content database.

The tabletop interaction platform was set up in a central area of the one-room Clubhouse environment. Workshop participants and other members of the community were free to interact with the story as it evolved over the course of the 10 days. Through social interaction and discussion around the story platform, the storytelling process became a collaborative and iterative activity. Workshop participants drew on the skills and ideas of their fellow Clubhouse members, and incorporated them into the creation of their own personal stories. In particular, we noticed that the tangible and shared nature of the story platform drew members of the community away from their individual activities and brought them together at the center of the room. Figure 4.5 shows a group of Clubhouse members viewing the multi-viewpoint story created by workshop participants.

Figure 4.5: Participants at the Clubhouse

A group of kids interacting with the *Tangible Viewpoints* application during a storytelling workshop at the Computer Clubhouse.

While the creation of individual story threads allowed them to share personal perspectives on life in their East Boston community, participants found that their personal threads were not entirely separate from one another. Their stories intersected at certain points, for instance when their activities coincided at school or in the clubhouse. These moments revealed the way in which their interpretations of events often differed from the interpretations of those around them. By providing a shared framework for the telling of personal stories, participants were able step back and examine their own lives and experiences from a broader perspective. In this way, they could begin to understand how their own stories formed a part of the larger collective story of their community.

4.3.2 Digital Dialogues Symposium

The second storytelling workshop was based around the Tangible Spatial Narratives application and was held at the Digital Dialogues: Technology and the Hand symposium held at the Haystack School of Mountain Crafts in Maine in September 2002. The symposium focused on the creation of artistic pieces in a studio-based environment, and the 65 participants were invited to use their hands in collaboratively forming materials, media, and ideas. The goal was to explore how technology and handcraft can be brought together, and to initiate dialogues and an exchange of expertise between these two traditionally separate communities. The storytelling workshop enabled participants to document the events taking place across the different craft studios over the course of the symposium. The documentary took the form of a living record – a piece that grew as the symposium progressed, and incorporated the different perspectives of the large number of people coming from a wide variety of backgrounds.

The story of the symposium progressed along three main axes: space (the symposium was spatially distributed across the Haystack campus and craft studios), time (the event lasted 3-4 days), and character viewpoint (the many symposium participants provided widely differing personal perspectives on the unfolding events). Based on these parameters, we provided a core narrative framework for the piece. Participants used digital video and still cameras to record their activities and experiences in the studio spaces. These clips were then annotated with the appropriate metadata and loaded into a database that could be queried according to different keywords or combinations of keywords.

Over the course of the symposium, participants used the tabletop media platform to collaboratively engage with their story as it was still being created. The map of the Haystack campus was projected onto the sensing surface and provided a spatial framework for viewer interactions. This spatial layout helped ground the digital story clips in relation to the actual events taking place in the real world. Viewers could associate the graspable pawns to different symposium participants, moving them around the studio spaces depicted on the map. They could also use a clock tool to navigate back and forth through time. In this way, they could follow and compare the activities of different participants across both space and time. Figure 4.6 shows symposium participants browsing their spatial story on the interaction table.

Figure 4.6: Participants at Haystack

Participants browse their spatial media collection during coffee breaks and leisure time at the symposium.

As people experimented with the tangible interface, their engagement with the video clips was enhanced by the fact that they were familiar with the people and events portrayed, and the social nature of the platform allowed them to share and reflect on this experience with others. As we observed at the Computer Clubhouse, the tangible platform drew users around it to jointly engage with their media collection during coffee breaks and leisure time. The collaborative exploration of their own evolving story fostered an exchange of ideas that participants could immediately bring back into the work environment and incorporate into the next iteration of story creation. As such, the movement between story creation and engagement became a cyclical process, with each part informing the evolution and meaning of the next.

4.4 Platform Requirements

The storytelling workshops served as exploratory evaluations for the prototype platform, bringing to light a number of important limitations and helping to identify the particular requirements for a tabletop media interaction platform. Ultimately, these observations lead to the development of the extensible media table architecture described in following chapter. The design requirements identified are as follows, and broadly correspond to the criteria for interactive table technologies discussed in Chapter 2.

(a) Scalability of the Display and Interaction Space in Size

In working with users, it became evident that the size of the prototype platform was too small to accommodate more than two or three users at a time. For the most part, this was not a problem in the Clubhouse environment which was already quite crowded with other furniture, and where typically only three people (the official workshop participants) were actively involved in the story creation process. In contrast, the Haystack space would have benefited from a much large interaction platform that could have enabled larger subsets of the 65-person community to interact with the system at once. The lesson to be drawn here is that different physical environments and application contexts benefit from different sizes of media interaction table, hence the need for a platform that can scale in terms of size.

It is also worth noting here that the overhead projection which used the specially constructed stand proved to be very cumbersome as it blocked one side of user access to the interaction surface and was difficult to transport and set up. Since hanging a projector from the ceiling does not allow for the system to be easily portable, the sensing technology should allow for the incorporation of an embedded display.

(b) Extensibility of the Object Namespace

Another major limitation of the prototype platform was the small number of interactive objects that the sensing technology was able to support. Even though the spatial application provided the ability to associate a physical pawn to different characters through a menu-style interface, a larger number of objects would have enabled a broader range of interactions. With a limited number of tools, it becomes necessary to give the tool a very generic shape if it is to be used across different kinds of application areas. A larger object namespace would allow for objects to take on a different physical form depending on their function within the media space and the particular application with which they are typically used.

(c) Portability of Interactive Objects between Platforms

This requirement was identified through speculation on a way in which many instances of the media table platform could be employed at once within different physical locations. If two friends each have a media table in their living room, one of the things they might want to do is bring their interactive objects to each other's tables. Or in another scenario, a software developer might create a naval simulation game that is packaged with its own set of interactive objects, and this application should be able to run on any instance of the media table platform. In both of these cases, the media table (regardless of size) needs to be able to identify and locate any interactive object. That is, the interactive objects need to be portable between platforms.

(d) Extensibility of the Application Space and Management of Objects and Applications

The modular software framework proved to be useful in terms of extending the set of applications that could run on the table platform. However the table did not provide adequate management of objects and applications, and switching between applications still needed to be done through the windows operating system using a keyboard and mouse. While it might be useful to provide the ability to connect a keyboard and mouse to the media table via USB, the basic interactions and application management should be done without them. A custom application manager is needed to keep track of the applications that are installed on the table and the particular objects that each application is associated with. The same application manager should provide the ability to easily switch between different applications. For instance, if a user is running a paint program and somebody else places an object from a naval simulation game on the table, the event could be handled by asking the users whether they would like to switch applications or stay within the current one.

Chapter 5

5. TViews Table

The TViews table is a media interaction platform designed for the shared living spaces within the home environment. The table is built using the extensible solution described in the first thesis claim. This requires dynamic sensing and identification of an extensible set of tagged objects on the table's surface, as well as a display that is integrated into the table's surface and can provide visual output that coincides with the movements of the tagged objects. The design of the sensing method and its particular implementation utilize a novel combination of sensing and communication technologies that are described in this chapter.

In the previous chapter, we discussed two initial user workshops that explored the use of interactive objects on a tabletop display as a platform for shared media and story interactions. The interactions sessions brought to light a number of issues and helped to identify a series of requirements necessary to the development of an extensible architecture for media tables:

(a) Scalability of the display and interaction space in size.

(b) Extensibility of the object namespace.

(c) Portability of interactive objects between platforms.

(d) Extensibility of the application space and management of objects and applications.

Before delving into the details of the TViews design and implementation, it is useful to first provide a quick summary of the combination of technical features that have been used to fulfill these requirements.

(a) In order to allow scalability of the interaction surface in size, it is important that the object positioning technology is at least somewhat independent of the size and scale of the interactive surface, in such a way to allow the surface to be constructed in smaller or larger versions and at different scales to accommodate different kinds of displays. This can be accomplished using a time-of-flight approach, in which the object positions are triangulated based on the time it takes for signals to travel from a small number of fixed transmitters (i.e. at least three) to a receiver embedded in each object. The TViews table is based on acoustic time-of-flight. Since acoustic positioning does not require antenna grids or other materials covering the interactive surface, it is possible to provide an embedded digital display.

(b) In order to provide an extensible object namespace, TViews uses a unique digital identification number for each interactive object. The current 64-bit number allows an extremely large object namespace. The ID could be extended to a larger number if necessary.

(c) Supporting portability of interactive objects from one table to another requires two things. First, a table must be able to identify any object from the entire namespace as soon as it is placed on its interaction surface. Second, any table regardless of its size needs to be able to determine the position of any object that is placed on its interaction surface. To accomplish the first point from a technical perspective, it is necessary to implement an enumeration strategy that can identify objects that are currently on a given table. For the second point, the position calculation based on triangulation of time-of-flight data needs to be done at the level of the computational system within the table rather than on the objects themselves. This way, the objects do not need to know anything about the size of the table on which they have been placed, and only need to be able to measure signal flight times and communicate them to the table.

(d) In order to support an extensible set of applications, TViews should provide an API (Application Programming Interface) layer based on an event model that sends events when objects are added to, moved on, or removed from the table. In this way, developers are able to easily create new applications for the table platform by registering them for input events from the table's control system. TViews also needs to provide an application and object manager to support multiple applications on the table and to keep track of interactive objects that are associated to the different applications.

5.1 System Overview

TViews is a multi-user digital media platform with a glass surface that can locate and identify an extensible set of tagged external objects as they are swapped and moved around within its area. The tagged objects act as multiple points of control for multimedia applications and enable shared interactions for small groups of users (see Figure 5.1). The interaction platform includes an integrated digital display that provides visual output for users interactions with the tagged objects. The process flow of key features implemented by the TViews table is summarized as follows. Details of the implementation are described in the following sections of this chapter.

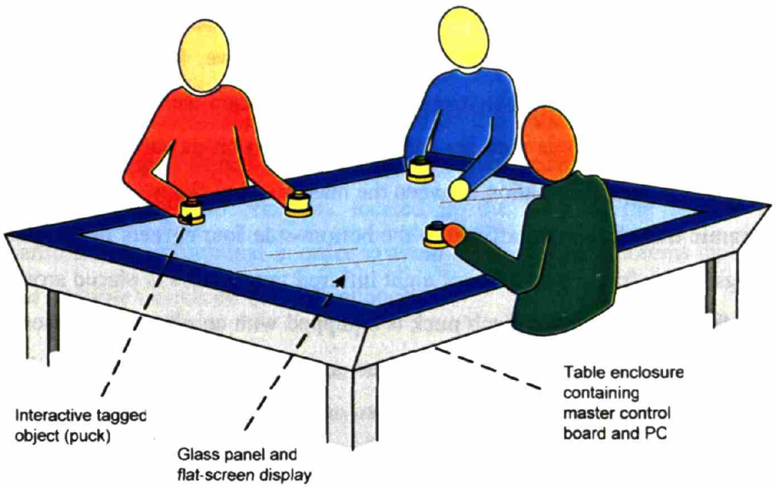


Figure 5.1: The TViews table

Envisioned physical form of the TViews tabletop media interaction platform.

1. Each interactive object is assigned a unique digital identification number.
2. An enumeration algorithm is used to determine objects placed on the interactive surface.
3. Physical sensing, based on acoustic time-of-flight from fixed transmitters, is used to locate the objects.
4. Identification and time-of-flight data is communicated to a system that estimates object position within the space of the interactive surface.
5. A digital display can be integrated underneath the interactive surface.

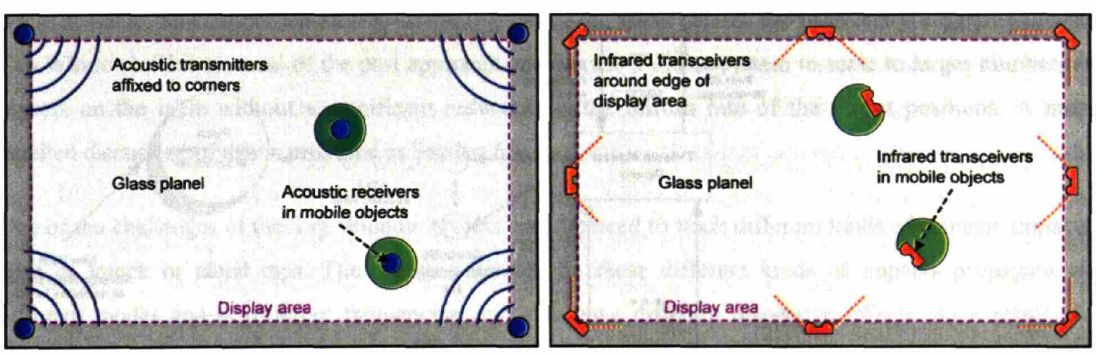


Figure 5.2: Sensor layout

Four acoustic transmitters are affixed onto the bottom-side corners of the glass plate and one acoustic receiver is embedded in the base of each interactive object (left). The acoustic sensors are used for locating the interactive objects on the tabletop. Eight infrared transceivers are placed around the edge of the display area above the glass plate and one infrared transceiver is placed in each interactive object (right). The infrared sensors are used to communicate data between the table and the interactive objects placed on its surface.

TViews uses a combination of acoustic position and infrared communication technologies to implement the table-based object positioning architecture according to the features outlined above. Inside the table, a master control board connected to the interaction surface manages the communication with and tracking of the large set of external objects (known as pucks) as they are placed and moved on its surface. Acoustic ranging pings are used to locate the pucks, and information between the master and pucks is communicated via infrared transceivers. Piezoceramic transducers are affixed to the bottom-side four corners of the glass surface to transmit the ranging pings, and a frame consisting of eight infrared transceivers is placed around the edge of the interaction surface for communication. Each puck is equipped with an ultrasonic sensor to pickup the acoustic wave traveling through the glass, as well as an infrared transceiver for data communication. Figure 5.2 shows the layout of the sensors on the glass, and Figure 5.3 provides a diagram of the entire system.

The design and development of TViews was an iterative process that consisted of several passes of initial testing to identify the basic system components, electronics design for the pucks and master board, firmware design for the pucks and master board, software development of a position estimation approach and software development of an application programming interface (API). These steps in the design process are covered in the remaining sections of the chapter. The physical and aesthetic design of an encasing for the pucks and table are covered in the thesis appendices.

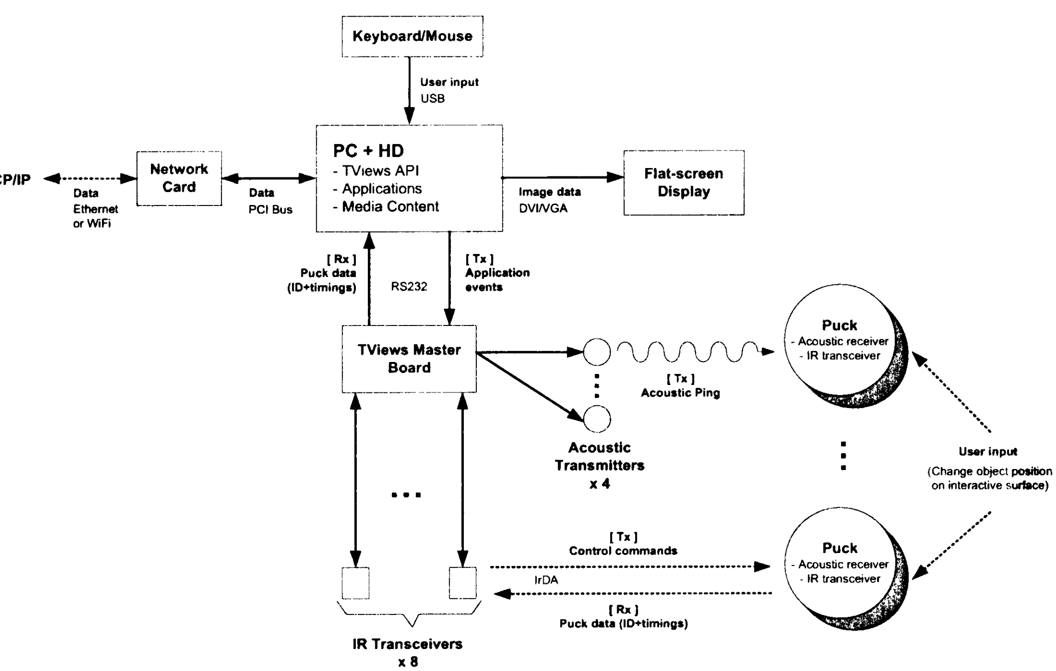


Figure 5.3: TViews system diagram

Block diagram illustrating the main components of the TViews table. The TViews master control board is located inside the table and manages the sensing of and communication with the interactive pucks present on the table at any given time. Data from the sensing system is sent from the Master board back to the PC, where it is decoded and used to control different kinds of media-related applications.

5.2 Initial Experiments

The general concept for the sensing part of the TViews system was to use a time-of-flight approach to locate the tagged objects on the surface of a glass panel by sending acoustic waves through the glass from fixed transmitters to receivers located in the base of the mobile objects. Through-glass acoustic transmission was selected in order to avoid the occlusion problems that arise with through-air transmission and multiple objects on the table at once.

The idea for the sensing approach was based on Professor Joe Paradiso's Tap Window project, a system for tracking taps and other impacts on large glass surfaces [Checka 2001, Leo 2002, Paradiso 2002, Paradiso 2005]. The first Tap Window used pick-ups made of Polyvinylidene Fluoride (PVDF) piezoelectric foil, and later small piezoceramic microphones. The pick-ups were mounted to a large glass window and were used to track a range of different of taps, from low-frequency knocks generated by the impact of a fist to sharp taps generated by a metal object. An early version of the project was used to track the impact of ping pong balls on a table during game-play [Ishii 1999]. In this implementation, small electret microphones were used to pick-up the sound, however these were found to be too sensitive to surrounding noise and provided poor coupling to the surface of the table.

An important difference between the TViews sensing approach and the previous work on the Tap Window and other acoustic tracking systems [Ing 1998, Devige 2003] is that TViews is used to track many objects on the table rather than a single tap at a time. In other words, the Tap Window is a passive approach, used to track impacts on glass, while the TViews table is used to track active objects on the glass. The acoustic receivers in the TViews system are placed in the base of the objects rather that affixed to the glass plate, while acoustic transmitters are affixed to the corners of the glass (where the receivers are mounted in the Tap Window). This reversal of the past approach enables the TViews system to scale to larger numbers of objects on the table without a significant reduction in the refresh rate of the object positions. A more detailed discussion of this is provided in Section 6.3.1.

One of the challenges of the Tap Window project was the need to track different kinds of acoustic impacts, such as knock or metal taps. The waves generated by these different kinds of impacts propagate via different modes and at different frequencies, and also have different dispersive effects. As a result, the characteristics of the first peak of the received signal can vary widely from one impact to the next, requiring complex signal processing in order to determine the exact location of the impact. The TViews system simplifies this, since the characteristics of the transmitted signal can be tightly controlled, resulting in simplified filtering and signal processing on the receiving end. The following subsections discuss the initial experiments that were performed to select the signal frequency and a functional combination of transmitters and sensors for the system.

5.2.1 Acoustic Tests

The initial experiments were performed with the setup shown in Figure 5.4. A function generator was used to drive an acoustic transmitter that was affixed to the glass at different frequencies. The receiver was mobile on the surface of the glass and the first arrival peak of the signal at the receiver was timed at different locations on the glass using an oscilloscope. Different combinations of transmitters and receivers were tested. Initial experiments were conducted on both 1/8" and 1/4" thick glass surfaces, however the 1/4" was eventually selected over the 1/8" since it provides a stronger surface for a large tabletop.

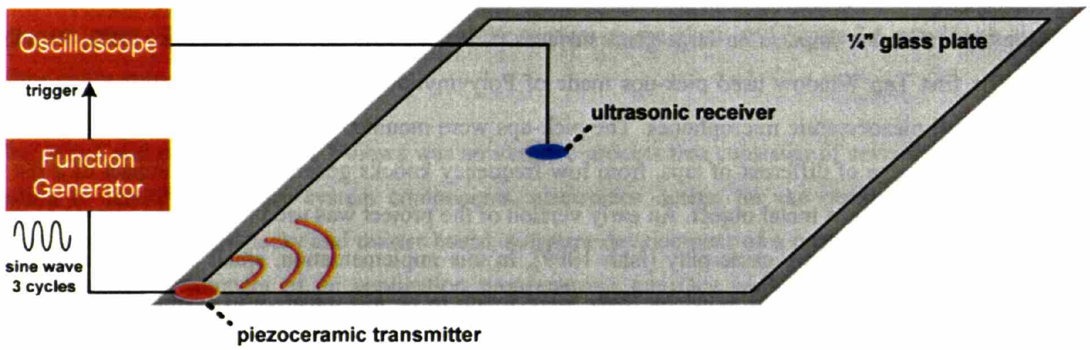


Figure 5.4: Acoustic experimental setup

Initial acoustic tests were conducted using a 1/4" thick glass plate with a piezoceramic transmitter affixed in one corner and a mobile ultrasonic receiver. Different combinations of transmitters and receivers were tested. A function generator was used to drive the transmitter with 3 cycles of a sine wave at different test frequencies.

For transmitters, we selected low-cost piezoceramic disc benders with a diameter of 20mm and attached them to the glass using a cyanoacrylate adhesive (crazy or super glue) as shown in Figure 5.5. In order to determine the optimal transmission frequency, we started at 40kHz (which is a common center frequency for many low-cost ultrasonic sensors) and tested for environmental effects. We found that by increasing the frequency well above 100kHz, we could significantly reduce the effects of background noises, such as tapping on the glass with metal objects or jingling keys in the vicinity of the sensor. Based on these observations, we selected a frequency of 160kHz for our initial tests. Since these piezoceramic disc benders are typically intended for low frequency applications, for instance as alarm clock buzzers, we provide their measured frequency response at 150-250kHz in Figure 5.6.

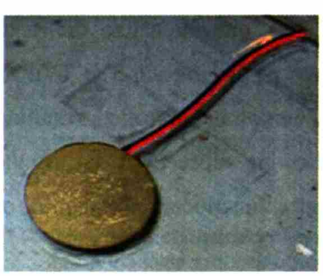


Figure 5.5: Piezoceramic transmitter

Low-cost piezoceramic disc benders were selected to transmit the signal through the glass and attached to the bottom side using a strong adhesive. The initial testing frequency was 160kHz.

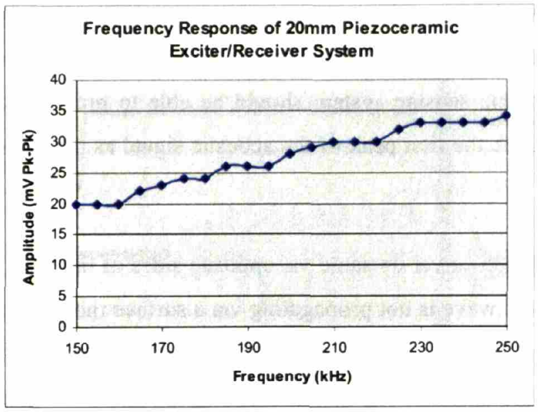


Figure 5.6: Frequency response of exciter/receiver system

This graph shows the measured frequency response from 150-250kHz of the 20mm piezoceramic exciter/receiver at 21cm apart.

While sound in air travels by compression and rarefaction of air molecules in the direction of travel, the molecules in solids can support vibrations in other directions. A number of different propagation modes of sound waves are thus possible in solids. The four principle types, based on the way the particles oscillate, are longitudinal waves, shear waves, surface waves and in thin materials plate waves [Auld 1990]. Longitudinal and shear waves are the two modes of propagation that are most widely used in ultrasonic testing. Longitudinal waves compress and decompress the material in the direction of motion, similar to sound in air. Shear waves vibrate particles at right angles compared to the motion of the wave. The angle at which the ultrasonic wave enters the material determines whether it will propagate via longitudinal, shear or both modes (illustrated in Figure 5.7). The velocity of shear waves through a material is approximately half that of the longitudinal waves.

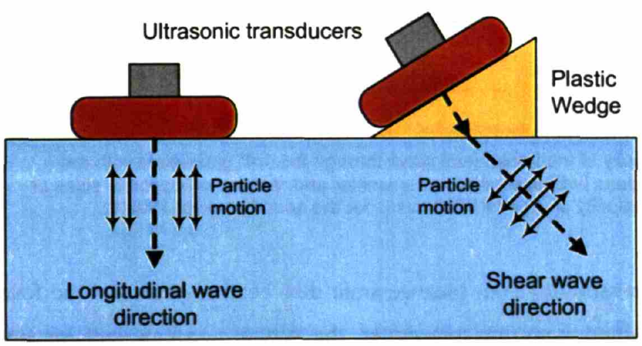
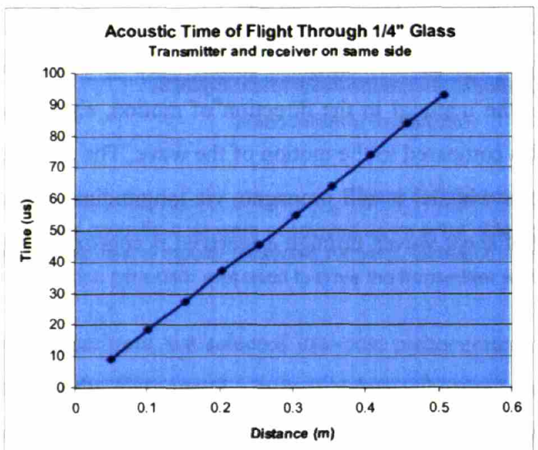


Figure 5.7: Wave propagation modes

Diagram illustrating the longitudinal and shear wave propagation modes in a solid material such as glass.

The phenomenon of dispersion relates to the variation of phase velocity with the frequency of a wave. Since glass is a dispersive medium, waves of different frequencies will travel through it at different velocities. We conducted experiments in order to determine the average velocity of our transmitted wave in the 1/4" thick glass plate. In the first experiment, the transmitter and receiver were placed on the same side of glass. In this case, we measured an average velocity of 5529.19 m/sec for the wave at a frequency of 160kHz. In the second experiment, the transmitter and receiver were placed on opposite sides of the glass. In this case, we measured an average velocity of 5564.36 m/sec. Figure 5.8 shows the distance vs. time plots of a sample set from each experiment. Based on these data sets, we estimated the wavelength to be roughly 35mm. Our data sets yielded a percentage error of 1.28% in the first experiment and 1.53% in the second experiment. Based on these numbers, the acoustic sensing system should be able to provide an accuracy of roughly 0.5mm if the pucks can reliably track the first peak of the acoustic signal as it travels through the glass.

Given that the results of the two experiments (transmitter/receiver on same vs. opposite sides of the glass) are roughly the same, we can conclude that the measured wave is not propagating via a surface mode. The speed of sound in glass is typically within the 4000-6000 m/sec range depending on the frequency of the wave and the type of glass used. In our experiments, the ultrasonic wave entered the glass at a 90 degree angle (as illustrated on the left side of Figure 5.8) and propagated at a velocity of roughly 5550 m/sec. Based on these two facts, we speculate that the measured acoustic wave was propagating via a bulk longitudinal mode.



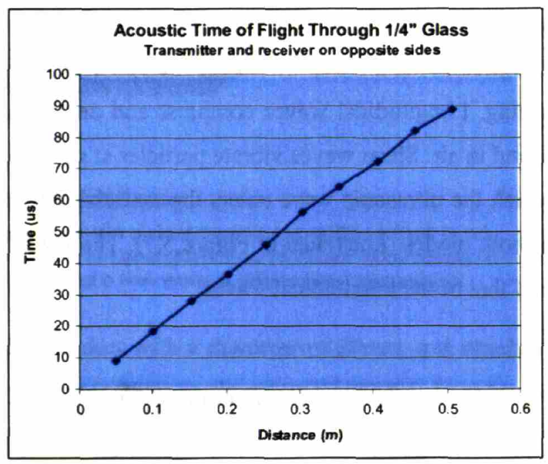


Figure 5.8: Initial acoustic tests

Experiments were conducted to measure the velocity of the transmitted wave through the 1/4" glass plate with the transmitter and receiver on the same side of the glass (left) and with the transmitter and receiver on opposite sides of the glass (right). The results yielded an average velocity of around 5550 m/sec for the sound wave at 160kHz.

In the TViews system, acoustic pings are transmitted from piezoceramic disc benders placed at the four corners of the glass. When a ping is transmitted from one transmitter, the system needs to wait for any acoustic reflections in the glass to die down before transmitting a ping from the next transmitter. In order to determine an appropriate waiting time between pings, we conducted an experiment to measure the duration of the acoustic reflections. The tests showed on the order of 4-5 milliseconds of reflections. Based on these results, we determined that a delay of roughly 6 milliseconds would ensure that the reflections from one ping did not interfere with the transmission of the following one. The oscilloscope screenshots in Figure 5.9 show the waveform of the received ping and the duration of the reflections.

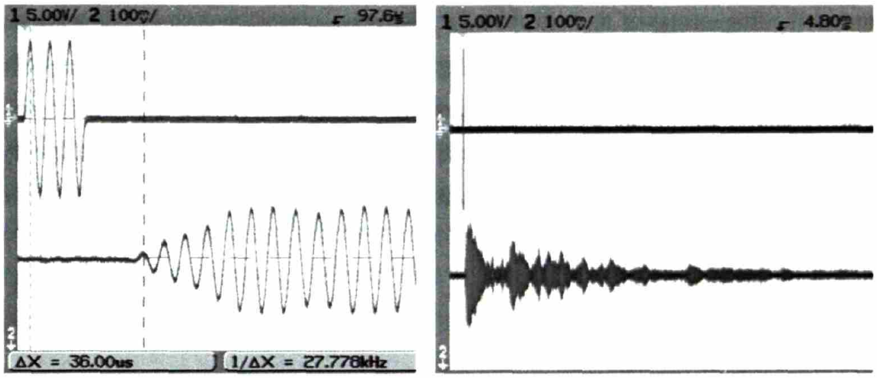


Figure 5.9: Received acoustic signals

Oscilloscope traces showing the acoustic signal transmitted and received through the glass and the resulting reflections and dispersion.

5.2.2 Sensor Selection

We tested a range of different pick-ups in order to choose a sensor that was appropriate for the TViews system. The sensor needed to be sensitive enough to pick up the signal traveling through the glass without picking up too much noise from other objects placed on the table or nearby sounds. Based on our tests, we narrowed our search to the two types of sensors describe below, which were used in the two different versions of pucks designed for the system (see Figure 5.10).

Figure 5.10: Sensors and pucks

The first version of pucks (bottom left) used piezoceramic disc benders to detect the transmitted signal (top left). These pucks are 5cm in diameter and weight 295 grams. The second version of pucks (bottom left) instead used ultrasonic air transducers (top right). These pucks are 4.75cm in diameter and weigh 130 grams.

It is worth noting here that the frequencies of the transmitted signal were selected to accommodate the two different types of sensors in each puck design. In the first case, we used a frequency of 160kHz as in the initial acoustic tests described in 5.2.1. For the second iteration of pucks, we needed to switch to a transmission frequency of 200kHz based on the center frequency that particular sensor. At this frequency, we measured a propagation velocity of roughly 4800 m/sec for the acoustic wave traveling through 1/4" thick glass.

Piezoceramic Disc Benders

The first sensor selected for the TViews system was a piezoceramic disc bender identical to the one used to transmit the acoustic signal. Piezoelectric sensors convert electrical energy into mechanical and vice versa, and as such can act as both transmitters and receivers [APC 2002].

Piezoceramic disc benders deform as illustrated in Figure 5.11. We found that the sensor needed to be sitting flat on the surface of the glass in order to receive the signal traveling through the glass. Moreover, a certain amount of pressure needed to be applied to the sensor in order for it to make good contact. For this reason, a weighting mechanism (shown in Figure 5.13) was designed to ensure that the pucks made proper contact with the glass surface.

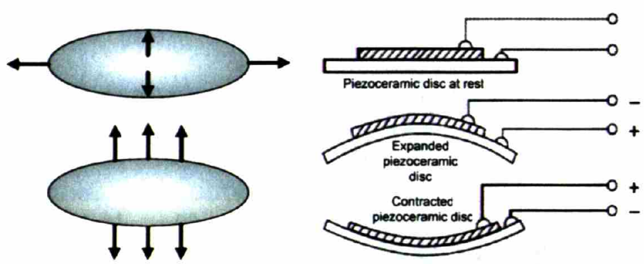


Figure 5.11: Disc bender vibration

The left side illustrates the modes of vibration of a piezoceramic disc. The right side illustrates the distortion of the diaphragm.

We also found that these sensors performed poorly when the puck was moved around on the glass and could only reliably read the signal when they were standing still. We speculated that this was due to a slip-and-stick problem, causing them to lose contact with the glass as they were moved. For this reason, we worked on a second version of the pucks using ultrasonic air transducers.

Ultrasonic Air Transducers

For the second version of puck design, we selected model 200KHF18 piezo transducers made by SensComp. These have a closed face sealed construction and a center frequency of 200kHz. The front coating (Teflon material) is intended to impedance match with air, however we found that it couples well into the glass surface as well. These transducers provide greater sensitivity allowing significantly improved pickup of the acoustic wave traveling through the glass, even when the receiver is mobile (see Figure 5.12).

Also, the sensor is less sensitive to lower frequency signals, which means that background noise poses less of a problem than with the piezoceramic disc benders.

While the coating provides good matching into the glass and very little pressure is required, the sensor still needs to maintain contact in order to receive the signal. We explored the possibility of using a non-contact transducer to pick-up the signal, but found that existing piezo sensors with the sensitivity required for this task are still very expensive. In the future however, this might be a worthwhile direction of research to pursue for the project.

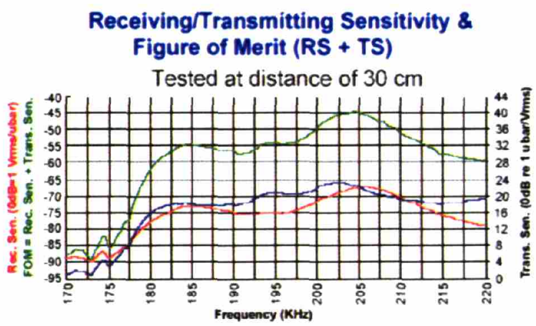


Figure 5.12: Transducer sensitivity

This graph shows the receive and transmit sensitivity of the SensComp 200KHF18 piezo transducers.

Based on our initial experiments with different kinds of sensors, we determined that we would need to construct a good signal filter and amplifier for the puck. The design of the electronics for the TViews system is described in the following section.

Size and Weight

The size and overall physical design of the two puck versions depended on the particular sensor used in each case. The piezoceramic disc benders used in the first version are 20mm in diameter, while the ultrasonic transducers used in the second version are 18.5mm in diameter. The size of the pucks could be potentially as small as the sensors used in each case, however additional size was needed in order to accommodate the hand-soldered circular circuit boards within the pucks. The first version pucks are 5cm in diameter, while the second version pucks are 4.75cm in diameter.

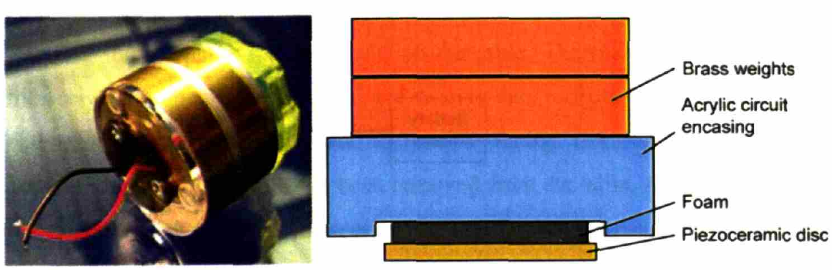


Figure 5.13: Puck weight

A weighting mechanism was designed for the pucks in order to ensure proper contact of the sensor to the glass surface.

In each case, the pucks also required some additional weight to ensure that the sensor would make good contact with the glass surface. A weighting mechanism was designed using brass rings. The design for the first version of pucks is shown in Figure 5.13, and when assembled these weighed 295 grams. As we have already mentioned, the sensor in the second version of pucks provided better coupling into the glass and as a result the design required less overall weight. For this reason, the pucks were decreased to a weight of 130 grams when assembled.

5.3 Electronics Design

The TViews system electronics include the master control board which is housed within the table and the sensor tags which reside within the mobile interactive objects called pucks. The design of the circuits for these circuits is described here.

5.3.1 Master Board

The master board controls the sensing and communication with the puck objects on TViews table and communicates the puck ID and position information to a PC via the RS-232 serial protocol. The master board is based on a microcontroller PIC16F877A chip. The block diagram in Figure 5.14 illustrates the different circuit parts. The amplifier/filter and infrared circuit components are discussed below.

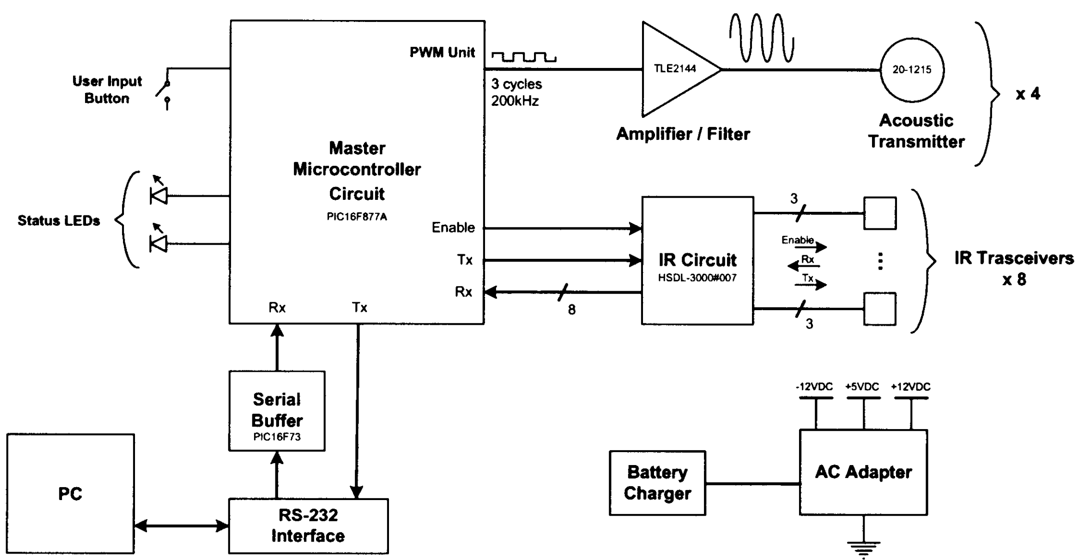


Figure 5.14: Master control board
Block diagram illustrating the different parts of the master control board circuit that is housed inside the TViews table.

Amplifier/Filter

A positioning cycle in the TViews system consists of a sequence of four pings, transmitted via each of the four piezoceramic transmitters in turn. The pulse width modulation (PWM) unit of the PIC microcontroller is used to generate three cycles of a square wave with a fundamental frequency of 200kHz. This signal is then sent through an amplifier and filtering circuit. The signal is amplified to a level of around 20V peak-to-peak. A band-pass filter is used to remove most of the harmonic frequencies, leaving only a 200kHz sine wave at its output.

Infrared Communication

Infrared was selected as the data communication method for the TViews table based on its low cost, small size, and low power requirements. We use one Agilent HSDL-3000 infrared transceiver in each puck and eight identical transceivers around the edge of the display area (see IR sensor layout in Figure 5.2).

The HSDL-3000 has a small form factor and low-profile. It provides a shut-down feature to achieve very low power consumption, and requires a supply voltage of at least 2.7V. Together these features made it a good choice for the small battery-powered puck circuits (see Section 5.3.2 for a discussion on the Puck circuit design and power issues).

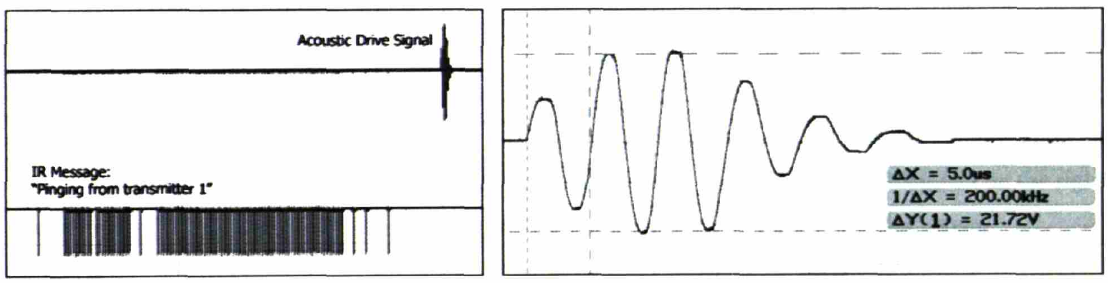


Figure 5.15: IR message and acoustic drive signal

An IR message is broadcast by the master board to notify the pucks on the table that an acoustic signal is being sent to a specific transmitter. The acoustic drive signal follows immediately (left side). A close-up of the acoustic drive signal shows that it has a frequency of 200kHz and an amplitude of roughly 20V peak-to-peak (right).

Another reason for selecting infrared for data communication was based on the potential it provides for inferring the orientation of the pucks on the table. The master board could keep track of which infrared transceivers are being used to send and receive data to/from a given puck, and then use this information to determine roughly which direction the puck is facing. Infrared also provides a simple way for the master board to detect when a puck has been removed from the table. As soon as the puck is removed it falls out of line-of-sight of the infrared transceivers in the table, which causes it to stop communicating. Of course, the line-of-sight requirement can also cause problems if a puck on the table is completely obscured by other objects. From our tests, we have not found this to be an issue. The eight transceivers around the edge of the table provide complete coverage and the acrylic encasing for the puck circuitry helps to reflect the infrared transmissions. As a result the infrared transmissions are unlikely to be blocked unless a puck is completely surrounded by opaque objects from all sides. An alternate approach for data communication that does not require line-of-sight would be to use radio, such as Bluetooth. However Bluetooth typically drains up to 30mA of current during data transfer, compared to 12mA for the infrared transceivers that are currently used in the system. Ideally, a lower power radio solution would be needed to maximize the active lifetime of the pucks during one battery charge cycle.

5.3.2 Puck

The puck circuit needs to be able to detect the incoming acoustic signal that is transmitted through the glass surface. The sensor used in the final version of the puck design is the SensComp 200KHF18 ultrasonic piezo transducer described in Section 5.2.2. The puck circuit is based on a microcontroller PIC16F628A chip. Each puck stores its own digital ID value, which is transmitted to the master board along with the time-of-flight measurements of the acoustic pings. The diagram in Figure 5.16 illustrates the different circuit parts. The amplifier/filter component of the circuit and the issue of power are discussed below.

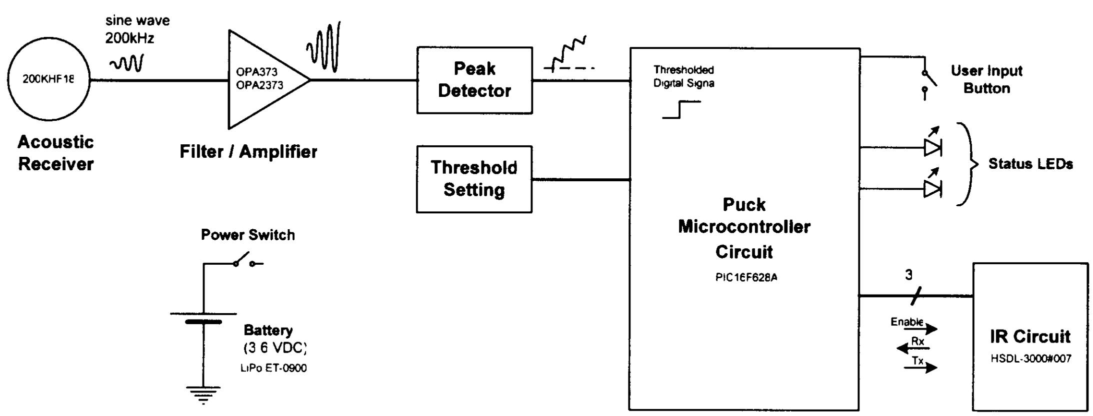


Figure 5.16: Puck circuit
Block diagram illustrating the different parts of the puck circuit.

Filter/Amplifier

The puck uses a signal thresholding approach to detect the incoming signal based on the maximum of the first arrival peak. The threshold can be manually tuned for each puck with a potentiometer. The threshold setting is typically around 250mV, a value that is above the noise floor but also well below the usual amplitude of the first peak of the incoming signal. Our initial tests described in Section 5.2.1 found that the average position error for a puck is very small (on the order of 0.5mm) as long as the pucks can reliably track the same peak of the incoming signal at every ping cycle.

The SensComp ultrasonic transducer used in the circuit has a selective frequency response centered around 200kHz. Nevertheless it still seems to pick up a certain amount of background noise which needs to be filtered out and then amplified. We use a first order Butterworth band-pass filter, which requires only a single operational amplifier (op-amp) thus allowing us to keep the puck's footprint as small as possible and its power requirements as low as possible. This filter has a center frequency of 201.2 kHz and a gain of 19dB. The 3dB bandwidth of the filter is 163kHz to 230kHz (see Figure 5.17).

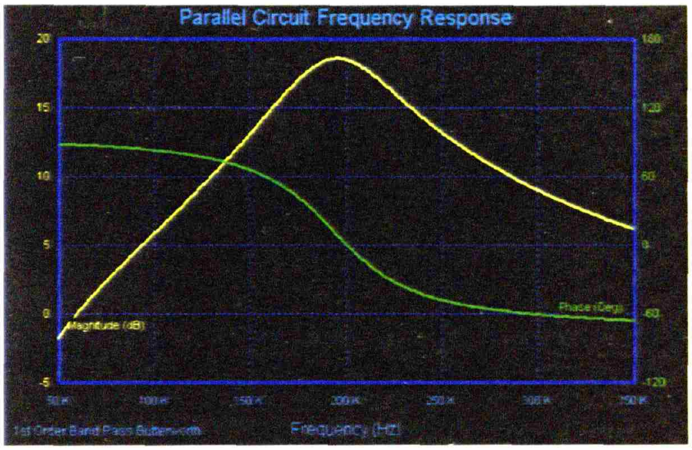


Figure 5.17: Frequency response of puck bandpass filter

The puck bandpass filter has a center frequency of 201.2kHz and a gain of 19dB.

Next, the signal is passed through two op-amp gain stages that have a combined gain of 43dB. This means that at the 200kHz center frequency, the puck's three op-amp filter/amplifier system has a total gain of 62dB. Finally, the signal is passed through a voltage doubling detector which keeps only the positive going cycles of the signal. The output from the peak detector is then compared to the threshold voltage using an on-board comparator on the PIC microcontroller. The peak detector is illustrated in the diagram on the right side of Figure 5.18. The left side shows the output of the peak detector on an oscilloscope screen.

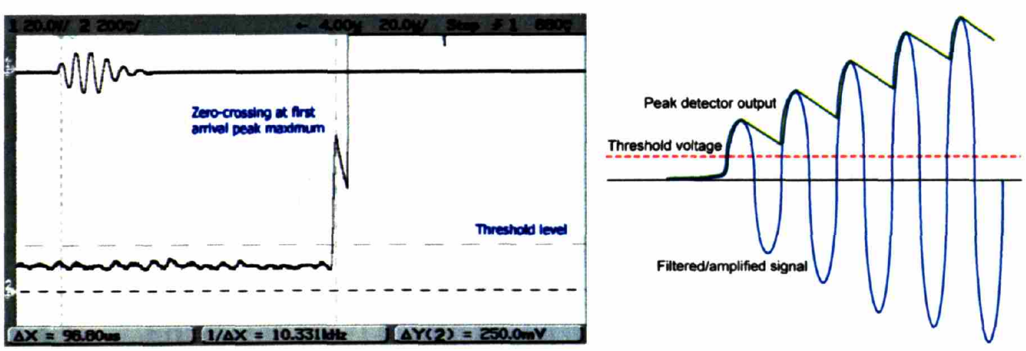


Figure 5.18: Puck circuit peak detector

The output of the peak detector portion of the puck circuit is shown on the left. The noise floor ranges around 150mV, so the threshold voltage can be set around 250mV, as indicated by the upper horizontal dotted line. The peak detector takes only the positive going cycles of the incoming signal, as illustrated by the diagram on the right, so thresholding is done on the first arrival peak of the incoming signal.

Battery Power

The average current drain of the puck circuit is around 12-15mA when active (i.e. when sending/receiving infrared data). The major components on the circuit (infrared transceiver, operational amplifiers and microcontroller) were all selected to have a shut-down or sleep feature. Whenever the puck stops receiving messages from the table for more than a couple of seconds, it will go into power save mode. When asleep, the puck's the current drain drops to under 50uA.

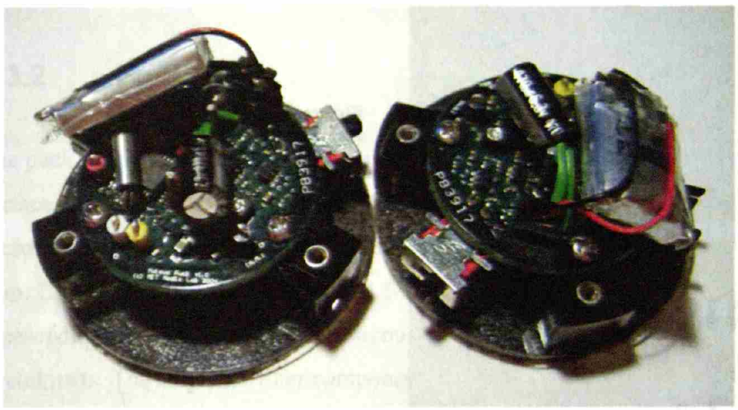


Figure 5.19: Pucks with battery

The puck circuit is a round disc of roughly 1" in diameter. Two pucks are shown here with E-Tec 90mah lithium polymer batteries attached.

The components on the puck all require a 3-5V supply voltage. We found that the IR transceivers stopped transmitting data properly if the voltage dropped much below 3V. For this reason, we needed a battery that could supply 3V consistently over the course of its lifetime or over one charge cycle. We also wanted to use rechargeable batteries so that users wouldn't need to change batteries all the time. Instead, a charger could be provided with the table and pucks could be recharged as needed.

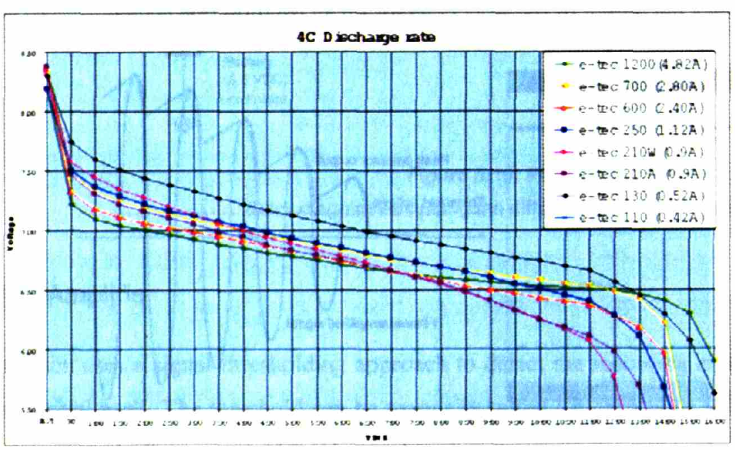


Figure 5.20: Battery discharge

We use E-Tec Hi-Output Lithium Polymer batteries which provide a good discharge rate for the pucks.

We selected E-Tec Hi-Output Lithium Polymer batteries for the puck circuit based on their small voltage and good discharge rate (see Figure 5.20). The cells are rated at 90mah with up to 0.5A discharge. The maximum permissible charge voltage per cell is 4.2V. Given the power consumption of the puck circuit, we estimate that a complete battery charge cycle will provide around 6 hours of active use. Since lithium polymer batteries can be damaged if they are allowed to discharge below 3V, a battery monitor was incorporated into the puck circuit. If the supply voltage is too low, the puck goes into shut-down mode and periodically flashes a red LED to indicate that it needs to be charged. Figure 5.19 shows the puck circuit with a Lithium Polymer battery attached.

5.4 Firmware Design

The control system managed by the master board consists of the three main algorithmic processes illustrated in Figure 5.21 that are used to enumerate and locate the pucks on the table. The system relies on the communication of data between the master board and pucks via infrared, and special messaging format has been designed for control and communication purposes. The TViews firmware was implemented in the Assembly language. The algorithms and message format are described here.

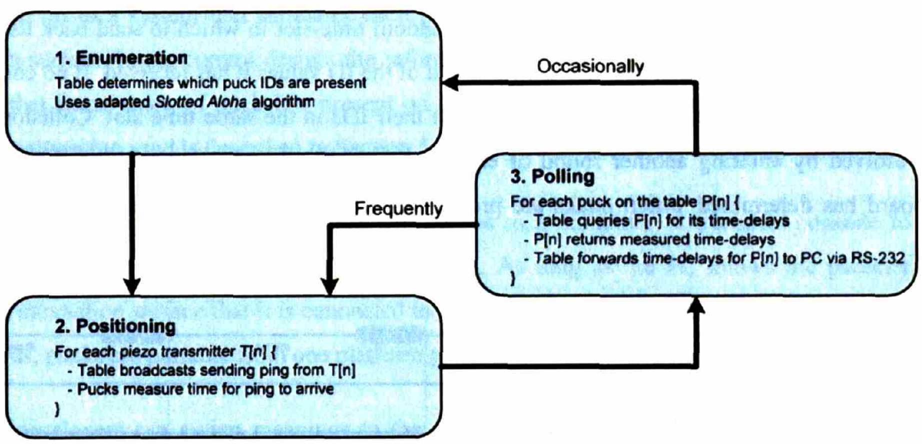


Figure 5.21: Firmware processes

The firmware on the puck and master boards consists of the three main algorithmic processes illustrated here. Enumeration is used to determine which pucks are present on the table. This is followed by the positioning and polling algorithms which are used to locate the pucks on the table. Every once in a while the system repeats the enumeration process to rebuild the list of current pucks.

5.4.1 Enumeration

Each puck contains a unique digital ID, currently represented by a 64-bit number. Given this large namespace of ID values, the master control board needs to determine which particular puck IDs are on the table at any given time.

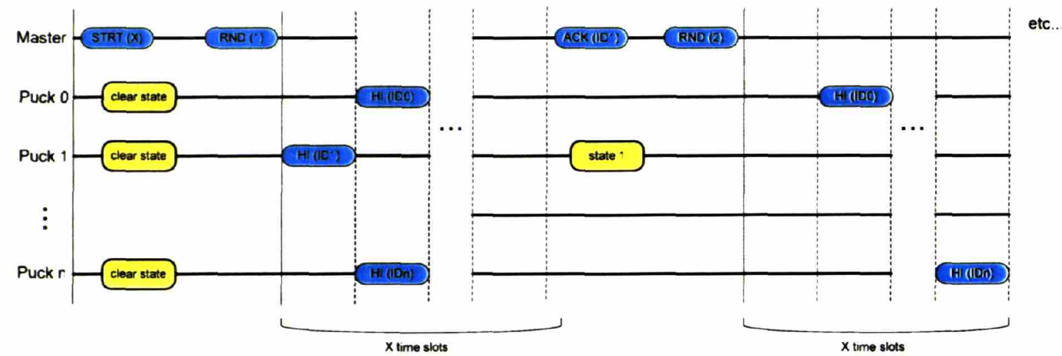


Figure 5.22: Enumeration process

The enumeration process is based on the Slotted Aloha Algorithm. Pucks announce their presence by transmitting their IDs during a randomly selected time slot of the enumeration round. Collisions occur if two pucks send their IDs during the same time slot, such as the one highlighted above. Another round of enumeration is then needed in order to resolve the collision.

Puck enumeration (illustrated in Figure 5.22) is accomplished using a variation of the Slotted Aloha algorithm [Abramson 1970, Roberts 1972]. When the master control board initiates a round of the enumeration procedure, it asks each puck to select a random time-slot in which to send back its ID value. At the end of the round the master asks for confirmation of the ID values it has received. If no confirmation is received, it means that two or more pucks have sent their IDs in the same time slot. Collisions such as this are resolved by entering another round of enumeration until all pucks are accounted for. Once the master board has determined which pucks are present on the table, it can then determine each of their locations.

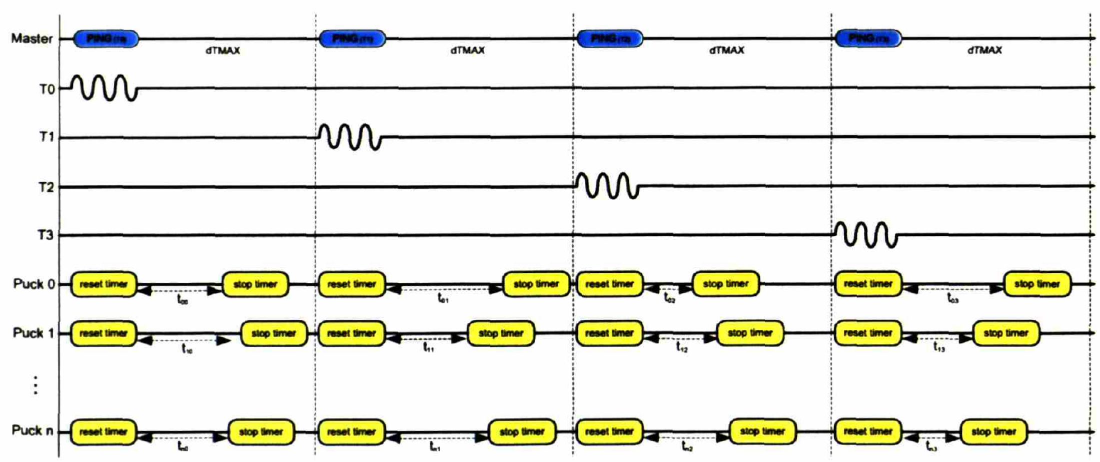


Figure 5.23: Polling process

One polling cycle is shown here. For each of the four transmitters, the master board broadcasts a message to the pucks on the table and transmits the acoustic ping consisting of 3 cycles of a sine wave at 200kHz. Each puck times the duration that it takes for the ping to reach its sensor and stores the value.

5.4.2 Positioning

The master board controls the timing and transmission of ranging pings in sequence from each of the piezoceramic transducers affixed to the glass. Before sending each ping, the master broadcasts a message to all the pucks on the table via IR that tells them to start their internal timers. Each puck stops its timer when it detects the arrival of the acoustic signal and stores the time-of-flight measurement. At the end of the positioning round, each puck has stored four values corresponding to the time-of-flights of acoustic pings traveling from each of the four piezo transmitters. The positioning process is illustrated in Figure 5.23.

5.4.3 Polling

Once the master board has identified all the pucks on the table and has transmitted a series ranging pings, it needs to gather the time-of-flight information from each puck. In the polling procedure, the master board asks each puck in sequence to return all four of its stored time-of-flight values. The master relays this information on to a system that estimates each puck's (x,y) position within the coordinate space of the interaction surface. In the current design, the information is relayed via the RS-232 protocol to a program on a PC that keeps track of puck IDs present on the table and triangulates their positions. The position estimation algorithm used is described in Section 5.5.

By off-loading the computation of position coordinates to a computer, it becomes possible to scale the interaction surface to different sizes and aspect ratios. As long as the PC knows the parameters of the particular interaction surface that it is connected to, it can resolve the identity and positions of any puck. In other words, pucks are portable from one platform to another regardless of size and scale.

Software developers can assign meanings to the pucks within an application environment, allowing the pucks to act as controls for the digital information space. The display placed beneath the glass interaction surface acts as coincident visual output for the placement and movement of pucks on the table. The pucks may thereby be associated to different graphical or multimedia elements within the on-screen environment.

5.4.4 Message Format

TViews uses a specially developed messaging format for bidirectional data communication between the master board, pucks and PC. The messages are 120 bits long and are parsed according to their operation type, an 8-bit value that follows immediately after the 16 bit header. A checksum at the end of each message verifies that the received data is accurate. The message format is designed to allow the eventual incorporation of custom message formats from external I/O devices that might be attached to the puck, such as buttons, dials or small displays. In the current implementation we have included a button add-on as well as LEDs on each puck that can be controlled by the PC inside the TViews table.

Messages sent from the master control board come in two forms: as broadcast messages, or as specific messages that address a single puck. The master sends broadcast messages to announce the transmission of an acoustic ranging ping, to announce the beginning of the enumeration process, and to announce the beginning of each separate enumeration round within the process. The messages sent to a single puck are specific commands for resetting its system state, polling for its time-of-flight measurements, or acknowledging its presence on the table. The master board also sends a "puck removed" message to the PC if it receives no response to one of these commands, since this means the puck has been removed from the interaction surface.

A puck responds to the commands of the master board in order to transmit its ID value, return its stored time-of-flight measurements, or confirm that its presence has been acknowledged on the table. The master board forwards the puck's time-of-flight measurements and ID value to the PC, where its current location is updated in software. The 64-bit ID value used to distinguish each puck could potentially also be used to classify the objects according to different kinds of data, such as the manufacturer, specific application package, or object type. Applications on the TViews table could then make use of this classification information to filter non-relevant puck IDs that happen to be placed on the table. Figure 5.24 shows the TViews message format and a potential breakdown of the puck identification number.

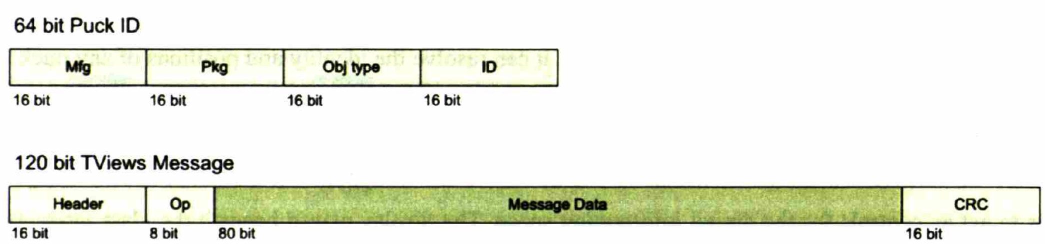


Figure 5.24: ID and message format

The TViews system uses a 64-bit puck ID. This number can be used to classify interactive objects by manufacturer, application package or object type as shown here. The messages transmitted between the master board, pucks and PC are 120 bits long and include a header, an operation value, 80 bits of message data and a checksum.

5.5 Position Estimation

In this section, we describe the real-time algorithm that is used to determine the exact location of the pucks as they move around on the surface of the table. The time-of-flight measurements gathered from the acoustic pings are first transformed into (x,y) coordinates using a range-circles method. The computed position values are then tested against a history filter which is used to eliminate any small changes in the measurements that might make the graphical display seem shaky. Finally, a calibration routine is used to generate a transform between the table coordinates (in millimeters) and display coordinates (in pixels). The position estimation is currently implemented in Java.

5.5.1 Position Calculation

The first stage of the position estimation is done using an acoustic ranging method. The pucks measure the time-of-flight of the acoustic pings from each of the four transmitters located at the corners of the table. The coordinates of the four transmitters are known values for any given table, and are based on its particular size. The velocity of the transmitted signal through the glass is also a known value, and was determined experimentally for the existing TViews implementation (see Section 5.2.1). The distance of a puck from the four transmitters can thus be determined based on the measured time-of-flight of the signal as follows:

Transmitter i position coordinates:	$(x_i, y_i) \quad i = 0,1,2,3$
Time-delay from transmitter i to puck:	Δt_i
Sound propagation velocity:	v
Distance from puck to transmitter i:	$r_i = v \times \Delta t_i$

This yields a system of four non-linear equations or "range circles" in puck coordinates (x, y):

$$(x - x_i)^2 + (y - y_i)^2 = r_i^2 \qquad i = 0,1,2,3$$

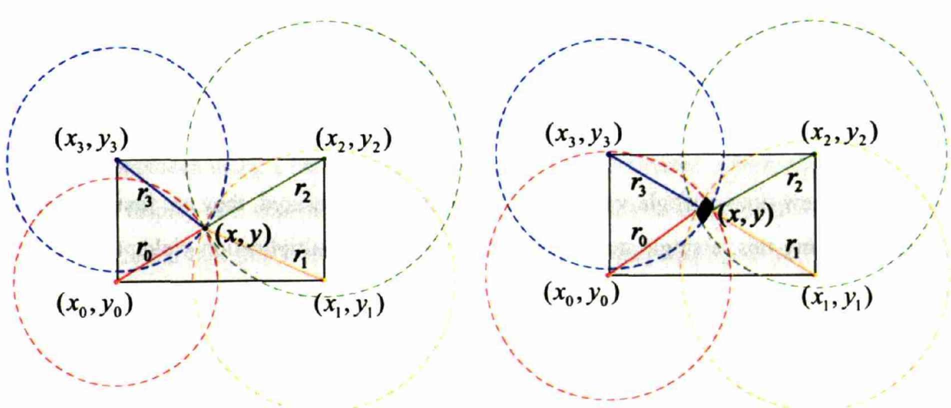


Figure 5.25: Range circles

These range circles illustrate the ideal solution point for a puck on the position table if the time-of-flight measurements are exactly accurate (left) and the more likely case of solution area due to measurement errors (right).

Since we have four equations and only two variables, the system is over-determined. Due to errors that might arise in the time-of-flight measurements, this system is unlikely to yield a unique solution. Figure 5.25 shows an ideal solution point at the intersection of the range circles on the left, and the more likely case of a potential solution area on the right. In order to find a unique solution from on this set of possible solutions, we need to use an error minimization method that will provide the best approximation for the (x,y) position.

Position Solution

The current approach used by the TViews table reduces the four non-linear equations to a system of three linear equations by subtracting the latter three from the first and thus eliminating the squared terms:

$$(x-x_0)^2-(x-x_i)^2+(y-y_0)^2-(y-y_i)^2=r_0^2-r_i^2 \qquad i=1,2,3$$

Or more simply:

$$2(x_i-x_0)x+2(y_i-y_0)y=(x_i^2-x_0^2)+(y_i^2-y_0^2)+(r_0^2-r_i^2) \qquad i=1,2,3 \quad (*)$$

This can be represented in matrix form as follows:

$$\begin{bmatrix} 2(x_1-x_0) & 2(y_1-y_0) \\ 2(x_2-x_0) & 2(y_2-y_0) \\ 2(x_3-x_0) & 2(y_3-y_0) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} (x_1^2-x_0^2)+(y_1^2-y_0^2) \\ (x_2^2-x_0^2)+(y_2^2-y_0^2) \\ (x_3^2-x_0^2)+(y_3^2-y_0^2) \end{bmatrix} + \begin{bmatrix} (r_0^2-r_1^2) \\ (r_0^2-r_2^2) \\ (r_0^2-r_3^2) \end{bmatrix}$$

This can be solved as follows:

$$AX=B+R$$
$$\Rightarrow X=(A^TA)^{-1}A^T(B+R)$$

Since the transmitter coordinates are known, the matrices $(A^TA)^{-1}A^T$ and B can be pre-computed.

When each set of four new time-of-flight values for a given puck is measured, they are first converted into distance values. Following this, a single matrix addition and matrix multiplication yields the puck's (x,y) position estimate.

This method of computing (x,y) minimizes the square of the distance between the lines expressed by the linear equations in (*) and the estimated position and is known as the *linear least-squares* estimation approach. Figure 5.26 shows the solution which results from linearizing the system of equations.

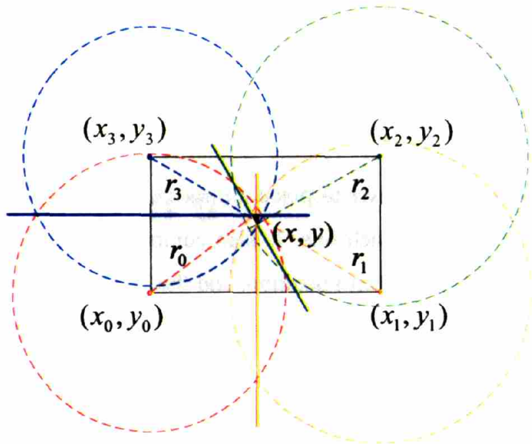


Figure 5.26: Linearized position solution

The range circles equations are subtracted to create system of linear equations that can be solved using a linear-least square approach.

It is worth noting here that since the system of linear equations in (*) is still over-determined, we can potentially use only three of the range circles to find a position solution. The positioning algorithm in fact begins by rejecting any time-of-flight measurements that result in distances that would be outside the space of the table. As long as there are three good measurements in any given ping cycle, a position solution is provided. The ping cycles with two or more bad measurements are ignored.

5.5.2 History Filter

As described above, the linear least-squares approach is not very computationally intensive and yields a reasonably accurate position estimate given reasonably accurate time-delay values. The problem arises in the cases where the measured time-delays are largely inconsistent with one another or with previous values and resulting in a large error in the position estimate. These errors will cause visible jumps or shakiness in the display of puck positions on the table's embedded screen.

For this reason, there needs to be an additional means of filtering bad data. The current approach used by the TViews table is a simple smoothing filter which saves a small shifting history window of past position values. Outliers are rejected by taking the median value over this small window of sequential estimates. We first tried this approach using a history window of 15 position estimates, which caused a noticeable lag in a puck's position display as it was moved around the table. We then reduced the history window to 7 position estimates, and found that this resulted in a considerably smoother display of positions without noticeable lag as long as the pucks are not moving too quickly. This simple filtering method has proved sufficient for our purposes at the moment, however it would eventually be worthwhile to examine the use of more sophisticated data filtering methods, such as recursive filters like the *Kalman filter* which can predict the state of a model in the past, present and future.

5.5.3 Calibration

A calibration routine has been implemented in order to determine the mapping between the table coordinates in millimeters and the display coordinates in pixels. This routine is similar to the type of calibration systems used by many touch screen devices. It asks the user to place a puck at three different points on the table surface and gathers position measurements for each one. It then computes the affine transformation matrix between the coordinate space of the measured (x,y) position, and the known display coordinate space. The calibration information is saved into a configuration file which is loaded by any application that runs on the table.

5.6 TViews API

The application programming interface (API) for the TViews platform is implemented in Java and runs on the PC housed inside the table. It allows developers to easily create different kinds of media applications that make use of the combination of real-time object tracking and embedded display. The API software keeps track of the incoming serial messages from the master control board and parses them into three main types of events: puck ID added, puck ID removed and puck ID updated.

The API employs a Java event model to fire notifications about these events to any applications that have registered themselves as listeners on the TViews platform. In the case of the puck updated event, it is first passed through the position estimator, which converts the puck's time-of-flight measurements into (x,y) coordinates as described in Section 5.5. The API can be extended to incorporate additional events to notify the application about user actions that make use of any external I/O devices that might be attached to a puck such as a button press. The API will eventually be extended to include support for bidirectional messaging, which would allow the application send messages to the pucks or to control specific properties. For instance, a puck might flash to draw attention. Or if the puck is equipped with a small add-on display, the application might send a text, picture or video message. Chapter 7 discusses some of the applications that have been implemented for the TViews table. The following chapter evaluates the overall technical performance of the system.

Chapter 6

6. Technical Evaluation

This chapter describes the evaluation and performance of the acoustic-based sensing system described in the previous chapter. We begin by evaluating the accuracy of the positioning approach and consider how it compares to the accuracy found in the Tap Window system, which provided the initial inspiration for our method. Next we examine the problem of acoustic losses resulting from sensitivity to background effects or the movement of the sensors on the interaction surface. Finally, we consider the scalability of the system in terms of the number of tracked objects and the size of the interaction area. In particular, we consider how signal attenuation might affect scalability in terms of size.

The tests described here all used an automated data collection program to record information about the position and movements of one or more pucks on the interaction surface. The data gathered included the original time-of-flight values and display positions, as well as the final positions after the history-based smoothing filter. For this reason, our measurements are given in pixel coordinates. The display used in the current implementation of the TViews table is a Samsung LT-P326W 32" display. One pixel corresponds to a size of 1square millimeter.

6.1 Position Accuracy

In order to evaluate the accuracy of the sensing approach across the entire area of the TViews table, a puck was placed at nine different locations around the table. At each location, 500 data samples were gathered and analyzed. Figure 6.1 shows a plot of the puck positions at the nine different locations, before and after the smoothing filter. The + symbols denote the actual position of the puck. The precision is the standard deviation for the distances of each data sample at a particular point from the actual puck position. The accuracy represents the distance from the mean position of all data samples at a particular point to the actual puck position. Before providing the results of the precision and accuracy tests, it is worth making a note here about the latency of the system. In the current implementation, a ping is transmitted every 7 milliseconds. After four pings are transmitted (i.e. after 28 milliseconds) the puck's time-of-flight measurements are transmitted to the PC via serial connection and a position estimate is calculated. This means that a new position estimate can in theory by generated every 28 milliseconds. The current implementation of the position estimation algorithm is written in Java, which increases the delay of the final graphical output by at least 2 or 3 times. To improve the latency of the final graphical output, the position estimation could eventually be implemented at the hardware level or as a device driver for the operating system rather than as high-level software.

For the raw position data, the standard deviation ranged from 2.21mm to 21.55mm, with an average standard deviation of around 6.39mm. This corresponds to a percentage error of 1.06% on average. From examining the data plot, we notice that the position estimates are considerably more reliable on the right side of the table. This might be due to an improper attachment of one of the left-hand transmitters to the glass surface, which could cause variation in the propagation of the sound wave from one ping to the next. It would also account for the relatively large difference in minimum and maximum standard deviation values.

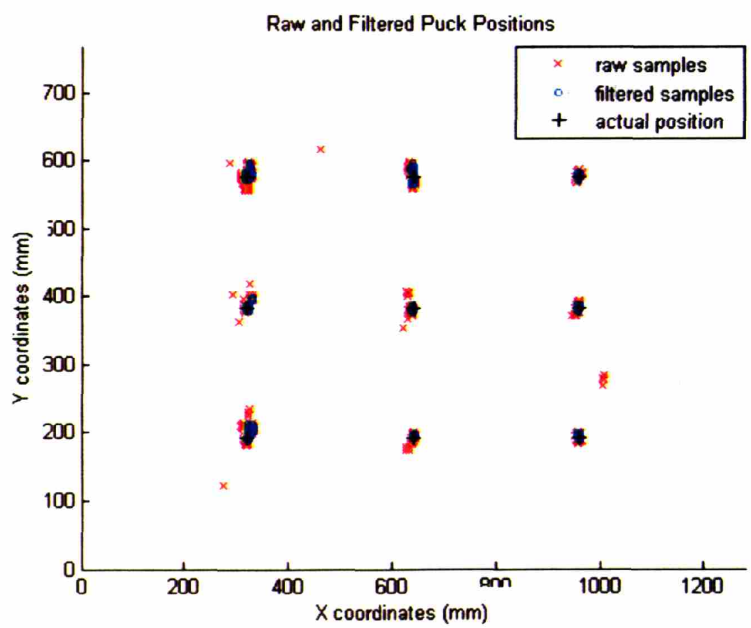


Figure 6.1: Raw and filtered position plot

This graph shows a plot of the raw and filtered puck positions at nine different points on the TViews table. We notice a significant improvement of the filtered data (blue circles) over the raw samples (red crosses). In particular, the extreme outliers have been completely rejected by the filtering algorithm.

For the filtered position data, the standard deviation ranged from 1.18 to 5.75, with an average around 2.47mm which is corresponds to a percentage error of 0.42%. This represents a considerable improvement over the raw sample precision, and demonstrates the effectiveness of even a very simplistic filtering algorithm. It should also be noted that the filtering algorithm does a good job in rejecting the extreme outliers from the raw position data, as can be seen on the plot in Figure 6.1. The raw data outliers correspond to the red crosses that are far removed from the actual puck positions. We see no filtered samples (blue circles) far from the actual positions.

The plots in Figure 6.2 show the mean of the data samples sets at each of the nine positions on the table. The accuracy (i.e. the distance from the mean position of all data samples at a particular point to the actual position) was found to range from 0.47 to 4.05 millimeters for the raw data, with an average accuracy of 2.6mm. For the filtered data, the accuracy ranged from 0.53 to 5.08 millimeters, with an average accuracy of 2.75mm. It is interesting to note that this type of measure of accuracy is not at all improved with the filtering algorithm. This can be seen in the graphs in Figure 6.2, where the mean of each position set lies close to the actual position both in the case of the raw data and in the case of the filtered data.

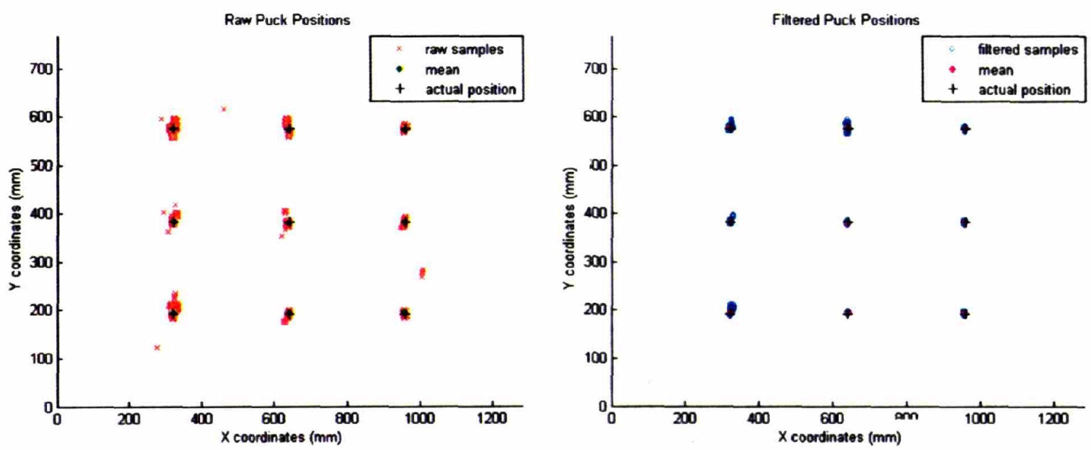


Figure 6.2: Means of raw and filtered samples

These plots show the means of the raw samples (left) and filtered samples (right). We see that the mean values lie close to the actual positions in both cases. Nevertheless, the filtered samples are more tightly clustered than the raw samples.

Another measure of accuracy for positioning systems is known as the *circular error probability* (CEP). It is defined as the radius of a circle within which the position estimates will fall a certain percentage of the time. The table in Figure 6.4 shows the 90%, 70% and 50% CEP of the raw and filtered position data. From the CEP we can see that the filtered samples are more closely clustered than the raw data, and hence provide greater accuracy overall.

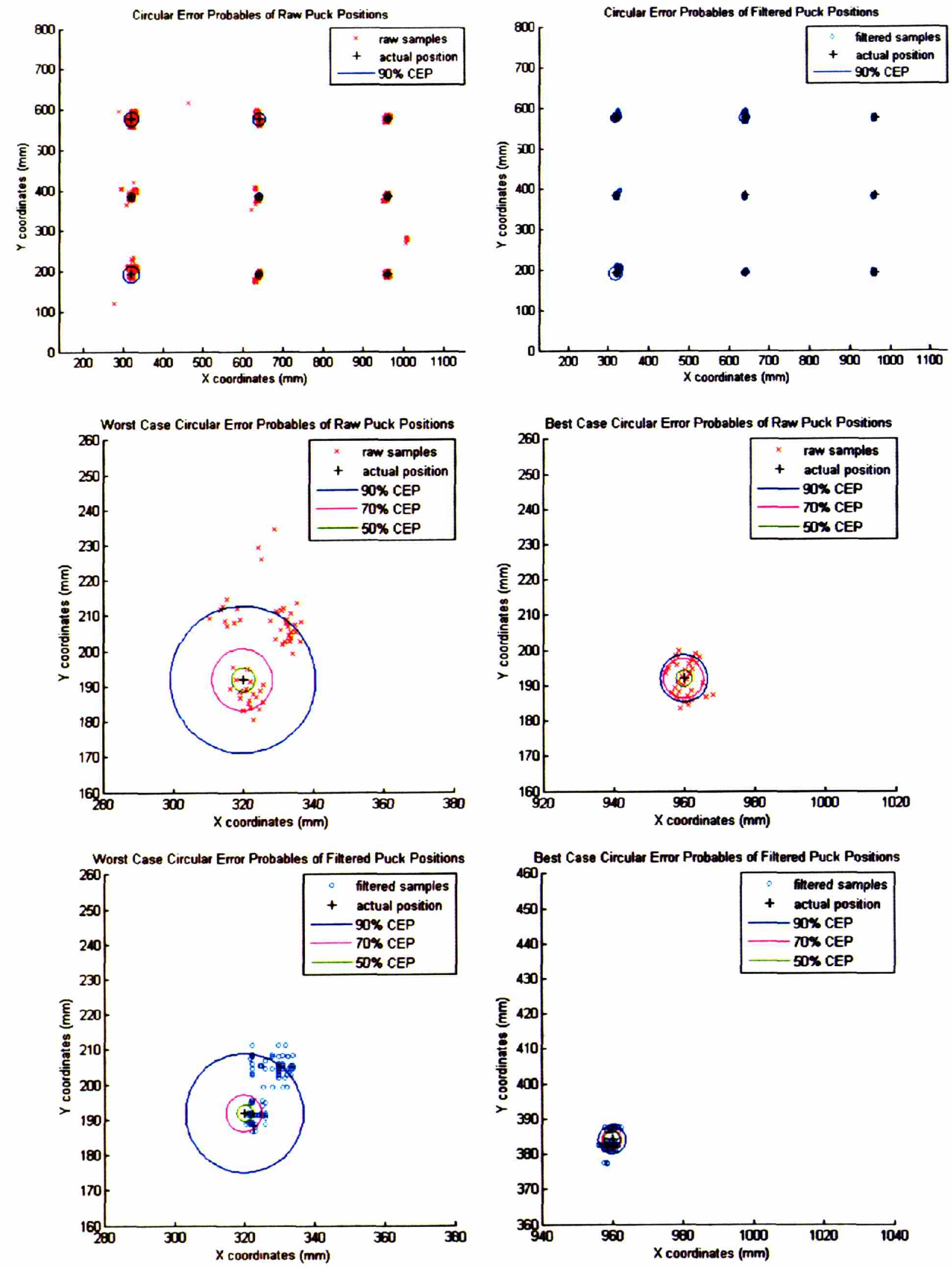


Figure 6.3: Circular error probability plots

The upper two graphs show the 90% CEP of the raw and filtered data for nine positions around the table surface. The four graphs on the bottom show the worst and best case CEP for the raw and filtered samples. From these close-ups we can see that filtered data provides significantly better accuracy than the raw data in both cases.

Figure 6.3 shows the circular error probabilities overlaid on the plots of the raw and filtered data samples. The upper two graphs show the nine different position tests on the table surface. The middle two graphs show the best and worst case circular error probabilities for the raw positions. The worst case corresponds to the bottom left of the table, which the best case corresponds to the bottom right. This suggests that there is possible a poor bond between the bottom left transmitter and the glass surface, or perhaps an error in the calibration caused the results to be skewed on one side of the table. The bottom two graphs show the best and worst case circular error probabilities for the filtered positions. The worst case corresponds again to the bottom left of the table, while in the best case here corresponds to the center right of the table. From these plots we see a considerable improvement of the positioning accuracy after filtering. We also notice from the table in Figure 6.4 that 90% of the filtered position estimates fall within roughly 8 millimeters of the actual position.

Circular Error Probability						
Percentage	**Raw Data**			**Filtered Data**		
	Best Data Point	**Worst Data Point**	**Overall Average**	**Best Data Point**	**Worst Data Point**	**Overall Average**
90%	6.69	20.81	11.48	3.93	16.90	**8.22**
70%	5.10	12.69	7.20	2.68	10.26	4.65
50%	2.29	11.25	4.97	1.70	9.36	3.42

Figure 6.4: Table of circular error probability

The circular error probabilities for the raw and filtered data samples in millimeters show that the overall position accuracy is improved after filtering. We show the best and worst data points on the table for raw and filtered data, as well as the average over all nine data points. We notice that 90% of the filtered estimates fall within roughly 8mm of the actual position on average.

For comparison, we can consider the Tap Window sensing system, which provided the initial inspiration for our approach. Their results showed an average accuracy of 2.0 centimeters and an average standard deviation of 1.6 centimeters for the tracking of knocks and metal taps on a large glass window [Leo 2002]. They concluded that this was sufficient for their purposes, since the average hand is much larger than 2.0 centimeters in diameter. Tap Window position plots are shown in Figure 6.5. After filtering, our system provides an average accuracy of 2.75 pixels (i.e. 0.275 centimeters) and an average standard deviation of 2.47 pixels (i.e. 0.247 centimeters), which represents a significant improvement over the Tap Window system. The reason for this improvement is largely due to the fact that we are dealing with a far more constrained system and a much higher frequency, since our sensor only needs to locate waves generated by 200kHz pings that travel at a known velocity through the glass. In the Tap Window system, different kinds of impacts generate waves at different frequencies and the exact speed of these is not known, which results in larger positioning errors.

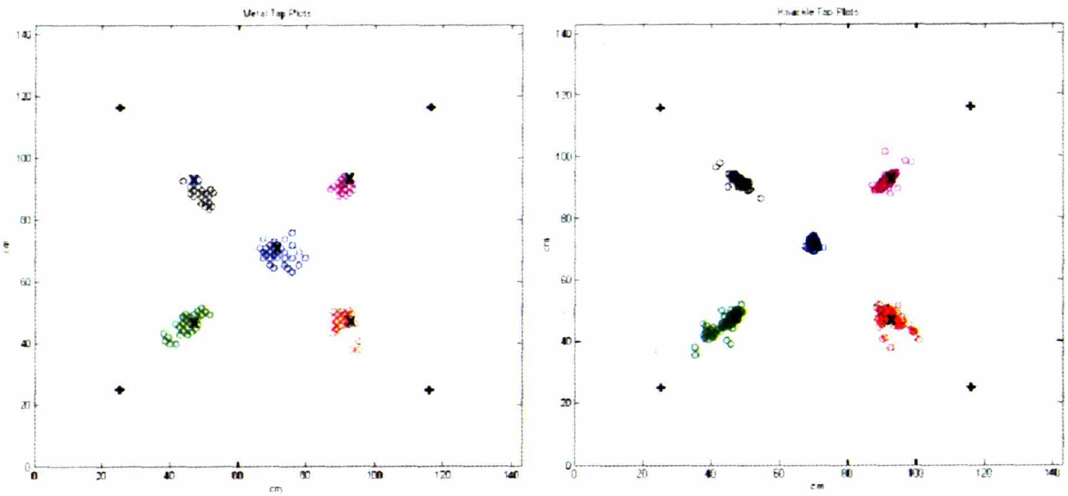


Figure 6.5: Tap Window positions

These plots show the detection of metal taps (left) and knuckle taps (right) in the Tap Window system, which provided the inspiration for our position sensing approach [Leo 2002].

Our initial sensing tests described in Section 5.2.1 predicted an accuracy of around 0.5mm for the system provided that we can accurately track the same peak of the incoming signal. This kind of accuracy would allow extremely fine control of the interactive objects. However given the 35mm wavelength of our signal, detecting one peak off would result in an error on the order of several centimeters. Given that our results show errors on the order of millimeters, we can conclude that our system is successfully able to track the same peak of the incoming signal from one ping to the next.

The current puck design has a base of 4.75 centimeters, and the sensor itself is 1.8 centimeters in diameter. Given the large size of the objects in the current system, our position accuracy has proved sufficient for our purposes. In the future, it might be useful to design a point contact sensor that could allow finer control for application such as drawing. In this case, it would be worth exploring how to improve the positioning accuracy. The following section looks at some of the error sources in the positioning system that result in undetected pings and decreased accuracy.

6.2 Acoustic Losses

In the TViews system, one positioning cycle corresponds to a sequence of four acoustic pings, one from each of the transmitters located in the four corners of the glass surface. Acoustic losses occur when transmitted pings are not received by the sensors in the base of the pucks. This can result in errors in the measured positions. Since the position estimates are two-dimensional, they can be computed from three pings alone. This means that as long as the sensor can pick up at least three out of the four pings, the system can provide a position estimate during that positioning cycle. If fewer than three pings are detected in any cycle, then a position estimate cannot be provided. In this section, we examine the two main sources of acoustic losses: background effects and movement of the pucks.

6.2.1 Background Effects

Background effects can be caused by a variety of different things, such as environmental noises, objects placed on the table (e.g. cups, books, pens, etc.), hands, elbows or fluid spills. In order to test the sensitivity TViews table, we gathered time-of-flight and position data while tapping on the glass with metal objects, knuckles and fists, and also with environmental noise, particularly the jingling of keys. This data was compared with data gathered without any background noise. The table in Figure 6.6 summarizes the findings of acoustic losses due to background effects. From a total of 2000 pings (which should result in 500 position estimates, since one cycle consists of four pings), only 1.4% or a total of 28 pings were lost. The system was able to compute a position estimate all but four times, resulting in only a 0.4% loss in position estimates. In comparison, only 2 pings were lost from 2000 when there was no noise and all positioning cycles were able to yield a position estimate.

	Without Noise	With Noise
Total Pings	2000	2000
Missed Pings	2	28
Percent Missed	0.1 %	1.4 %
Total Position Estimates	500	500
Lost Position Estimates	0	4
Percent Lost	0 %	0.4 %

Figure 6.6: Losses due to background effects

This table summarizes the losses due to background effects. Despite a large amount of background noise which included people tapping on the table with metal objects, knuckles and fists and environmental sounds like keys jingling in the background, the system was unable to compute a position estimate only 0.4% of the time.

The plots below show the raw and filtered data samples with and without background noise. Without noise we found an accuracy of 3.91mm and standard deviation of 3.36mm for the raw data, and an accuracy of 3.08mm and standard deviation 1.51mm for the filtered data. The data gathered with background noise yielded an accuracy of 2.66mm and standard deviation of 14.49mm for the raw data, and an accuracy of 2.09mm and standard deviation of 1.26mm for the filtered data. This can be seen clearly from the plots in Figure 6.7, where the raw samples of the data generated with background noise (i.e. right side) seem to be less tightly clustered than in the case without noise. The median filter succeeds in rejecting the outliers and as such the filtered samples are tightly clustered regardless of noise effects.

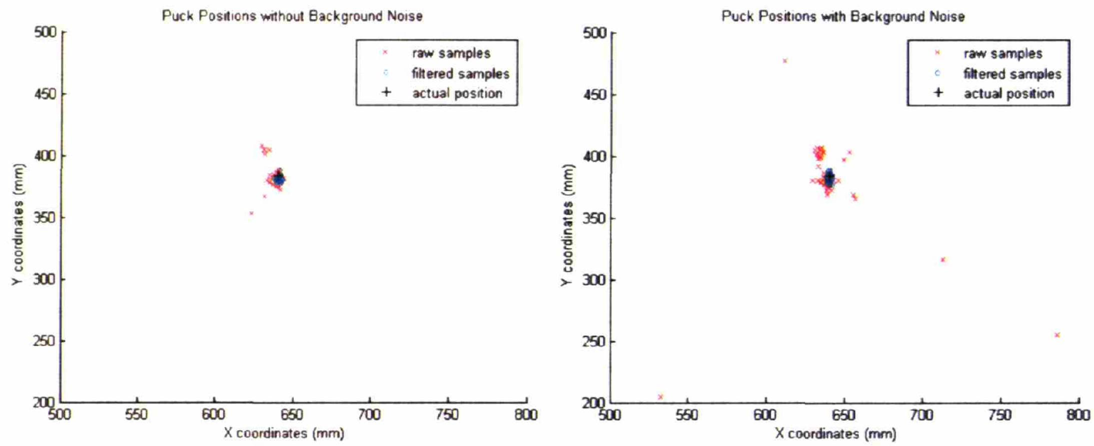


Figure 6.7: Position plots with and without background effects

These graphs show raw and filtered position samples without background noise (left) and with background noise (right). We see a greater number of outlying samples in the raw data in the case with background noise. These outliers are successfully rejected by the filtering algorithm.

Overall the system performs very well despite the effects of background noises. Since the puck only needs to look for acoustic waves at a particular frequency, we were able to band-pass filter out most of the noise at the hardware level. Furthermore, the ultrasonic sensor used in the final puck design has a center frequency of 200kHz and is less sensitive to higher and lower frequencies, as was discussed in Section 5.2.2.

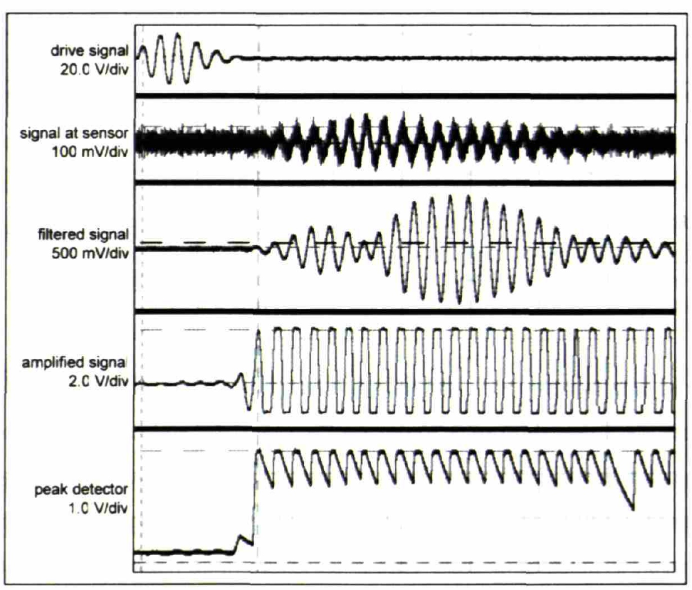


Figure 6.8: Detected signal

These oscilloscope traces show the signal detected by the puck at various stages of the circuit. A noisy ping at the sensor is filtered to reject noise and then amplified. The last trace shows the output of the peak detector.

Figure 6.8 shows oscilloscope traces at various stages of the puck circuit. The top trace shows the acoustic ping at 200kHz. Below this, we can see the signal picked up at the sensor. At this stage, there is still quite a bit of background noise. The following two traces show the filtered signal and amplified signal, which is considerable cleaner. The last trace shows the output of the peak detector. The threshold for detecting a ping is set to above the noise floor but below the level of the first peak.

6.2.2 Movement

The second major source of positioning error happens as the pucks are moved around the surface of the glass. We gathered time-of-flight measurements and position estimates while moving a around the table slow and then fast. The table in Figure 6.9 summarizes the findings. When the puck moves slowly, the puck misses 0.85% of the pings but the system is still able to provide a position estimate 99.8% of the time. Much greater losses can be seen when the puck moves quickly. In this case, 10.2% of pings are missed and position estimates can be computed only 90.4% of the time, which indicates a considerable decrease in performance.

	Slow Movement	**Fast Movement**
Total Pings	4000	2000
Missed Pings	34	204
Percent Missed	0.85 %	10.2 %
Total Position Estimates	1000	500
Lost Position Estimates	2	53
Percent Lost	0.2 %	10.6 %

Figure 6.9: Losses due to movement

This table summarizes the losses due to movement of the pucks. We notice that the system is able to compute a position estimate the vast majority of the time as long as the puck is moving slowly. A fast-moving puck results in a much greater loss of position estimates, in this case 10.6%.

The plots in Figure 6.10 show the raw and filtered data samples for a puck moving around the table slowly on the left and quickly on the right. As we can see from these plots, the slower movement generates more accurate position data. In addition to missing a large percentage of pings, the system has trouble accurately resolving the position of a fast-moving puck on the table. This can be seen from the right-hand plot, which shows a large number of outlying raw position values (i.e. red crosses that are not on the outer square path of movement). These bad values are not always rejected by the history filter, resulting in outliers within the filtered samples as well (i.e. blue circles that are not on the outer square path of movement).

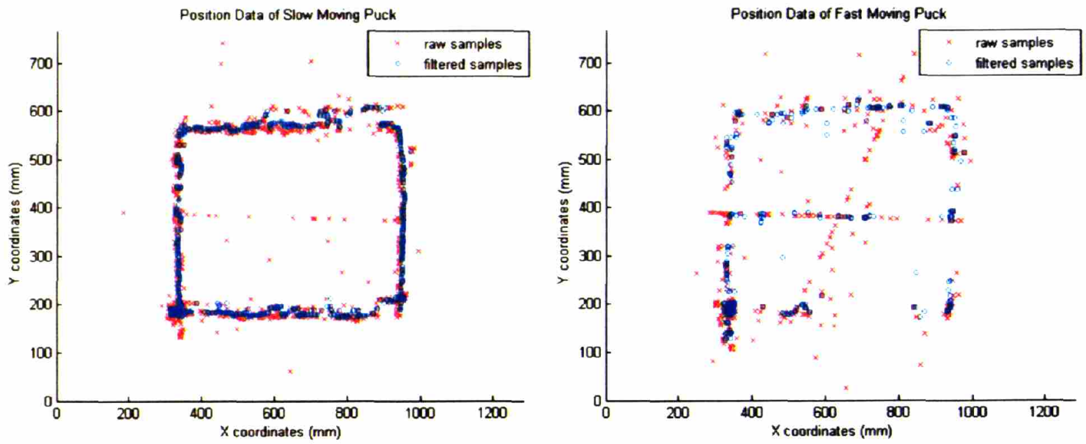


Figure 6.10: Position plots for moving puck

These graphs show raw and filtered position samples for a puck moving slowly (left) and quickly (right). Fast moving pucks cause a much greater number of erroneous position estimates, most likely caused by poor contact of the sensor to the glass surface.

This bad data results from poor contact of the sensor to the glass as the puck moves around on the table. As described in Section 5.2.2, we tested several different sensors during the hardware development stages. The ultrasonic air transducers used in the final puck design were found to couple into the glass much better than the piezoceramic disc sensors. Nevertheless, when these sensors move around there is still somewhat of a slip-and-stick problem that causes the puck to either miss the signal traveling through the glass or to detect it too late as it reflects back from the edges.

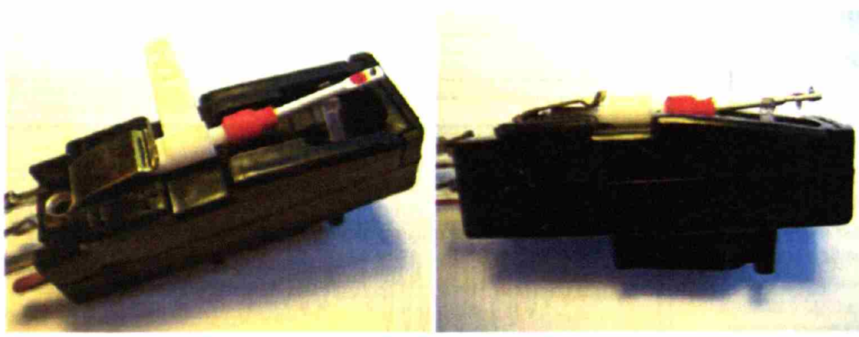


Figure 6.11: Ceramic phonocartridge

Top and side view of the ceramic phonocartridge used for our preliminary point-contact sensing tests.

One possibility would be to use a point-contact sensor, similar to a phonograph needle but that could operate at a much higher frequency. This could also allow the pucks to be designed as a pen or stylus, and their overall size could be decreased. Some preliminary tests show that a point-contact sensor might be a worthwhile approach to pursue. We tested ceramic and magnetic phonocartridges to see whether they could pick up the acoustic signal traveling through the glass (see Figure 6.11). We found that the ceramic cartridge needle was able to detect the acoustic signal when placed at a 45 degree angle and connected to a 10x gain pre-amplifier (see Figure 6.12). The need for this specific placement might be due to the dual-channel nature of the phonocartridge, which contains two piezoceramic elements for the left and right audio channels respectively. Since we connected the pre-amp circuit to one set of contacts for one channel only, we found that the cartridge responded only when held at an angle that corresponded to that pickup. We also found that the frequency response of the parts we tested was far too low for our purposes since they responded only to frequencies below 20kHz. Overall these preliminary tests were still limited, and more testing will be needed to assess whether this approach is truly viable. At this stage we used only limited gain and did not explore specific mounting strategies for the cartridge with respect to the types of wave modes excited. There is clearly room for optimization at both these levels.

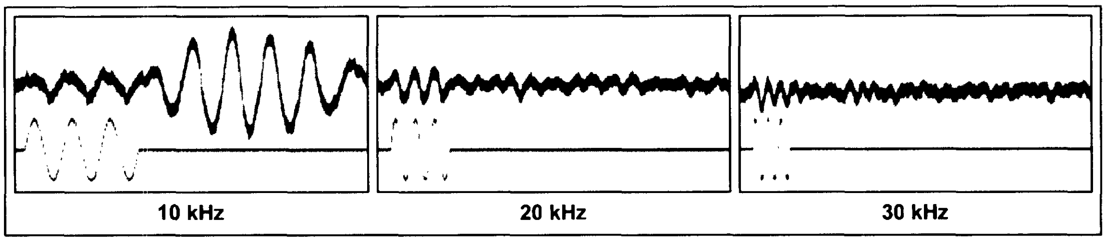


Figure 6.12: Ceramic phonograph cartridge response

These oscilloscope screenshots show how a ceramic phonograph cartridge responds to an acoustic drive signal transmitted through the glass at three different frequencies. Clearly the cartridge responds better at lower frequencies. For this sensing approach to be used in the TViews system, a cartridge that responds at much higher frequencies would need to be designed.

In general, for a phonocartridge sensing approach to be adapted for use in the TViews system, a cartridge that is sensitive to much higher frequencies would need to be used. Many standard phonocartridges are limited to the audible range (~0-25kHz). Nevertheless certain high-end phonograph cartridges preferred by audiophiles have higher frequency responses and may have a better chance of working for TViews. Another possibility would be to look at special cartridge designs such as those used in phonograph-based video systems that use mechanical-contact needles. The earliest example of these was called Phonovision and was invented by British television pioneer John Logie Baird. It consisted of several minutes of a 30-line video image mechanically recorded onto a wax disc [McLean 2005]. In recent years, Austrian artists and engineers have experimented with a similar approach they call VinylVideo, which allows both audio and video information to be pressed onto a conventional long-playing record and then playback using a standard phonograph turntable that is connected to a television set using a special adaptor [VinylVideo 2005]. These experiments in using phonograph technology to record video signals suggest that phonograph cartridge can be made to operate at frequencies that are well beyond the audible range.

Another possibility would be to find a highly sensitive non-contact sensor that could be designed to sit slightly above the glass within the base of the puck. This sensor would need to detect the signal traveling through the glass despite the air gap in between. We discussed this possibility with researchers at Ultran Laboratories, developers of ultrasound sensors for industrial and biomedical applications located in Pennsylvania. They offered to design a non-contact sensor for the TViews system at a price of $1,400.00

per sensor, which was not a feasible cost for our purposes. As ultrasound technologies progress and the applications become less specialized, it is possible that such highly sensitive sensors might eventually come down in cost enough to make them a viable option for the TViews table.

6.3 Extensibility

In order support the thesis claims, this section examines the extensibility of the sensing system from a technical perspective. The system can scale both in terms of the number of tracked objects and in terms of the size of the sensing area. Based on these scalability criteria, we need to evaluate how the system handles multiple pucks on the surface at once, and how it performs when as the pucks are moved farther away from the transmitters as would be the case on a larger surface.

6.3.1 Number of Interactive Objects

In order to test how the system performs with more than one puck at a time, position data was gathered while two pucks were on the surface at once. The data gathered indicated a 0% loss of position estimates for both pucks, meaning that the presence of a second object did not interfere with the sensing in the first object. This result was expected given that the system performed well despite background effects and objects placed on the glass in the tests described in Section 6.2.

	Raw Data		Filtered Data	
	Accuracy (mm)	**Average σ (mm)**	**Accuracy (mm)**	**Average σ (mm)**
Puck #1	11.64	15.07	6.41	19.69
Puck #2	0.94	6.15	6.36	3.41

Figure 6.13: Accuracy and precision for two pucks

This table shows the position accuracy and average standard deviation for two pucks placed on the table at the same time. This does not represent a significant change from the data gathered with a single puck on the table at a time, indicating that the system is able to locate multiple pucks at once.

The accuracy and precision of the system did not show significant change with two pucks on the table at once, which demonstrates the system's ability to locate multiple pucks at a time. The table in Figure 6.13 summarizes the accuracy and average standard deviation of position estimates for the two pucks at once. It is worth noting here that with increasing numbers of pucks on the table, the refresh rate of position estimates will decrease slightly, since the polling phase of the system will need to loop through more pucks.

However the positioning phase will not take any longer with multiple pucks than with a single puck, since all pucks are able to time the acoustic pings in parallel.

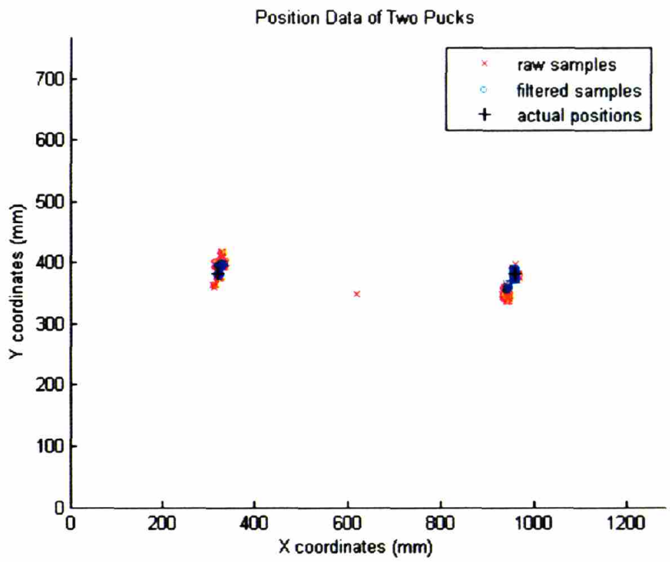


Figure 6.14: Position plots for two pucks at once

This graph shows raw and filtered position samples for two pucks placed on the table at the same time.

It is also worth noting here that there are eight infrared transceivers placed around the display and interaction area for communication purposes. We did not find any occlusion problems in the communication and control of the system with multiple pucks placed on the table at once. When tested, we found the infrared transceivers to have a viewing angle of roughly 90 degrees, meaning that four transceivers in the corners of the table would be sufficient for the pucks to communicate from anywhere on the table's surface. By using eight infrared transceivers, we provide an over-determined system which ensures that in normal use the pucks will always be able to communicate with at least one or more transceivers in the table. The position plots in Figure 6.14 show the samples gathered for two pucks placed at opposite sides of the table. As with a single puck, the system is able to provide a reasonably accurate position estimate for two pucks.

6.3.2 Platform Size

When sound travels through a medium, its intensity diminishes with distance. In idealized materials, sound pressure (i.e. signal amplitude) is only reduced by the spreading of the wave. Natural materials on the other hand all produce an effect which further weakens the sound. This weakening results from two basic causes: scattering and absorption. This combined effect of scattering and absorption is called *attenuation*, and can make it difficult to scale the area of the sensing surface in size. The larger the sensing surface, the harder it will be for a receiver to receive a ping from a transmitter on the far side of the table.

To test the attenuation of the signal in the glass, we placed the receiver at a fixed distance of 20cm from one of the transmitters and looked at the received signal when the region in-between is open. We compared this with the case when a hand is pushing down hard on the glass between the transmitter and receiver. Figure 6.15 shows that there was no change in the received signal between the two cases, demonstrating that we excite a mode that is not attenuated.

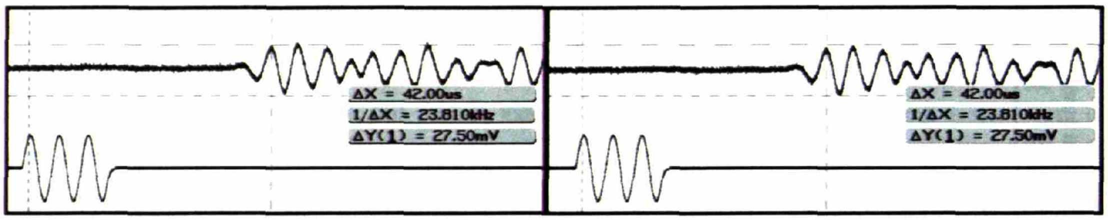


Figure 6.15: Signal attenuation

The oscilloscope screenshot on the left side shows the received signal when the region between the transmitter and receiver is open. The screenshot on the right shows the received signal when a hand is pushing down hard on the glass between the transmitter and receiver. In both cases, the transmitter and receiver are 20cm apart. Since there is no change between the two cases, we conclude that we excite a mode that is not attenuated.

We also examined the effects of dispersion on the signal across the diagonal of the table, which is 32 inches in length. Dispersion is the phenomenon that causes a wave to separate into components of varying frequencies. We noticed significant decrease of the amplitude of the first arrival peak of the signal with distance, as shown in graph in Figure 6.16.

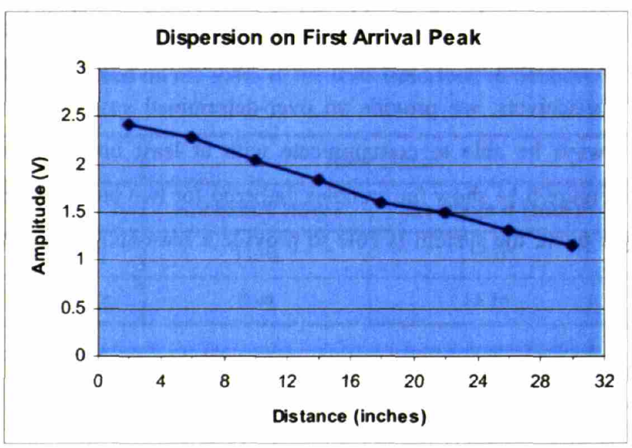


Figure 6.16: Dispersion of first arrival peak over distance

This graph shows the dispersion on the first arrival peak of the signal traveling through the glass surface over a distance of 32 inches. The amplitude of the first peak at a distance of 29 inches is roughly half of what it was at a distance of 2 inches.

The oscilloscope screenshots in Figure 6.17 show that despite the significant decrease of the amplitude of the first arrival peak across the table, it still remains well above the threshold (indicated by the solid line). Based on these results, we can conclude that with the current sensing configuration it should be possible to vary the size of the table to accommodate slightly larger coffee tables without any need for modifications to the hardware.

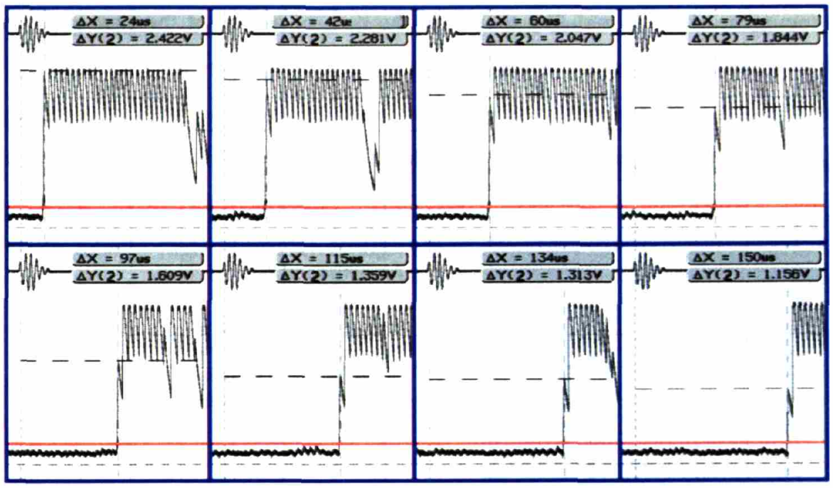


Figure 6.17: Dispersion of first arrival peak and threshold

This sequence of oscilloscope screens shows the dispersion of the first arrival peak of the received signal across the glass surface. Even at the far side of the table, the first peak remains well above the threshold level indicated by the solid red line.

While the screenshots above show the output of the received signal from the peak detector (after noise filtering and amplification stages), the screenshots in Figure 6.18 below show the output of the received signal after noise filtering only (before the gain stage and peak detection). In this case, we can see the effects of dispersion and reflections on the entire received signal waveform. The first two pictures on the top row show that when the receiver is near the edge of the table, the dispersive effects are much greater, most likely because the signal is bouncing back from the edges of the glass. In the first picture, it is even difficult to differentiate the first envelope of the signal.

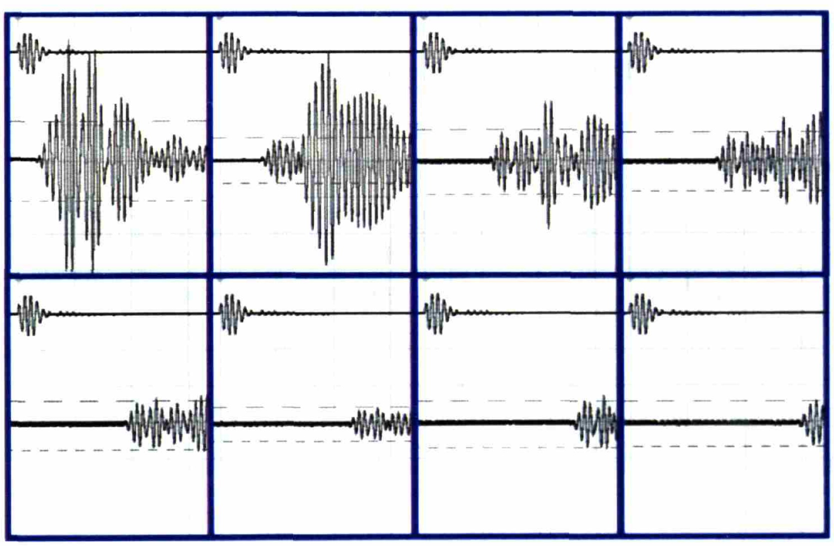


Figure 6.18: Dispersion of received signal waveform

This sequence of oscilloscope screens shows the effects of dispersion on the received signal waveform before it is sent through amplification and peak detection.

The graph in Figure 6.19 shows the amplitude of the first envelope of the incoming signal across distance in logarithmic scale, and demonstrates that the maximum amplitude of the first envelope decreases as the receiver is moved farther away from the transmitter. It is worth noting that the amplitude of the received signal also depends on how much pressure is applied to the receiver. In order to construct a much larger table (e.g. conference room table size instead of coffee table size), the system would need a way of dealing with the dispersion and attenuation of the signal. We measured the time of arrival of the first envelope maximum and compared it to the time of arrival of the first peak.

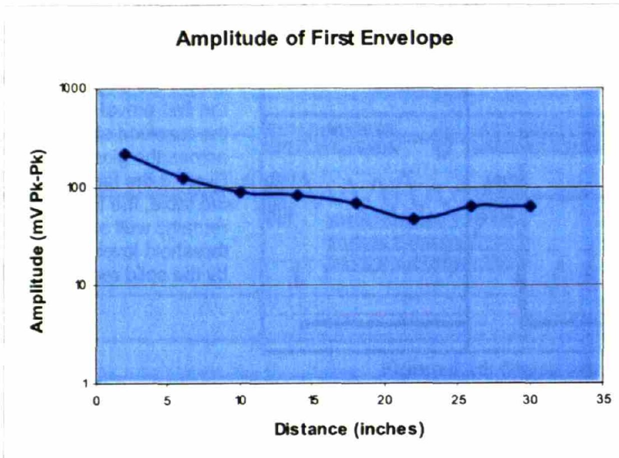


Figure 6.19: Amplitude of first envelope

Shows the amplitude of the first envelope of the received signal across the surface of the glass in logarithmic scale.

The graphs in Figure 6.20 demonstrate that it should be possible to use the first arrival envelope for the purposes of positioning instead of the first arrival peak alone, as in the current system. By doing this, we can potentially avoid the problems in positioning that are caused by the breakdown of the first arrival peak over distance due to dispersion. However the first arrival peak detection approach is much simpler to implement in hardware, which is why it was selected for this first version of the TViews platform. Detecting the first envelope maximum might be implemented in future versions of the system and will require considerably more complicated signal processing at the hardware level.

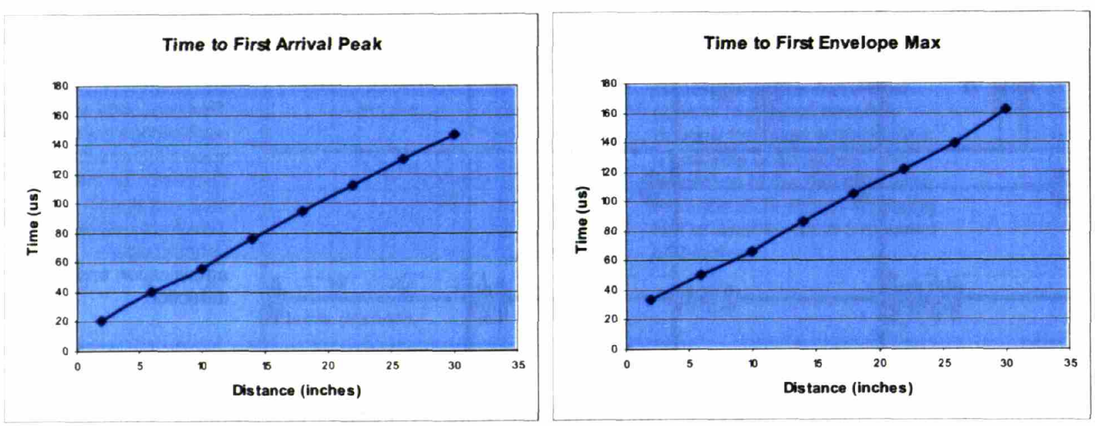


Figure 6.20: Time to first arrival and first envelope

These graphs show the time to the first peak (left) and the time to the first envelope maximum (right). The current system uses the first arrival peak for thresholding and position estimation purposes. With more complicated signal processing, it should be possible to instead use the arrival time of the first envelope maximum to estimate puck positions.

Another possible solution to handle dispersion and attenuation would be to drive the transmitter with a stronger signal in order to enable it to propagate farther before dropping below the threshold level for detection. In the case of very large tables, the best solution would most likely be to increase the number of transmitters around the edge of the table. For instance, transmitters might be placed at the midpoints of each edge as well as at the corners. The system would then be able to triangulate each puck's location based on the time-of-flight measurements from the nearest three or four transmitters.

Chapter 7

7. Applications and Use

The previous two chapters of this thesis presented the technical implementation and evaluation of the TViews table. In particular, the discussion focused on the development of an acoustic-based tabletop sensing technology that is scalable to different sizes and that enables an extensible set of interactive objects to be moved from one table platform to another. This approach allows multiple people to interact together in both physical and distributed space, and enables them to have natural interactions with digital media in their leisure time. Notwithstanding, such a design can only become economically viable and valuable for everyday users if it can support powerful and engaging applications that will generate demand. This chapter therefore looks at media table application development, focusing particularly on media and entertainment activities for the home environment.

TViews provides a scalable platform framework that defines a way in which many different media table applications can run on the same platform at the same time as well as on many connected platforms. TViews interactive objects can be associated to a particular application based on their unique functionality or physical shape, or they can be used as generic controls for multiple applications. Moreover, the compact sensing and display design allows the table to be setup in everyday living environments where there is little or no support for infrastructure that is external to the table itself. While individually the applications discussed in this chapter could have been created on previous media table prototypes based on sensing technologies such as computer vision or electromagnetically actuable tags, only the TViews table provides a technology that can easily bring the media table into a normal person's everyday home environment.

The object sensing method discussed in the previous chapters has been used to construct two instances of the TViews table, one located at the MIT Media Laboratory in Cambridge and the other at the Samsung research center in Suwon, Korea. A total of eighteen interactive pucks and ten different sample media applications have been built over the course of the development and testing of the TViews table. All pucks and applications can run on both tables, and the pucks can be swapped between applications running on different tables. Several of the applications make use of the expandable I/O feature of the pucks through the use of add-on buttons that provide customizable functionality within the application space.

Figure 7.1: Two TViews tables

TViews tables built at the MIT Media Lab (left) and at Samsung research labs (right).

In this chapter, we examine the application level extensibility of the TViews table. We begin with a broad discussion of media table applications and design considerations, and provide a brief overview of four of the media application prototypes that have been created for the platform. The remainder of the chapter discusses our observations of the TViews table in use within the living room of a real-world apartment. These preliminary trials looked at how people engaged in shared and sociable interactions around the table using the four different media applications and also provided the opportunity to brainstorm with people from different backgrounds about the potential scope of the media table application space.

7.1 Tabletop Application Design

As we discussed in Chapter 2, tables come in a variety of forms and are used across most cultures and many kinds of physical environments. Tables are shared horizontal surfaces that are elevated from the ground and around which people gather to do lots of different things, such as eat, play games, tell stories, or draw. On tables, people often do multiple things at the same time, and they make use of many physical objects at once, like tools and materials. People share and exchange these objects, and when doing so they often coordinate their gestures and actions. Furthermore, their interactions with one another as they engage in various activities are generally very conversational and sociable.

There are two particular areas that we were interested in exploring in our work on the TViews table: sociability and design. The first area – sociability – relates to user experience. The TViews table built at the MIT Media Lab is designed for a specific physical setting: the home. How do people appropriate a media table into this existing physical environment and how does this platform support natural social interactions within a shared space? The second area – design – relates to the broader space of tabletop application design. What are the issues designers need to bear in mind when they are developing applications for this new interaction platform?

7.1.1 Media Table Sociability

Multi-purpose media tables tap the wealth of digital content and applications that exist in cyberspace and open up possibilities for people to engage in highly sociable face-to-face interactions around them. On a desktop interface, each single person remains completely in control of their own little portal into the digital realm. In contrast, casual and sociable interactions in the physical world are characterized by shared control between multiple people, where different people can each do different things at once or where they can share in the same thing at the same time. Media tables that provide multiple points-of-control for meaningful simultaneous multi-user interactions within a digital media application context have the potential to enhance the way in which we jointly share and interact with digital media. They also provide opportunities for new kinds of gaming, storytelling or creative applications to emerge.

To give a specific example, consider the way we browse pictures and tell stories. In the days of physical photographs, this was a shared physical activity that happened amongst friends and family members, often in the living room where people gathered around a shared table. With the emergence and proliferation of digital photography, photo browsing generally happens one on one with the computer, and the face-to-face interactions that used to take place have been completely lost. The following sequence is taken from a photo-browsing session on the TViews table that involved three people using three pucks to navigate travel photos on a map of Ireland. In this particular case, Fred and John went on a trip to Ireland together and are using a geographic picture browser (discussed in Section 7.1.3) to explore their shared photo collection. They are also showing their photos to Amy, who was unable to accompany them on their trip and is seeing the photos for the first time. Please note that the names used here are pseudonyms.

Fred: [Moving puck to new location]

Amy: [Leaning over to see Fred's pictures but still holding her puck] *Oh, the new paint!*

Jack: [Focusing on his own puck at the other side of the table] *Mmm hmm...*

Amy: [Taking her puck and moving it aside to look at Fred's picture] *That's a nice color.*

Jack: *You hadn't seen that yet?*

Amy: *No.*

Fred: *It looks just like the outside.*

Amy: [Focusing back to her puck at a different location] *Matt...*

Jack: [Looking at the picture Amy is indicating] *Matt Malloy.*

Amy: *Malloy's.*

Fred: [Switching focus from his own puck to Amy's puck] *Mom was very happy to see Mr. Malloy.*

Amy: [Switching locations] *We've already been to that location...* [Switching locations again] *Are you in this one? Yes, I see...*

Jack: [Looking at the new location of Amy's puck] *I like some of these ones right here.*

Fred: [Looking over] *Ah yes, driving on the sand bar, haha...*

Amy: [Focusing back to Fred's pictures for a moment] *I'm sure you're proud of your work.*

Jack: [Pointing at picture from the puck Amy is holding] *Do you see this one right here?*

Amy: [Looking back to her puck to see what Jack is showing] *Yes.*

Jack: *This was an island off the coast and we were driving by over here* [indicating location on map] *and we saw some cars driving over and we were wondering what was going on over there. And mom said "oh, they do auto commercials on the beach."* [Amy takes another puck and drags aside the image Jack is talking about for a closer look] *So we drove closer and it turned out that when the tide is out you can actually drive... you can't really see it in this picture because it's zoomed out...* [Pointing at picture again] *but there are road signs that go all the way through.*

Amy: [Leaning over to look] *Oh weird!*

Jack: *And it's basically what the locals do... they drive out onto the beach but you can only do it at certain times of day.* [Stepping through pictures on puck] *The other picture might actually show it better here...* [Stopping at picture] *That one, see... there's a road sign.*

Amy: *Oh yeah, neat!*

Even in this short sequence, we clearly see how people are able to fluidly switch focus between their own puck interactions and those of the others around them. The nature of their interactions transitions easily from the way they used to browse physical photographs on a table, and allows casual conversation and informal storytelling to emerge around digital media content. This example shows how a traditional activity like photo-browsing can transition easily onto a novel interaction platform. It also demonstrates that a novel interaction platform like a media table can transition easily into existing spaces like the home living room by making use of and adapting to existing social practices and conventions within the shared environment.

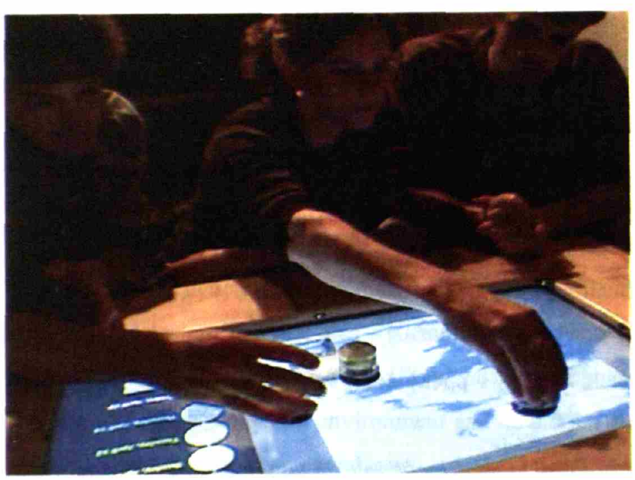


Figure 7.2: Media table browsing and storytelling

This photo shows the people from the interaction sequence above as they browse travel photos and tell stories around the TViews table.

7.1.2 Design Considerations

Media table applications are by no means limited to photo browsing and storytelling. Over the past decade, tangible interface researchers have created prototype applications that range across a variety of application domains and contexts. Brygg Ullmer provides a nice overview of application domains relevant to the broader area of tangible interface design in [Ullmer 2001] and suggests that tangible interfaces are generally suited to activities that require or benefit from collocated cooperative work. Media tables in particular provide a shared horizontal workspace for these interactions, which is not necessarily the case for all tangible interfaces. Example application domains that have been explored for tabletop platforms include urban resource planning [Underkoffler 1999], business management and supply chain visualization [Patten 2001], and musical performance [Patten 2002]. Section 7.1.3 describes four particular application prototypes that have been developed for media sorting, geographic media browsing, game play, and visual improvisation on the TViews table. Section 7.2.4 provides a categorization of potential tabletop media applications according to the different physical contexts in which they might be used.

Many combinations of digital tabletop applications and tangible control are possible. All the same, designers need to think carefully about how the mode of interaction and the intent of any one application might impose constraints on the design of the interface. Looking at past work on tabletop applications and creating our own prototypes has inspired us to formulate a taxonomy of design considerations for media table applications, shown in Figure 7.3. This taxonomy highlights issues that are specific to the media table design space, and does not cover questions that relate to the broader area of graphical user interface design as a whole. Many of the issues that come up in graphical interface design are also encountered when designing for tabletops, for example the question of how media content information can be visualized on a display surface using approaches such as hierarchically layered views or continuous spaces that can be panned and zoomed. On shared tabletop displays, the particular areas to consider range across the design of the interactive objects, the approach used for interface and control, and the strategies for connecting applications across multiple tables. Depending on their intent, certain types of applications might point to specialized solutions within one or more of these areas. This can impose constraints on the interface and interaction design. Other types of applications might allow a greater level of flexibility in the interface and interaction design. As such, we can consider design solutions that range from less constrained to more tightly constrained approaches within each of these areas.

In terms of object design, we need to think about how the objects or pucks will be used to control the application and if and how they should be customized. Depending on the application the pucks might act as generic controllers, like a stylus that could be used to grab onto any virtual media object. On the other hand they might be given a fixed meaning designated by their color, shape, or other physical attributes. For example in Underkoffler's Urp system, the interactive objects are permanently associated to a specific digital meaning and functionality based on their physical form [Underkoffler 1999]. That is, the physical building models are attached to corresponding virtual building models and cannot be used to control a different kind of virtual media object, such as the wind for example.

At the level of the visual interface, since media tables are a shared platform we need to think about how multiple users interacting through multiple points of control will coordinate their activities and how the design can be used to enhance the experience of all participants. This can be done through free simultaneous movement of objects, or with more constrained approaches like enforced turn-taking or coordinated control. For instance, the interaction with a picture sorting application might be best served by an interface that allows continuous and simultaneous movement of the interactive objects. In this way, multiple people could browse and organize a collection together, perhaps selecting images that are interesting to them and storing them within their own particular interactive objects. In contrast, drawing a square in a graphical drawing application might use coordinated control between two objects in order to anchor one corner and then stretch out the square with a second object. This style of interaction was used in GraspDraw, a two-handed drawing application created on the ActiveDesk [Fitzmaurice 1995]. In the case of a digital board game, the rules of the game might impose a turn-taking approach in the game-play, which is common in many traditional tabletop games such as chess or checkers. However new types of games might also be designed to allow simultaneous collaborative engagement of players with multiple objects at once. Another important issue that arises in the visual design of tabletop applications is the question of image or interface orientation, since users are likely to view the display surface from different sides while seated around the table. The question of interface orientation is addressed further in Section 8.2.

Finally, tabletop designers need to think about how multiple networked media tables coordinate views and user interactions. Some of the design issues that come up here are similar to those that arise when connecting desktop application environments. Multiple views into the media space can be tightly coordinated so that remote users will always see the same thing. A less constrained approach might allow each table to act as an independent window into a larger virtual environment. This approach is generally used in online role-playing games, where different players can be located in different parts of the virtual world at any given time, meaning that they will see different things on their separate screens even though they are interacting within the same virtual space. Beyond the coordination of the visual interface, tabletop applications also need to consider how the presence of remote objects is displayed on connected tables. In a less constrained approach, connected tables might only see the results of actions that have been performed by remote objects, such as the placing of a game piece. Other applications might lend themselves to a tighter coupling of object presence. For example, a networked version of the Urp system displayed the footprints of remote buildings on a connected table so that remote users could see the way they were being moved in real-time [Underkoffler 1999].

Considerations		Approaches	
		Less Constrained	More Constrained
Object Design	**Control and mappings**	Objects as generic handles or control devices (e.g. puck, stylus)	Objects with specific fixed meaning or functionality
	Extensions and customizations	Generic input/output add-ons (e.g. buttons, dials, sliders, lights, displays)	Physical shape reflects object's meaning in virtual space
Interface and Control	**Shared interaction approach**	Simultaneous movement of individual control points	Enforced turn-taking or simultaneous movement with coordinated control
	Multi-viewpoint approach	Directionless interface with free rotation of all virtual media objects	Fixed interface elements or automated re-orientation of media objects
Networked Tables	**Visual interface approach**	Tables provide independent views into the media space	Tables coordinate their views into the media space
	Remote object presence	Results of remote actions and object movements are displayed	All object movements and actions are display

Figure 7.3: Taxonomy of tabletop design considerations

This table provides a taxonomy of interface design considerations for the development of multi-user media table applications. These include in particular the design of the objects, the interface and control, and the networking of multiple media tables. Design solutions range from less constrained to more constrained approaches.

7.1.3 Media Application Prototypes

The different media application prototypes developed for the TViews table serve to demonstrate its extensibility within the application space. While they are not fully featured applications, they have allowed us to explore tabletop interactions across different media-related domains. They also serve to address some of the design considerations discussed above and have helped us understand how designers might create applications and content for a very novel and sociable platform within the home. The four application prototypes described here range across media content organization, media browsing, game play and visual improvisation. A discussion of these applications in use within the home environment follows in Section 7.2.

Picture Sorter

Since the first commercially manufactured photo cameras became available in the mid 19th century, the photographic process has achieved mainstream use across the world as a means of everyday image capture. Photographs record the passing moments and memorable events in people's lives, allowing them to live on as visual traces that are permanently solidified in the physical material of the photographic paper. Gathered in photo albums or collections, people can return to them time and time again. This personal repository of memories can be organized, re-organized, browsed and shared together with friends and family members many times. Often, the activity of creating a family photo album is a joint activity that involves sorting, selecting and grouping the images from a larger collection. As a child, I remember sitting at the dining room table with my mother and father, sorting through the photos from a recent trip or a birthday party. It was a fun shared activity that elicited countless reminiscences and stories as we carefully selected the best images to paste into a large book that we could later show off to our friends.

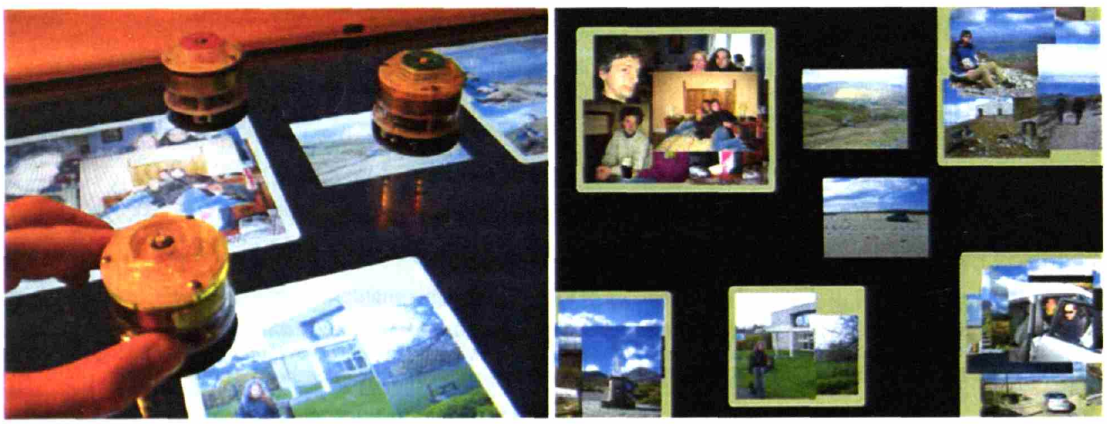


Figure 7.4: Picture sorter

A collection of images can be organized by dragging images into small clusters around the surface of the TViews table, similar to the way physical photographs are sorted into piles on a tabletop. The left side shows a photo of the application running on the table. The right side shows a close-up screen capture of a collection of images that have been partially sorted into clusters around the screen. Clustered images are indicated by the beige-colored border that surrounds them.

Over the past decade, we have moved into the era of digital photography. Rolls of film are quickly being replaced with ever-increasing capacities of digital storage, and the lengthy process of analog processing that generates viewable photographs from rolls of film negatives has been replaced with the instant gratification of immediately viewable images. These photos can be shared via mobile messaging, downloaded to laptop and desktop PCs, uploaded to picture sharing websites online, or simply printed out in regular paper form. This transformation in the photographic process allows people to quickly capture far greater numbers of images, but it also requires better tools for organizing these large image collections. Many such tools exist, such as Apple's iPhoto or Google's Picasa, but managing large image collections can be a tedious and repetitive task as it involves manually entering keywords on a computer with no face-to-face interactions between people. The leisurely group activity of sorting through a pile of physical photographs on a table has been replaced with single-user point-and-click interfaces for image organization.

The TViews picture sorting application explores how a tabletop platform can bring back some of the shared fun into the process of organizing digital photographs. The application makes use of the metaphor of a shoebox of images that is dumped onto a table surface for sorting. The images show up in a pile at the center of the TViews table, and the pucks are used to sort them into smaller clusters. Unlike physical photographs which can only ever be in one pile at a time, the digital nature of the application allows the same photograph to be sorted into several different clusters. While the application currently provides only basic sorting functionality, users would eventually be able to provide annotations for their photographs and the system could incorporate intelligent sorting features based on these annotations or on other aspects of the images. The image clusters could also be saved as slideshows, posted to the web for remote access, or viewed within different browsing views such as the map browser discussed in the following section. Figure 7.4 shows the picture sorting application running on the TViews table.

Map Browser

As digital photography continues to spread and evolve, camera technologies are becoming more and more intelligent, and the information they capture along with the visual image itself allows software tools to automatically classify and retrieve images based on their metadata tags.

Figure 7.5: Map browser

In this application the pucks are used to navigate a collection of images on a spatial map display. In this case, the image collection is from a vacation on the West Coast of Ireland. The left side shows a user viewing a set of images over the coast of Ireland. The image thumbnails cluster around the puck and can be enlarged by clicking the button on top. The right side shows the corresponding screen capture.

Nowadays, most digital cameras store the date and time as well as a variety of additional information, such as the aperture, shutter speed and other camera settings that were used when the image was taken. It is also possible to attach GPS (Global Positioning System) receivers to some digital cameras in order to record geographic location information, and in January 2005 Ricoh released the first digital camera with a fully integrated GPS receiver, the Ricoh Pro G3. Certain cameras, including many of the camera-equipped cell phones, allow users to add voice annotations to their photographs. One can imagine that in the not-so-distant future digital cameras will also incorporate sensors to keep track of ambient or environmental information such as weather conditions.

The map browser that was designed for the TViews table organizes images on a spatial map based on the time and location at which they were taken. The application is similar to the Tangible Spatial Narratives application described in Section 4.2.2, however in this case a timeline on one side of the table is color-coded by day and small colored dots at each location on the map indicate the days that photographs were taken there. Users attach the pucks to different days on the timeline and drag them around the map to reveal the images. The images appear clustered around the puck, and can be zoomed by pressing the button on top of the puck. When an image is zoomed, another puck can be used to grab hold of it and drag it to another part of the table for separate viewing. Figure 7.5 shows the map browser displaying a collection of images from a vacation on the West coast of Ireland.

Pente

Games of many different kinds have played an important role in human recreational and social activities. They can be both competitive and cooperative in nature, they can make use of skill, strategy or chance, and they can be played in many forms, with cards, boards, tiles or even the entire body. With the advent of digital technology, game designers have made extensive use of emerging digital technologies to enhance game-play by immersing viewers into virtual worlds with stunning graphics and complicated artificial intelligence (AI) based rule engines. While many of these games can be played in a networked mode with thousands of players at a time, they no longer provide the face-to-face social interactions common to more traditional games.

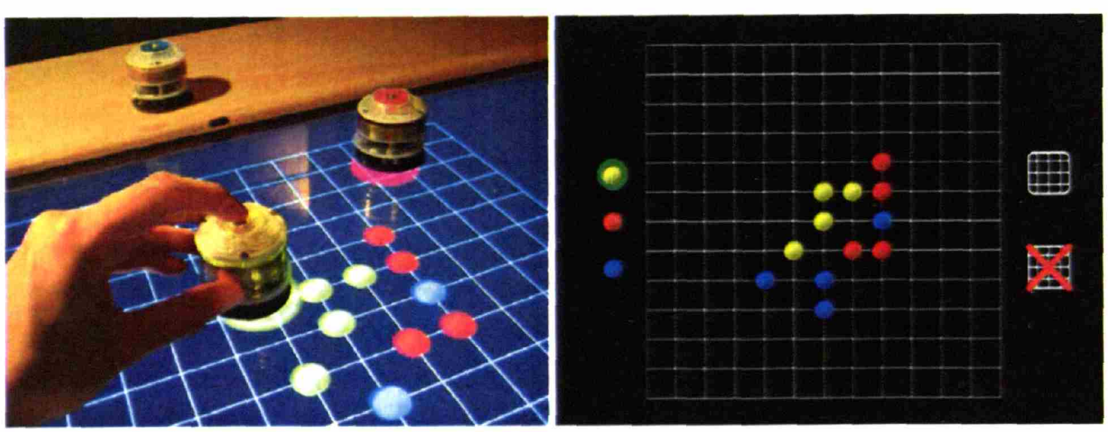


Figure 7.6: Pente game

This game of Pente on the TViews table supports two or three players at a time and can also be played in networked mode between multiple tables. The left side shows a photo of a three player game in progress. The right side shows a screen capture of the same game. The icons on the left of the board indicate the player turn (currently yellow based on its green border) and the icons on the right allow players to start a new game or quit the application.

We have implemented a simple Pente board game for the TViews table to demonstrate digital boardgame-play on the tabletop platform. The game can be played with two or three players, and the goal is to place five stones in a row on the grid or to capture five pairs of an opponent's stones. Each player gets a puck which allows them to drop their stones onto the grid. There are three different pucks used for the game: yellow, red and blue. The yellow puck comes with a yellow icon on top, and it can place only yellow stones on the table. This aspect demonstrates how the pucks can be physically customized for a particular application, and how the physical shape of the interactive objects can be permanently linked to different meanings or functionality within the virtual space of the application. Moreover, if the red puck is moved to a different TViews table running the Pente application, it will retain its identity as a red puck in the game. Figure 7.6 shows the game of Pente on the TViews table.

In addition to the basic game features, Pente can be played in a networked mode from two different tables at once. In this case, each player's moves show up on both tables at the same time. For instance, two players in the game might be located at one table, while the third player is located at a different physically remote table. The idea of networked tabletop game-play could eventually be extended to include many existing networked games, such as online role-playing or simulation games.

Springlets

Computers enable a variety of improvisational interactions with visual or auditory media, ranging from simple painting programs to real-time control of music or video sequences in a media performance. A tabletop display can provide a shared space for these kinds of interactions to unfold.

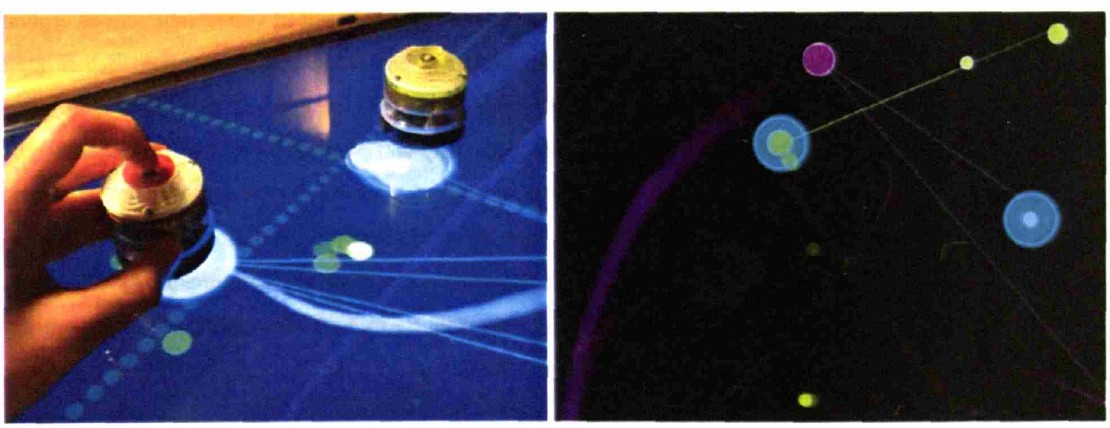


Figure 7.7: Springlets

In the *Springlets* application, the pucks are used to propel masses around the table that leave colorful trails behind them as they bounce around the screen. The left side shows a user grabbing hold of a mass. The right side shows a screen capture where two masses have been trapped by pucks (indicated by the translucent turquoise sprites).

The *Springlets* application is a simple example of visual improvisation on the TViews table. Two virtual spring objects (masses connected together with springs) can be controlled by the pucks, leaving colorful trails behind them as they bounce around the display area. Users latch onto the masses with a button press, and drag them around the table causing the attached masses to follow behind. A second button press drops the masses, propelling them forward on their own. Once the spring objects are in motion, they dance around the table and users can engage in improvisational play as they try to trap the masses in order to control the movement and display of the colorful trails on the display area. Figure 7.7 shows *Springlets* on the TViews table.

7.2 Media Table Interactions

In our home environments, we typically gather around tables in spaces like the living room, dining room and kitchen, and these table surfaces are often used to share physical media artifacts such as photographs and magazines, or to play tabletop board or card games. In transitioning to the digital realm however, household members need to remove themselves from the shared table space, relocating their media interactions to a TV or to a desktop computing platform with a single keyboard/mouse and a vertical screen setup. As a result, user interactions with digital media do not involve as much spontaneous or face-to-face interaction or sociability as those that center around more traditional physical media.

In this section we describe a preliminary trial that was conducted to examine the TViews table in use within the home environment. The goal of the study was to see how people engaged in shared interactions around the table using the different media applications described in the previous section, and to gather their feedback and suggestions. The informal and situated nature of this preliminary trial allowed us to observe how one particular home environment assimilated the physicality and playful intent of the table, and drew the focus of participants away from the novelty of the platform and the limited functionality and development of the example applications used. We begin by discussing the location and setup of the trial and the flow of the interaction sessions. We conclude the section by providing a summary of the feedback gathered from participants. Chapter 8 provides a broader discussion of the results, focusing on the implications on future research directions for the TViews table.

7.2.1 Location and Setup

In order to situate the TViews table within a real-world home environment, we selected a principal volunteer who was willing to offer the use of his living room for the purpose of our preliminary testing and evaluation. The volunteer was a young professional who lives in a one bedroom apartment in Cambridge.

The table was moved to the apartment for a several week period, during which small groups of people were invited to interact with the table.

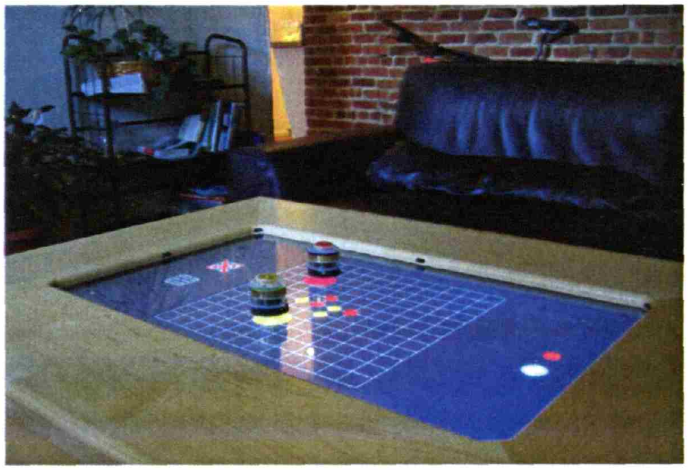


Figure 7.8: TViews table in living room

The TViews table was setup in the living room of a one bedroom apartment for several weeks to observe tabletop interactions in a realistic setting.

In addition to the principal volunteer, sixteen other people came to try out the table typically in groups of two or three at a time. Given the small size of the apartment, larger groups were difficult to accommodate. Most of the participants were digitally savvy young professionals and students aged 25-35. Their professions ranged across technology-related fields (project management, consulting, software engineering) to landscape architecture, law, library services, publishing and marketing. The following section describes the way the interaction sessions were held and the types of data and feedback that were gathered.

7.2.2 Interaction Sessions

The interaction sessions were conducted in an informal manner as small social gatherings during which people could try out the different prototype media applications on the TViews table. The apartment owner acted as a host for the social events, and the invited guests were for the most part friends or family members that he sees on a regular basis. The host created a relaxed atmosphere for the interaction sessions, and participants could play with the table in a realistic setting rather than in a contrived laboratory space.

Since the participants were mostly young professionals with full-time jobs, the interaction sessions were typically held in the evening or on weekends, and generally involved an informal dinner followed by casual chatting and social interaction in the living room, where participants sat on a couch and chairs around the TViews table. At this point, they would try out the different applications on the table, often choosing to interact more or less with certain ones depending on their particular interests. As the evening wound down, we engaged people in an informal brainstorming session to gather their feedback about the table and to see what they imagined would be interesting applications and physical contexts for this novel consumer appliance. Figure 7.9 shows participants interacting with several of the media applications on the TViews table.

Figure 7.9: TViews multi-user interactions

Close-up images of multi-user interactions with several different applications on the TViews table: viewing pictures in the map browser on the left, depositing a stone in a game of Pente in the middle, and improvisational play with Springlets on the right.

We used video and audio recording for data collection purposes during the interaction and brainstorming sessions. Participants were also asked to complete a questionnaire before leaving. The questionnaire was used to gather background information about each participant's level of media and technology use, and to get some specific comments and feedback about the interaction sessions. The following section presents a summary of the feedback and results. A broader discussion of the implications is provided in Chapter 8.

7.2.3 Observations and Feedback

We present here a summary of the observations and feedback that was gathered over the course of the interaction sessions. This is presented from the perspective of the table's technical performance, interactions with the different types of applications, and general comments from the brainstorming sessions and questionnaires.

Technical Performance

Overall the system performed well, and participants were able to use the pucks without difficulty. The only significant technical issue that came up had to do with the accuracy of the position sensing technology. A number of people commented that the pucks were not precise enough for certain interactions, such as dropping a Pente stone at an exact point on the game board.

There seem to be two main sources for the positioning inaccuracies. The first of these is positioning error. This generally results from poor contact of the pucks to the surface of the table, causing them to get incorrect readings of the transmitted acoustic signal. As we discussed in Chapters 5 and 6, it is necessary for the sensor to make good contact with the glass surface in order to pick up the first peak of the signal that is traveling through it. If the contact is poor and the second peak is detected instead of the first, this can result in up to several centimeters of positioning error, or worse yet the puck might miss the acoustic signal altogether. Another cause for poor contact seems to be improperly mounted sensors. For instance, of the three pucks used for the Pente game, the red one seemed to work reliably most of the time and provided only small positioning errors. In contrast, the blue puck's computed position consistently drifted several centimeters from the puck which could be corrected only by applying pressure. When examined closely, we found that the sensor on the blue puck was mounted slightly crooked and would generally not sit flat on the glass unless pressure was applied.

The second major source of positioning inaccuracies was a lag in the display of the puck positions as they were being moved. Currently the position estimation algorithm is implemented in Java, which is too slow to keep up with the floating point computations that are needed in order to estimate in real-time the positions of all the pucks on the table as they are moved around. Eventually, these calculations should be handled by a low-level system driver that is optimized for the particular position estimation approach and hardware platform used.

Picture Applications

[Example Interaction Sequence]

Amy: [Dragging an image collection to a location] *Two pictures from Jill's home town... or college...*

Fred: [Switching focus from his own puck] *Oh, the college... I took these!*

Amy: *That's the college?* [Moving to next picture in the collection] *Oh... and there she is in her big coat... it's cold there.*

Jack: *Cold, rainy and wet...*

Amy: *Rainy and wet in Ireland...*

The pictures used in the Picture Sorter and Map Browser were from a recent trip that the host took to Ireland with some of his family members. People adjusted quickly to the use of multiple pucks to browse and sort the images, and much of the time two or more people would be viewing different collections at the same time. We observed that when this was happening, people were able to fluidly and repeatedly switch their focus between their own interaction and that of others. This seamless switch in focus is common when people browse physical photographs on a table, and demonstrates that this natural type of interaction transitions easily into the tangible tabletop space. We also observed a lot of shared interactions, where one person would be controlling a puck, and the other person would use a second puck to drag images from the first person's collection in order to take a closer look at them. Again, this shows that the TViews table provides people with the ability to interact in a similar way with digitally stored pictures as they would with physical ones.

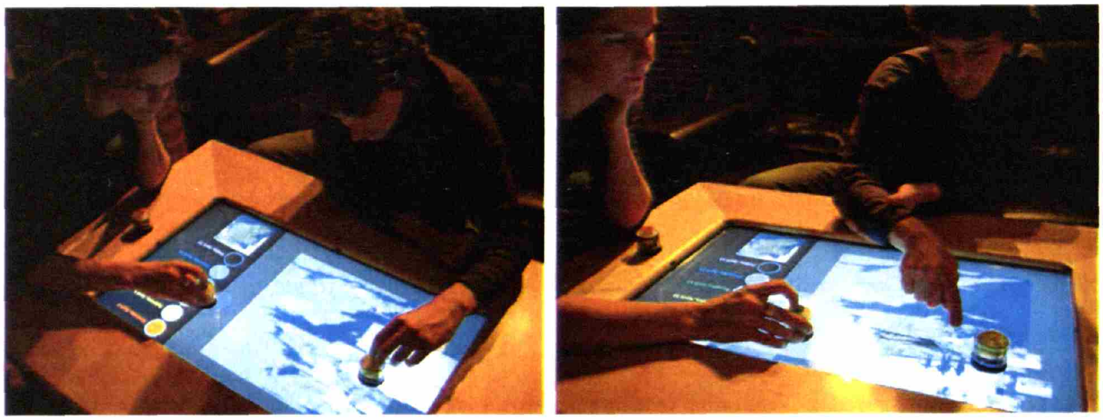


Figure 7.10: Map browsing interactions

This pair of images shows a couple of people switching their focus as they interact with the spatial picture browser. In the left image, each person focuses on their own puck. In the right image, the first person has switched their focus in order to look at an image from the second person's collection.

The map browser was the more successful of the two applications. People generally don't want to organize photo collections that are not especially relevant to their own lives. In this particular case, they had the option of browsing the images on a geographic map that provided a physical and spatial context for the collection. By framing a photo collection with context (provided in this case by the application) and story (provided in this case by the host), even an unfamiliar photo collection can suddenly become fun to browse. The host told many stories about his travels around Ireland, while his family and friends navigated the pucks around the map, asked questions, and searched for particularly interesting photos. Some people suggested that the sorting application and map browsers should be paired together as two different views of the same collection – one for organizing and editing the collection, and the other for searching, browsing and viewing the images.

In both applications, large numbers of images were sometimes difficult to handle when they were all displayed at once. This was more problematic in the Picture Sorter, since all of the images remained visible at all times. In the Map Browser, only the particular days or locations that a user was viewing were visible at any given time, which worked well as an organizational strategy. One person suggested that a zooming approach in the Picture Sorter could be used to zoom in and out of different clusters of images in order to support multiple different views or examine only subsets of the image collection at a time. In this way, it would also be possible to support multiple levels of clustering, where sub-clusters could be created within higher-level clusters.

This question of how to visually represent and manage large collections of pictures or other kinds of data on the screen is an issue that comes up in traditional graphical user interface design as well. Potential strategies include hierarchical views and spatial layouts that can be panned or zoomed. For media table interface design, there is an additional parameter that needs to be considered – that of directionality.

Currently all the pictures on the TViews table face in one direction only (i.e. the normal orientation of the flat-screen display in the table). Yet people often sit on all sides of the table when they interact, and so text and pictures appear upside down or sideways to certain users and can be difficult to view. Section 8.2 discusses the problem of orientation on tabletop displays and considers possible approaches that could be used to address the issue.

Figure 7.11: Interface orientation

The left-hand image shows people interacting with the picture browsing application from different sides of the table. The person on the left side needs to angle his head in order to see the pictures with the correct orientation. The right-hand image shows people on opposite sides of the table playing a game of Pente. The application interface is designed to be viewed equally well from all sides.

Another question that was raised for the Picture Sorter was how to annotate or tag the image clusters. Since a media table does not necessarily provide a keyboard device, text input can be problematic. Several ideas came up during the brainstorming sessions. Some people suggested using an on-screen keyboard where the letters could be selected using the pucks. Another idea was to provide a keypad-device as an add-on for certain pucks that could be used in the same way that a cell phone keypad is used for text messaging. One user also suggested that it would be nice to be able to use a normal cell phone to send text messages to the table or to specific pucks on the table.

Game Play

[Example Interaction Sequence]

Bob: [Pointing] *But you've gotta put it there...*

Tom: [Pointing] *Right, because he'll have...* [Indicates region of pieces on board]

Bob: *No, I guess it doesn't really matter.*

Jack: [Laughs]

Tom: *Ah, we'll put it here...* [Places piece]

Jack: *I love my friends.*

Tom: [To Bob as he prepares to place piece] *So you gotta knock that out, and then he'll have* [indicates area on board]... *and you'll get to put another piece somewhere.* [Bob places piece]

The Pente game proved to be very popular, particularly with participants who were already familiar with the board game. The puck interaction was very natural, and people did not focus on the technology at all during game-play (aside from the times when a sensing error caused a mistake in a person's move). Even though Pente is a turn-based game, all participants said they preferred to each have their own puck rather than to share a single puck between multiple people. Since traditional board games typically provide separate pieces for each player, this is a well-known interaction style and it provides players with a physical object that they can identify with during game-play. We observed that several people actually held the puck in their hands even when they were not using it, rather than leaving it sitting on the table. This behavior brings up an interesting design issue, which is how to map the pucks to the virtual objects within the game space. Different board games use different approaches to map the playing pieces to the space of the game board. For instance in a game of chess or Monopoly, the pieces must remain on the board at all times and they move around mostly within the space of the board (unless they are captured for instance). In contrast, in a game such as Pente the stones are picked up from a central bin at each turn and deposited onto the game board, which suggests a mapping where pucks are used to drop stones rather than act as stones themselves. The question of mapping physical interaction objects to the application space will be discussed further in Section 8.1.

The enthusiasm that people had for the *Springlets* application was quite surprising. We had initially thought that the application might be too simplistic to provide an interesting example, but we found that many people became very engaged with the improvisational form of interaction, calling it "addictive" and "mesmerizing". People often turned the interaction into a form of game play, where they would try to capture the bouncing masses with their pucks, sometimes even using two pucks at a time (one in each hand) or trying to coordinate their movements with those of other players. Many participants said they wanted to see more games on the table that would engage them in collaborative or competitive play where they have to coordinate their movements with one another while simultaneously trying to control a dynamic system in the virtual space. Along those lines, a number of people suggested that simulation games would be particularly appropriate, such as the line of popular games produced by Maxis (SimCity, The Sims, etc.).

General Comments

In addition to the application-specific comments gathered during the interaction session, we also held a more general brainstorming session at the end of each session and asked participants to fill out a simple questionnaire. The results of the questionnaire are summarized in the graph in Figure 7.12.

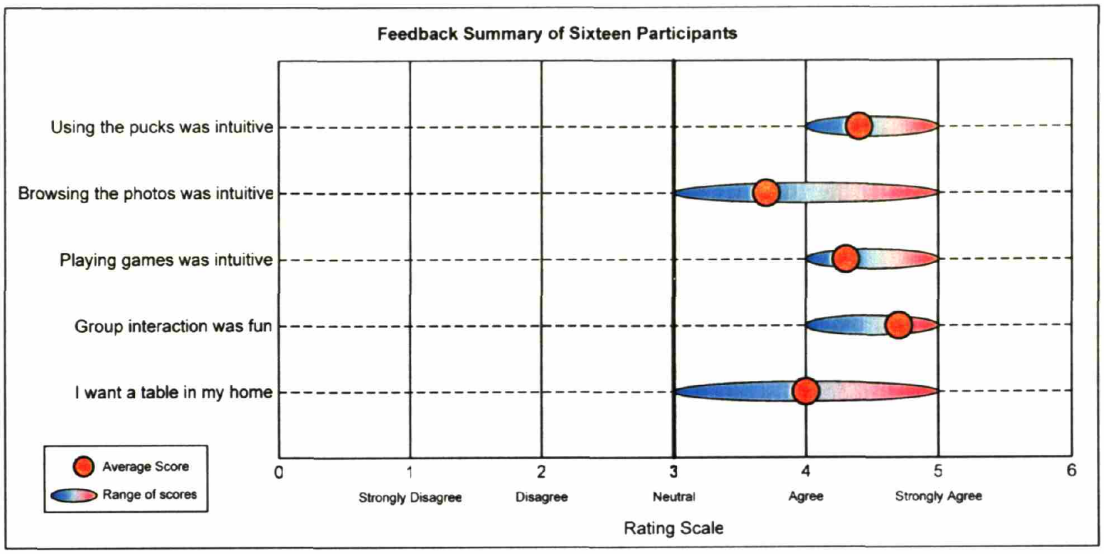


Figure 7.12: Participant feedback summary

This bar graph provides a summary of the results from the feedback questionnaire. The rating scale ranged from 1 (strongly disagree) to 5 (strongly agree). The shaded ovals show the range of ratings for each question, while the circles show the average rating.

In general, people found the pucks intuitive to use and they liked the idea of a shared tabletop interface for the home. On average, people found the picture sorting and browsing activities less intuitive than the games. This result was somewhat surprising, since we had imagined that the picture sorting which is based on a physical-world metaphor would be very easy to understand. One reason for this result might be the positioning errors, which sometimes made it difficult to grab and hold the photos. Another reason might be that the pucks were acting only as generic handles, and so the picture sorting could have been done just as easily with a touch-based table display. The question of object mappings and the pucks as physical handles will be discussed further in Section 8.1.

In the case of the Map Browser, it seemed like the association of pucks to days of the week was not immediately obvious to most people, however once they understood this mapping people had no trouble figuring out how to navigate the map space and find images. In terms of the mapping alone, the approach we used in the past (in the *Tangible Spatial Narratives* application discussed in Section 4.2.2) gave better results. In *Tangible Spatial Narratives*, physical pawns were associated to people within the application space and could then be moved to different locations around the map. This seemed easier for people to grasp than the current approach of associating pucks to different days of the trip.

Overall, people all found the shared interaction to be a lot of fun. When asked whether they would like to have a media table in their home, the responses ranged from neutral to a very positive "yes". Some people were hesitant to add another technological device to their lives and worried that it might demand too much of their time. Several people said they would like many of the surfaces around their home to be media-enabled, in such a way that they could turn them on or off as desired, and so that they could use them in place of their regular desktop PC for everyday tasks such as checking their calendar, finding directions, or managing other media devices. A few people said they would love to have a table like this simply to play games. One person suggested using the table for a new form of multi-person digital game-play in which success or survival in the game would involve group dynamics and the simultaneous control of many objects on the table at once. The example he proposed involved a group of people all contributing to a real-time simulation that uses multiple control points to balance a tilting world where virtual objects are in danger of falling off from different sides unless the players cooperate to keep them on the surface. With this kind of game, it would be possible to use the digital system to give players the illusion of a 3D world even though they are actually playing on a planar surface. This form of game-play could be extended to encompass many different kinds of real-time systems simulations of far greater complexity, for instance the control and balancing of complete ecosystems. These types of games could run on one individual table at a time or could involve a potentially global player community across many connected tables at once.

7.2.4 Application Space and Scope

During the brainstorming sessions, participants suggested a broad range of applications for media interaction tables. These were by no means limited to interaction within the home environment alone. Brygg Ullmer has suggested a range of application areas that are applicable to tangible interfaces in general in [Ullmer 2001]. Although there is significant overlap, it is useful to consider the categorization of application domains that are relevant to media table interactions specifically.

Since different applications are suited to different physical contexts, we have structured the categories of media table applications according to the physical settings that came up in our discussions with participants: home, workplace, classroom, military, public places. The information is summarized in the table on the following page. This is not intended to be an exhaustive list, but should provide a sense of the breadth of the potential application space for a media table platform.

Physical Settings	Application Areas
Home	Personal or home management - Information retrieval (diaries, calendars, recipes, directions, etc.) - Management of home devices (appliances, lighting, security, media center, etc.) - Management of portable devices (cell phones, PDAs, MP3 players, etc.) - Messaging and remote communication
	Leisure or entertainment activities - Gaming (board games, networked games, simulations, learning, role-playing, interactive stories, etc.) - Virtual terrariums (fish tanks, etc) - Audio control (mixing, playlists, etc.) - Media browsing and editing (photos, videos, audio)
Workplace	Meetings and conferences - Data sharing and visualization (presentations, simulations, etc.) - Video conferencing and remote connectivity
	Design and planning - Interface design (visual layout, prototypes, etc.) - Systems design (electrical, mechanical systems, etc.) - Physical design (architecture, urban design, etc.)
	Control applications - System control (aircraft carriers, supply chain management, etc.)
Classroom	Teaching classroom material - History, geography, math, physics, biology, etc.
	Shared creative activities - Drawing, painting, music composition, etc.
Military	Mapping - Geographical information databases, information retrieval
	Strategic planning - Visualizing troop movements, simulated scenarios, etc.
Public places	Virtual tours - Information kiosks in museums, etc.
	Table games - Pool, foosball, air hockey (e.g. in coffee shops or bars) - Gambling (e.g. casino tables)
	Shared online access - Networked game-play in coffee shops, community centers, etc. - Chat rooms

Figure 7.13: Media table application areas

This table provides a sense of the broad range of different application areas that can be explored for media tables across physical contexts ranging from home settings classrooms and public spaces such as coffee shops or museums.

Our research collaborators at Samsung in Korea also came up with a number of different application areas that were grounded within the idea of a media table that can connect to a user's home entertainment center. Initially, their interest in the project was focused on the table as a universal control console that would be able to replace the remote control devices that are currently used to control televisions, DVD players, audio systems and other media devices. They expanded this idea to include applications that could log family history, assist with family scheduling for vacations and other events, support movie and text messaging to and from other portable devices, maintain personalized preferences for media devices and assist in the creation of play-lists for photos, music and movies. Figure 7.14 shows several interaction scenario sketches created by interface designers from Samsung. The first (shown on the top left) shows how a sensor embedded in the base of a digital camera could allow pictures to be downloaded directly to the table surface. The second scenario (top right) shows how slideshows might be created from digital content that is stored in a puck using a few simple gestures. This example emphasizes the importance of the interactive objects since it allows us to imagine how a relatively small set of gestures can be used to derive a wide range of meaning in the application space by associating the same gestures to different functions based on the physical meanings of the interactive objects. The third scenario (bottom left) shows how an existing device such as an mp3 player could be used on a media table to find the commonalities between different people's playlists. The final scenario (bottom right) shows how visual and auditory content stored in separate pucks could be combined to create a slideshow with music. What is interesting to notice here is that all of these design scenarios show only a single person using the media table at a time. We have become so used to thinking in terms of one user at a desktop PC, that even the designers who create applications for a media table platform often lose sight of the fact that it is a shared and sociable space.

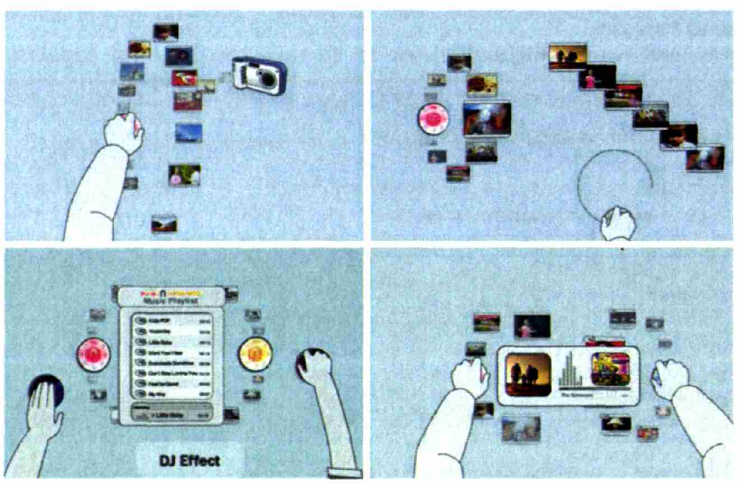


Figure 7.14: Samsung interaction scenarios

Downloading pictures from a digital camera (top left). Creating a slide show (top right). Combining two audio playlists (bottom right). Building a picture slideshow with music (bottom right).

An important point to highlight in this discussion on the scope of the application space, is that the TViews table is designed as an extensible framework that can enable this broad range of media applications and interactions. TViews tables can be constructed at varying sizes to suit different physical contexts, such as larger tables for public spaces and meeting rooms, or smaller tables for homes, coffee shops and other tightly constrained settings. The same basic sensing and communication system can be used across all these tables, and interactive objects and applications can be easily moved from one table to another. The tables can also be connected to support a variety of networked applications. This extensibility opens up a wide range of possibilities for application designers, and points forward to a rich space of future work.

Chapter 8

8. Discussion

The living room space is a very different environment from an office or a study. The latter two spaces are physically suited to single person productivity-oriented tasks at a desk. In contrast, the living room is a social setting where far more spontaneous and face-to-face interaction takes place. Sitting at a desk, people interact primarily with information, be it in digital or paper-based form. For this reason, computer interfaces that sit on people's desks focus on enabling seamless interactions between single users and digital information. This information can still be shared with other users, but the sharing happens remotely via networks of personal computers and servers.

In social spaces such as a living room, the focus of information exchange shifts from person-to-computer to person-to-person. Some media interactions that take place in a living room can be quite passive, such as watching television or listening to the radio. But even these often invite conversations amongst the people in the room. At other times, the living room becomes a lively space as people interact both with media and with each other while playing games or exchanging stories. A computer platform designed for the living space needs to take all of this into consideration by accommodating shared interactions with media that do not restrict the control and display of information to a single person alone. For this reason, a tabletop media interaction platform should be accessible and viewable from all sides, and should provide multiple points-of-control through simultaneous interactive objects.

In this chapter, we take a closer look at the major design and interaction issues that were raised when people tried the TViews table in a home environment. We begin by looking at the different ways that physical interactive objects can be mapped to a virtual media space. We also examine the difference between touch-based and object-based interaction on a table display and identify specific cases where the latter is more appropriate. Next we look the issue of orientation within the visual interface on a table display.

8.1 Multiple Objects, Mappings and Extensions

Interactive applications that use physical control points on a display surface invite different mappings between the physical and virtual spaces. In order to provide coherent and consistent interactions for users, application designers need to consider which mappings are appropriate in different cases. At the most basic level, the physical objects can serve either as generic handles for media manipulations, or as specialized objects that retain a fixed meaning within the application space. Rather than considering these as distinct categories, it is more useful to think of them as the two ends of a spectrum, where the space in-between represents the a range of different possible mappings that can provide different combinations of generic control and specific functionality (see Figure 8.1).

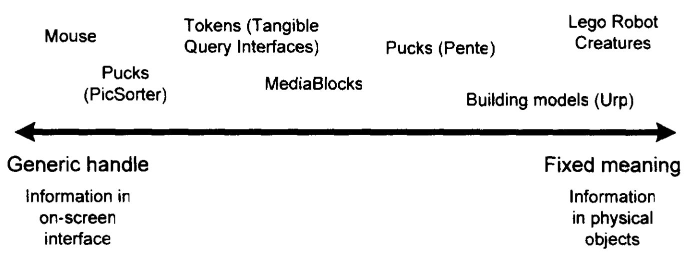


Figure 8.1: Object mapping spectrum

Mappings between the virtual application space and physical interaction objects range from generic control to fixed associations. This diagram shows several examples in this spectrum.

8.1.1 Generic Handles

The most obvious example of a generic handle is a mouse, since it can be used to grab hold of any virtual object from any application space and manipulate it in different ways. Touch pads are another example of generic interaction points, although in this case there is no object, and fingers or hands are instead used for the manipulation of media elements in the virtual space. In the case of the TViews table, the Picture Sorter application provides multiple generic handles to grab and sort individual images or entire clusters at a time. With its currently limited functionality, the Picture Sorter does not differentiate between the different interaction points even though each one is equipped with a unique identifier. While it is important that the interface provide multiple simultaneous points of control in order to allow multiple users to work together, the existing functionality could perhaps be more easily accomplished using a multi-touch system since these generally do not distinguish between the different touch points. However eventual versions of the Picture Sorter application might provide features such as interaction logging for different users or the ability to store picture collections within individual physical objects. While these kinds of functionality could still make use of the pucks as generic control points, they could no longer be supported by a multi-touch tracking table.

Touch-based systems begin to break down when some of the content or meaning moves out of the on-screen application space into the physical objects themselves. In the case of media organization, people might want to bring to the table the collections they have stored within their own interactive devices. On the table these interactive devices might still act as generic handles for manipulating images and collections, but they also have an additional level of functionality as personalized storage devices. Add-on input and output elements on the objects could then allow the images to be copy to the table for sorting. Conversely, new images could be copied onto any interaction device with a few simple drags and button clicks. Small displays and sliders or pressure pads on the objects might be used to scroll through their contents, and the media table would act a shared space for friends to view and swap their separate media collections. The sensor tags could even be built directly into the base of existing portable media devices like mp3 players or digital cameras, allowing these objects to serve a dual purpose. Brygg Ullmer explored the concept of media blocks and other physical tokens for storing and manipulating information in [Ullmer 2002]. His system focused on query tasks for large data content sets, and his tokens were designed to be used together with structures called constraints through which the data could be manipulated and retrieved.

Separate pucks with unique identities are also required in cases where the interactive system needs to track the particular interactions that happen with each object. For instance, an application might derive information about a particular user's preferences based on their history of puck interactions. In this case, the system would first need to ask users to identify themselves when using a puck. From that point, it would be able to track their interactions and in the case of media browsing it might use the data to make suggestions or generate automated playlists. In this example the physicality of the interactive objects is not being used. The same functionality could be accomplished using a touch system that is able to distinguish between multiple different users. The problem is that touch tablets typically do not provide this functionality. The one exception is the DiamondTouch table developed by researchers at MERL [Dietz 2001]. This technology can track up to four users at a once, however it is still quite cumbersome since it requires users to be coupled into antenna pads on their chairs thus restricting their ability to move freely around the table.

It is worth noting here that most touch technologies are still limited to single-point tracking which is not appropriate for multi-user interactions. Capacitive and resistive touch-screens tend to get confused by multiple touches. Many touch surfaces also cannot tolerate objects being placed on top of them, which would be problematic for use in a home setting where people typically place all kinds of things on their tables (cups, coasters, pens, keys, etc.). Systems that can track multiple touches include the FingerWorks Fingerboard [FingerWorks 2005], Tactex smart fabric technology [Tactex 2005], JazzMutant's Lemur [JazzMutant 2005] and a multi-touch tablet created at the University of Toronto in the mid-80s [Lee 1985]. Most of these multi-touch surfaces have very small surfaces that are most appropriate for a single person using multiple fingers. Lemur is the only one to provide an embedded visual display.

Generic interaction objects can also be used in cases where a dynamic real-time system requires many objects to be continuously controlling different elements in the on-screen space simultaneously. In this case, finger touch alone would not be sufficient, since at times objects might need to remain positioned at a specific spot on the table while uses shift their focus to other areas and manipulations. A simple example of this is the *Springlets* application, where one can fix a mass to a certain location simply leaving the puck attached to it while other pucks are used to trap the remaining masses. In this way, users can position pucks at several key points and rapidly shift between them. One user suggested an interesting application that relates to this concept: a learning application that controls the functioning of the human body. Users would be required to control different biological and chemical processes within the body and monitor them in real time. In this case, the pucks need not be only generic objects, but could also be provided with specific functions for tuning different parameters within the system. For instance, add-on input devices such as pressure pads, dials or light sensors could be added to control functions specific to certain body parts. This idea of real-time dynamic control extends to other kinds of simulation systems for both learning and game-play. An interesting example of this is John Underkoffler's Illuminating Light system, in which the manipulation of physical lenses on a display surface generated a simulated hologram on the display [Underkoffler 1998]. These examples gradually lead toward the other end of the spectrum, where physical interactive objects are assigned fixed meanings within the interaction space.

8.1.2 Fixed Meanings

In the case of Underkoffler's holograph setup as well as his urban simulation system [Underkoffler 1999], the physical form of the interactive objects was representative of their virtual counterpart within the application space. That is, objects that represent buildings in the virtual space look like buildings in the physical world, while objects that represent lenses in the virtual space look like real lenses. As such, these objects have a fixed meaning and as a result can be used to control only specific media objects or perform specific functions within the virtual application space. An example of this is seen also in the TViews Pente game, where each player used a specialized piece to control their own set of stones on the board. The pieces were equipped with yellow, red, and blue colored icons on top in order to physically distinguish them from one another. During gameplay, we noticed that users would identify with their own piece, often holding onto it even when they were not using it to make a move on the gameboard. This identification with physical playing pieces can also be seen during play with traditional board games. In games like Monopoly, some people can be very selective when choosing their playing piece, preferring to be a car rather than a thimble for instance.

The possibilities for assigned fixed meanings to interactive objects extends beyond the notion of physical form alone, since the objects in TViews can also be provided with customizable functionality through the use of add-on elements including storage capacity or input/output devices such sensors, displays, buttons, and other elements. We have already looked at how these elements can be used together with objects that otherwise act as generic interaction handles or how sensor tags can be embedded into existing portable media devices. It should be noted that objects with fixed meanings fall entirely into the space of the application designer, since they can tailor the object in whatever way they feel is most appropriate for their particular application, either through physical design, input/output customizations, or custom functionality with the virtual media space. At this point, it is worth looking at a specific example to illustrate this point.

In the case of evolutionary or simulation games, users can design their own creatures and launch them into a landscape to see how they will behave or to test their ability to survive with other creatures under a certain set of environmental conditions. One example of this in the purely virtual space is the A-Volve piece designed by interactive artists Christa Sommerer and Laurent Mignonneau [Sommerer 1997]. In this system, users draw virtual creatures and then send them off to live and evolve in a water filled pool. Another example in the physical world is the Lego robots that kids build from Programmable Bricks [Resnick 1996]. These robots can be equipped with physical sensors and actuators that control their behavior within the physical world. The TViews table provides a space where these two approaches to evolution and simulation might eventually be combined. Physical creatures could be created from the pucks and various physical and sensory customizations, and then placed into a complex virtual environment on the media table. In this space, they would be able to test their survival skills and instincts under a variety of different conditions. This interaction space could potentially provide a far greater level of complexity than the physical space alone, through complex virtual terrains and environmental conditions. These landscapes might even be created by the system users, and could be networked together to generate a global virtual world for evolutionary game-play to unfold on many connected tables. The creatures in the virtual space would then be controlled by their physical counterparts, and affected by the specific physical customizations provided by their users. For instance a creature that equipped with a physical temperature sensor might convey some of this information into the virtual space. This might affects its behavior, perhaps giving it a fever or making it become hot-tempered above a certain temperature threshold. Physical creatures placed on the same table might also be able to interact with one another, generating appropriate actions within the virtual space, and creating another interesting combination of physical and virtual game-play for groups of users in the same space.

8.2 Point-of-View and Directionality

When designing applications for a table display, one needs to consider the point of view of different users interacting with the system. Vertical displays are designed to have a single orientation since they are viewed from the front only. In contrast, horizontal display surfaces on a table can be viewed from many different angles since people generally sit at different sides. In the Pente and Springlets applications, the interfaces were designed to be directionless and could be equally well viewed from all sides. The question of orientation within the interface came up in particular with the two image-related applications, since photographs can be properly viewed from one direction. In thinking about multiple viewing angles, we can look to the area of board game design where the issue has been resolved in a number of different ways. Many board games such as Pente, Go and Othello have no inherent directionality since the board consists of a simple grid. Some games such as Scrabble provide a directionless board together with pieces that have a specific orientation (e.g. letter pieces). In this case, a principle orientation is often selected during gameplay, or at times no single orientation is determined and different pieces face in different directions depending on how people choose to place them on the board. Finally, other games such as Monopoly use an approach where elements on the surface of the board are oriented towards the closest edge. Figure 8.2 shows several examples.

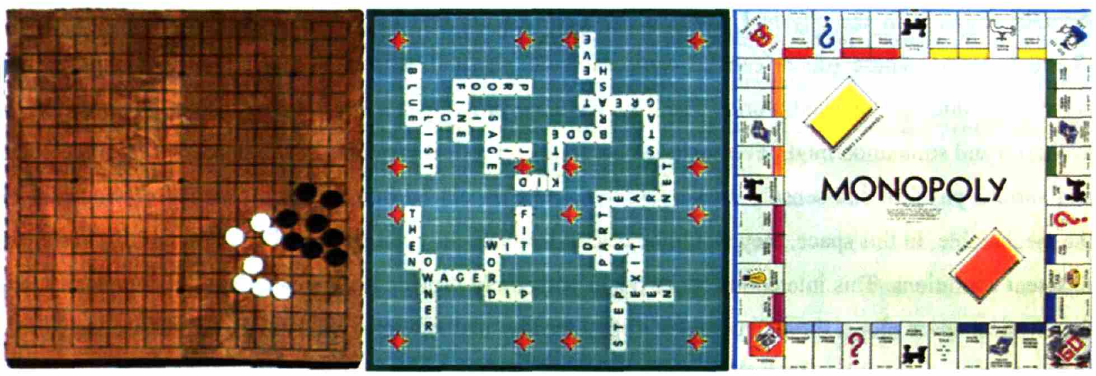


Figure 8.2: Board game orientation

The Go board on the left can be viewed equally well from any of its four sides. While the Scrabble game board in the center has no inherent directionality, pieces face way different ways depending on how players have put them on the board. The Monopoly board on the right show a board game design where all visual elements face the nearest edge.

We envision two different approaches for handling different points of view on a table display. The first is based on the visual presentation strategy used in Monopoly, however it needs to be extended in order to accommodate dynamic graphics through the automated rotation of media objects based on their current position. This approach has been explored by researchers working on the DiamondTouch table at MERL in their Personal Digital Historian (PDH) system [Shen 2003]. In this example, the application is realized on a circular table, which uses a radial coordinate system to position all thumbnails and media objects in an orientation that faces the outer edge of the circle. Another example is the LumiSight table from NTT, which has a square form and provides a different screen image with the correct orientation for participants on each of the four sides [Matsushita 2004]. Since this solution can make it difficult for users on the far side of the table to view certain objects, a lazy-susan sort of approach can be used to spin the entire interface around at once.

A second approach for handling orientation is to provide an interface that is effectively directionless, allowing users to control the orientation of individual graphical elements themselves. In this case, designers need to consider how the rotation of interface elements should be controlled. One possibility is to equip the interactive objects with a rotational input, such as whole-object rotation sensing, or an add-on dial. Another option is to provide orientation handles in the corners of the media objects on the on-screen display that could be activated for instance with a button press. Each of these interface orientation approaches has different advantages. While the first approach requires no additional input from users and is perhaps cognitively easier to manage, the second approach provides finer control over individual elements. It is also possible to provide users with the option to switch between these approaches, to provide a combination of the two, or to set a fixed angle of possible orientations depending on how people are seated around the table at a given time. The DiamondSpin application programming interface for MERL's DiamondTouch table provides the option of combining these approaches by describing each media object in polar coordinates with respect to the center of the table. Objects automatically oriented themselves to the outside, but could also be re-oriented in order to be viewed from different angles.

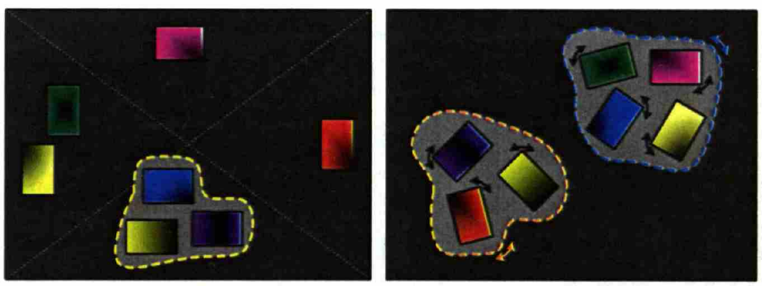


Figure 8.3: Multidirectional interface approaches

On the left, thumbnails automatically face the nearest edge. On the right, each thumbnail and cluster can be rotated freely using a handle in its corner.

Another interesting question is the design of fixed visual interface elements within certain media table applications. Static icons within the interface might not be reoriented at all if they can be visually designed to be readable from different directions. In the case of the TViews Pente game, several static icons were used such as a player-turn indicator, as well as new game and quit options. All of these icons were designed symmetrically in order to be equally well viewed and understood from any direction. In the cases were text is required to convey information, the art of *ambigram* design could be explored for tabletop interfaces. Artists such as John Langdon and Scott Kim specialize in the visual presentation of words, playing with illusion and symmetry to create words that can be read in different ways or from multiple points of view [Langdon 1992, Kim 1981]. These multi-directional words are called *ambigrams*.

Figure 8.4: Ambigram

This ambigram was designed by John Langdon for Dan Brown's novel Angels and Demons, and is perfectly symmetrical along the horizontal axis. It is shown right side up (left) and upside down (right).

The question of interface orientation also came up with users in discussions around the map of Ireland displayed in the Map Browser application. Spatial maps typically present an overhead view of a geographical region, and as such they should have no overriding orientation apart from the textual labels or location names. Yet we are nevertheless accustomed to seeing maps in a particular orientation, with North facing upwards by convention. A number of artists and cartographic experts have challenged this notion in an attempt to overturn a single-minded world view that is oriented in favor of the dominance of the Northern hemisphere (both economically and in terms of land mass). A famous example is the upside-down map of South America from 1943 by Uruguayan modernist Joaquín Torres-García. Torres-García placed the South Pole at the top of the earth, suggesting a visual affirmation of the importance of that continent and in an effort to present a pure revision of the world. Other examples include a number of world maps from Australia and New Zealand where the Southern hemisphere appears on top. Figure 8.5 shows the Torres-García map and an upside-down map of the world. It is worth noting also that navigation systems in cars also typically reorient themselves so that the direction of travel always faces upwards rather than maintaining the conventional orientation.

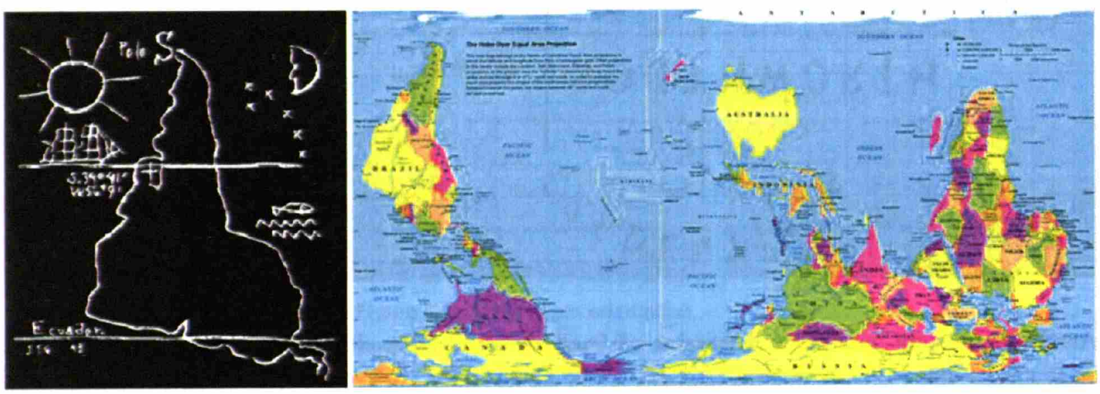


Figure 8.5: Upside-down maps

The left side shows the map of South America drawn by Uruguayan modernist Joaquín Torres-García in 1943. The right side shows a map of the world where the Southern hemisphere is placed on top.

Chapter 9

9. Conclusion

> *"Don't imagine you know what a computer terminal is. A computer terminal is not some clunky old television with a typewriter in front of it. It is an interface where the mind and body can connect with the universe and move bits of it about."*
>
> -- *Douglas Adams, Mostly Harmless*

The computer as we know it today, with its vertical screen, keyboard and mouse, is a malleable multi-purpose tool that can be used by different people toward widely differing ends. Yet the actual complexity of the digital medium is far greater than this particular implementation of the interface and interaction modality would seem to imply. At the lowest level, streams of bits can be shaped and reshaped to represent many different kinds of information that can be viewed and modified in real-time by the hand of a human interactor. The means of interaction is governed by the shape and affordances of the interface of each particular platform.

As we discussed at the beginning of this dissertation, the interfaces that shape our digital interaction change over time, often independently from the underlying algorithmic constructs and data representations. Across the history of digital computing, the interfaces presented to users have taken on a variety of forms: from the card punch and reader, to the keyboard, mouse and vertical screen of personal desktop systems, to the small screen and keypad of modern day handheld devices. These and other interfaces have shaped the way we perceive and understand the realm of computing and the types of operations and interactions we can perform within it. While the range of applications covered by these interfaces is broad, the types of interactions they afford between people are limited to those that are necessarily mediated through the technology. They cannot engage people in face-to-face interactions with one another around digital media content.

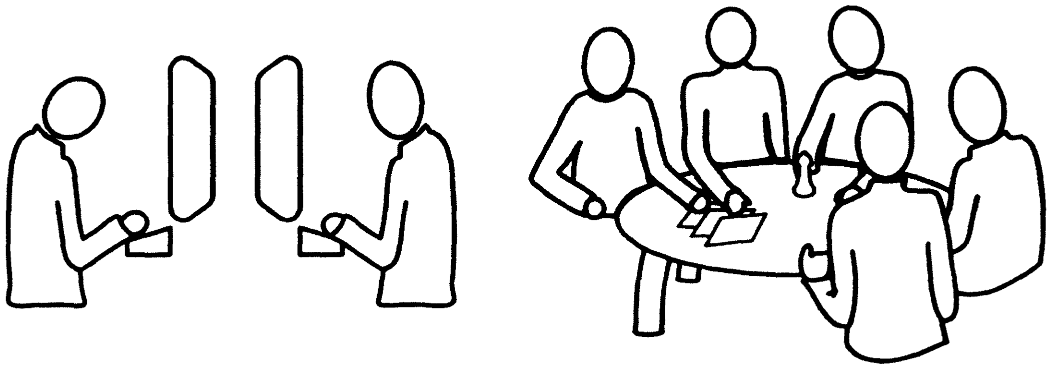


Figure 9.1: Media interactions
The left side shows two users interacting with media content on desktop computers. The right side shows a group of people engaging with physical media artifacts around a tabletop. In the former case, there is little room for face-to-face sociable media interactions. The tabletop is a much more suitable space for sociability and casual conversation amongst users.

The emerging area of tangible interface research has proposed new kinds of interfaces that bring our digital interactions into physical spaces, surfaces and objects, where they can become more collaborative and sociable in a way that our non-digital interactions have always been. The research presented in this dissertation has built on prior work on interactive tabletops as spaces for shared interactions around digital media content. While past prototypes have shown the value of this kind of interaction, they have all faced technological barriers: small sensing surfaces that are difficult to scale, limited numbers of tracked objects, and overhead projected displays that are cumbersome and difficult to setup in everyday spaces. This thesis has formulated a method for the creation of a scalable and general purpose media table that can extend across different physical contexts and can support a broad range of media applications and interactions. To conclude, we provide a brief summary of the thesis contributions and suggest some future directions for this research.

9.1 Contributions

In supporting the thesis statement and claims, the dissertation has made a number of specific contributions discussed in Section 1.3. These include:

1. Identification of scalability parameters for media table platforms

2. Formulation of an extensible method for media table platforms

3. Development of an innovative sensing approach for dynamic object tracking on glass surfaces

4. Development of an Application Programming Interface for media table development

5. A taxonomy of interface design considerations for media table applications

6. Prototype designs for media content browsing, digital storytelling and game play applications

9.2 Future Directions

Designing tabletop media platforms and applications for shared spaces encompasses a broad range of research areas. These range from low-level sensing design and hardware/software development, to the creation of high-level application and interfaces, and finally to the physical and mechanical design of the table and interactive objects themselves. This thesis has made contributions in all of these areas, and there is potential for future work to explore several specific research directions in greater depth: the technical design of the platform and sensors, the management of tabletop applications and interactive objects, and the development of media applications across a variety of domains and physical settings.

9.2.1 Technical Design and Development

The results of our technical evaluation suggest future research in the areas of sensor design and signal propagation. First of all, there is a need to improve the contact of the acoustic sensors with the glass surface when the pucks are moving so that they will not lose sight of the signal. Possibilities to explore include the use of point-contact sensors like phonograph needles that can operate at a high frequency, and non-contact sensors that could sit slightly above the glass. Our initial tests with ceramic phonocartridges have shown that it is possible to pick up a low frequency signal traveling through the glass and suggest that this is a worthwhile direction to pursue. Using this kind of point-contact approach for sensing, it might be possible to create objects in the form of a pen or stylus which could provide greater tracking precision than the current circular base puck design. A pen or stylus would be better suited for certain tasks such as drawing or writing than the current pucks. Secondly, the dispersion of the signal as it travels through the glass limits the scalability of the table in terms of size. The current configuration is ideal for coffee tables and could most likely be used for dining room tables as well. In order to create larger interactive tables, for instance for a conference room or banquet hall, it would be necessary to expand the system to support a greater number of transmitters around the edge of the table surface. It might also be necessary to use thicker glass for larger table surfaces.

The TViews table currently uses an infrared approach for data communication. This approach requires direct line-of-sight between the object and the infrared transceivers placed around the edge of the glass. In the current configuration, eight transceivers provide an over-determined system so that the pucks on the table are always able to communicate with the table system (unless they happen to be completely surrounded, which is unlikely to be the case in normal use). For future implementations, it would be worthwhile to explore a radio-based data communication approach in order to eliminate the need for line-of-sight between the interactive objects and the data transceivers located in the table.

Approaches for sensing the orientation of the pucks would also be an interesting area of future research. Our initial tests suggest that it might be possible to use the eight infrared transceivers in the TViews table to infer the approximate orientation of the pucks, however this has not yet been implemented in the current design. Sensing the orientation of the pucks would provide designers with an additional degree of freedom in the development of media applications and interactions. For instance, virtual media objects could be easily rotated simply by spinning the pucks around, which could help to address some of the issues regarding a user's viewing angle on a tabletop surface that were discussed in Section 8.2.

9.2.2 Table and Application Management

An interesting area of future research is at the level of the table and application management. The current TViews API and media applications are implemented in Java and run on a regular Windows PC that is contained inside the table. However files and folders are not an ideal metaphor for tabletop interactions, which tend to be far more media centric and involve shared interactions between multiple people at once. There needs to be a new visual metaphor for organizing tabletop applications and media content that can take the shared nature of the tabletop space into consideration. This kind of metaphor should provide a means for managing the interactive objects across media applications, and for coordinating the way users switch between different applications that are running on the table at the same time. Different interactive objects might be associated to different applications that launch automatically when they are placed on the table. For instance, placing a digital camera with an embedded tag on the table might launch a photo sorting application. Or if objects from several applications are placed on the table at once, then the table might instead provide a means of selecting a particular application or perhaps switching from one application to another.

9.2.3 Application and Object Design

There is a broad range of potential applications for media table platforms, and tabletop researchers have thus far only scratched the surface of this emerging area for human-computer interactions. Different media applications are suited to different physical contexts and settings, such as the home, classrooms, workspaces and public spaces. Yet while many combinations of digital applications and tangible control are possible, the intent and mode of interaction of any particular application imposes constraints on the design of the interface and on the negotiation of shared control on the tabletop. Much research is yet to be done on further characterizing the different kinds of media applications possible for tabletop environments, and on creating consistent design strategies that can span across different application domains.

Prior media table prototypes have been one-shot approaches which were used to demonstrate the value of specific interaction or application concepts. They have not focused on creating a strong underlying technical framework, and the technology of interactive tables has remained unreliable and cumbersome, preventing media tables from making the leap into our everyday environments and gaining widespread use. Furthermore, there has been no general purpose model for media table platforms that could easily allow large numbers of interactive objects to be built and to run across multiple platform instances at once. Now that we have an extensible method for creating media tables and an easy API for tabletop development, we would like to grow the community of developers who can create applications for the platform based on ideas that researchers already have. For instance, the possibility to build many tables and to connect them together opens up the space for new kinds of multi-person game play that can bridge the worlds of already existing physical and digital games.

Together with the development of the application space, we would also like to push forward the design of interactive objects, providing custom shapes for different applications as well as possibilities for additional input/output elements like small displays or sensors. We would also like to put the tags into existing digital media devices, such as mp3 players or digital cameras, in order to provide new ways of sharing and exchanging the digital contents within them.

In closing, we return to the diagram which illustrates how the development of an extensible technical solution and general purpose method for media tables can open up the application space and allow a broad range of applications and concepts to emerge. If we can now continue to grow the application space, we hope this will feed back into the development of the platform itself. Through this cycle of growth that pushes on both the platform and application development in turn, we hope that media tables can make it into our homes soon.

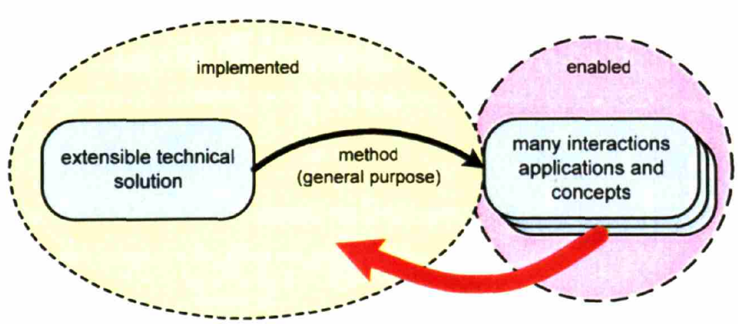


Figure 9.2: Thesis approach revisited

Now that we have an extensible method for creating media tables, we can grow the application space. This will in turn feed back into new platform developments. The cycle of growth will hopefully allow media tables to make it into our homes soon.

Appendix A

A. Circuit Designs

The following pages show schematics for the TViews table master control circuit and puck circuit.

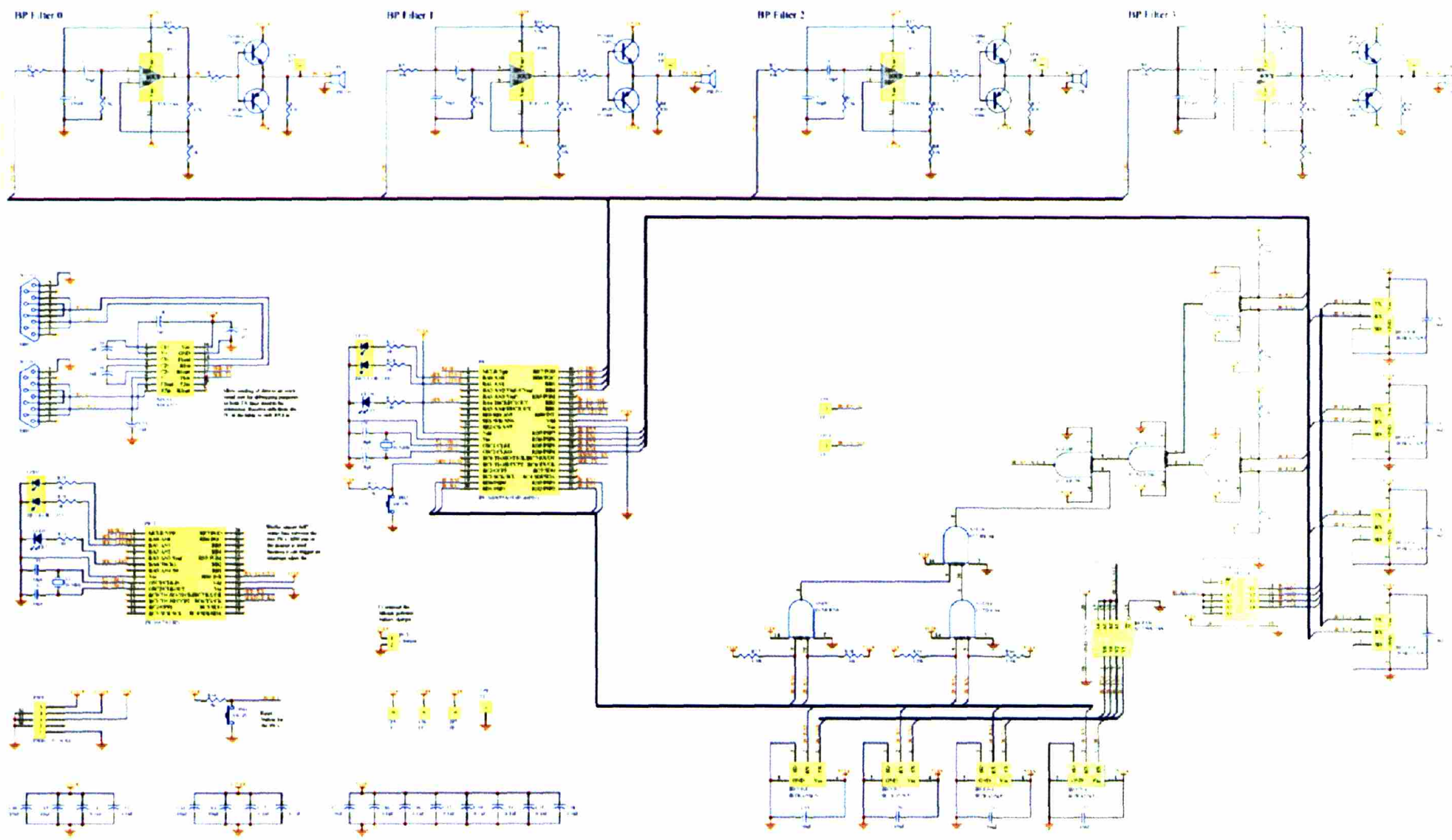


Figure A.1: Schematic of master control circuit.

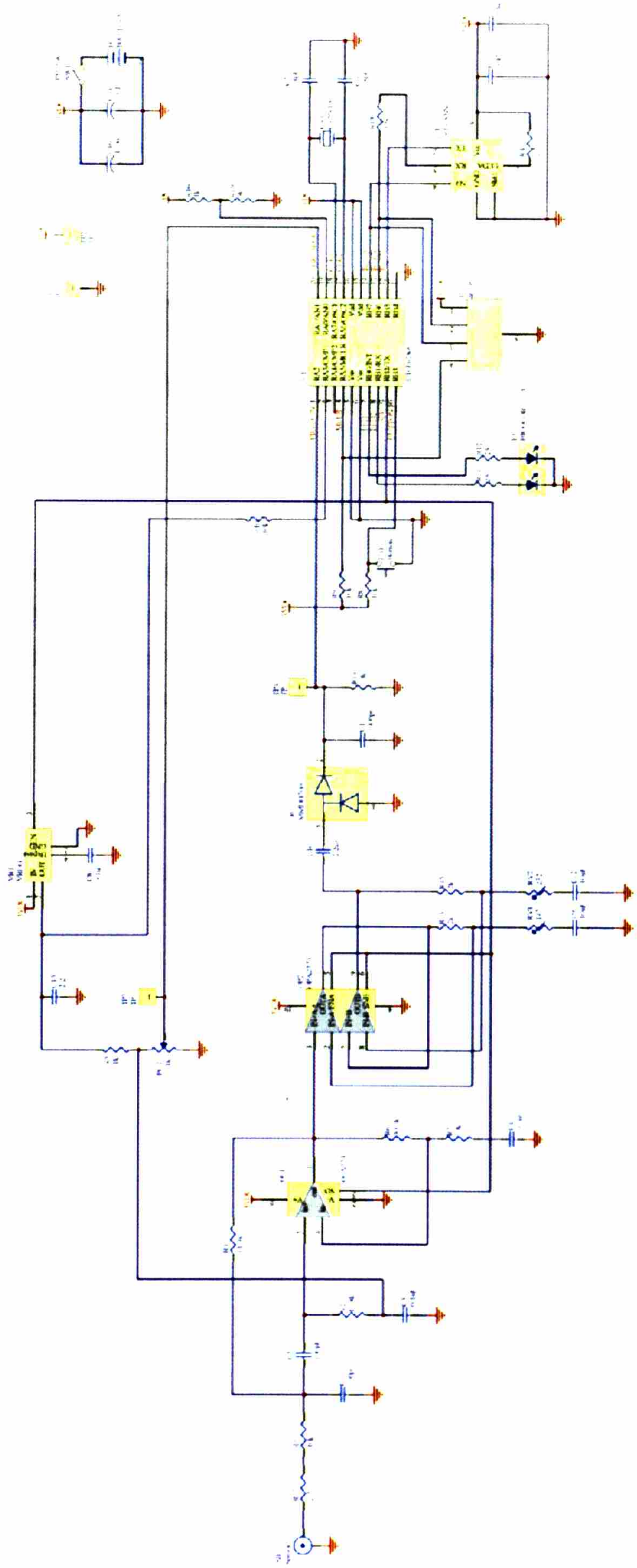


Figure A.2: Schematic of puck circuit.

Appendix B

B. Firmware Diagrams

The firmware developed for the TViews table master control board and pucks was implemented in Assembly by undergraduate student Carsten Jensen and was based on the specification illustrated in the state diagrams on the following pages. The master control board firmware runs on a PIC16F877A microcontroller from Microchip, while the puck firmware runs on a PIC16F628A microcontroller.

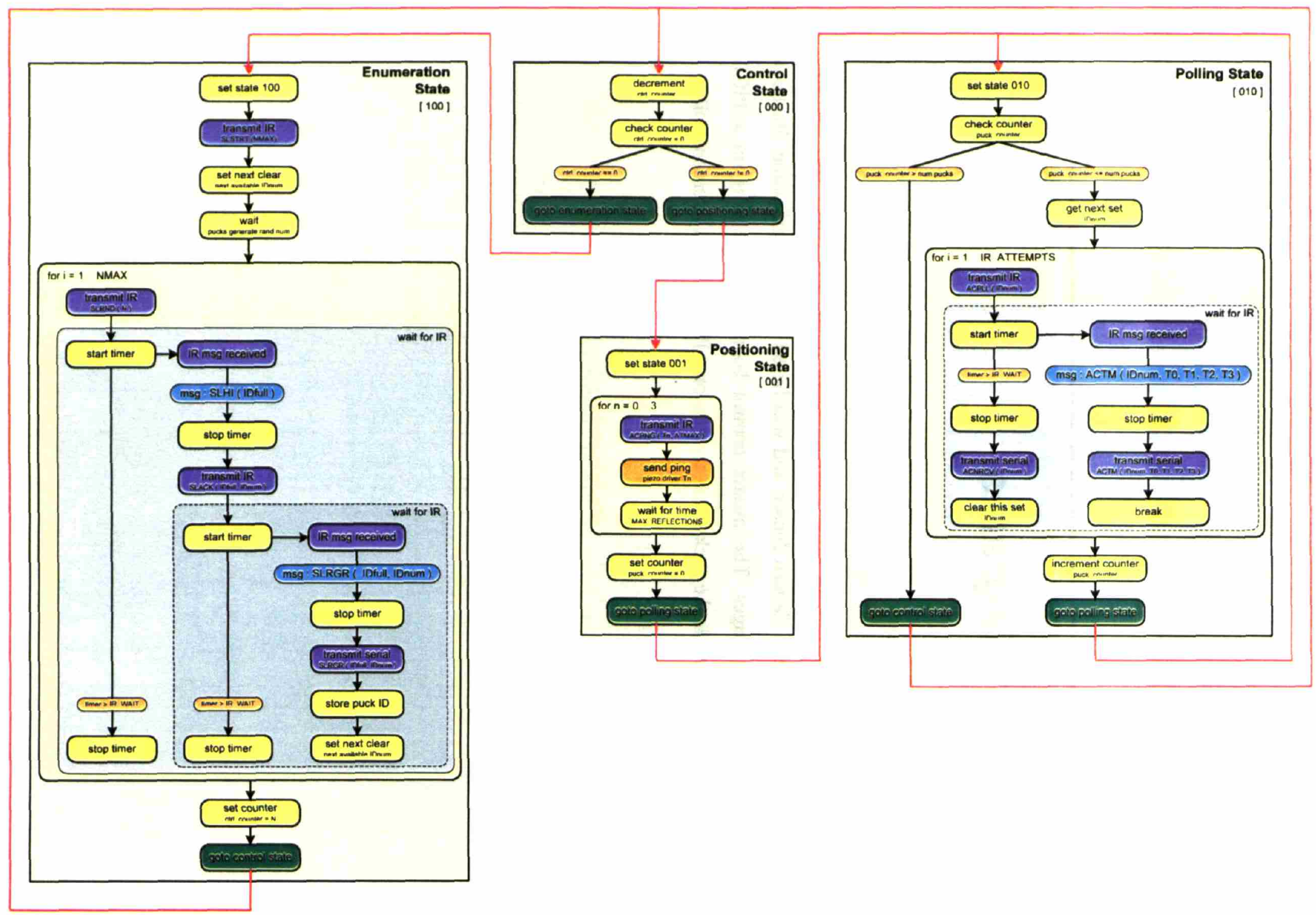


Figure B.1: Master firmware state diagram

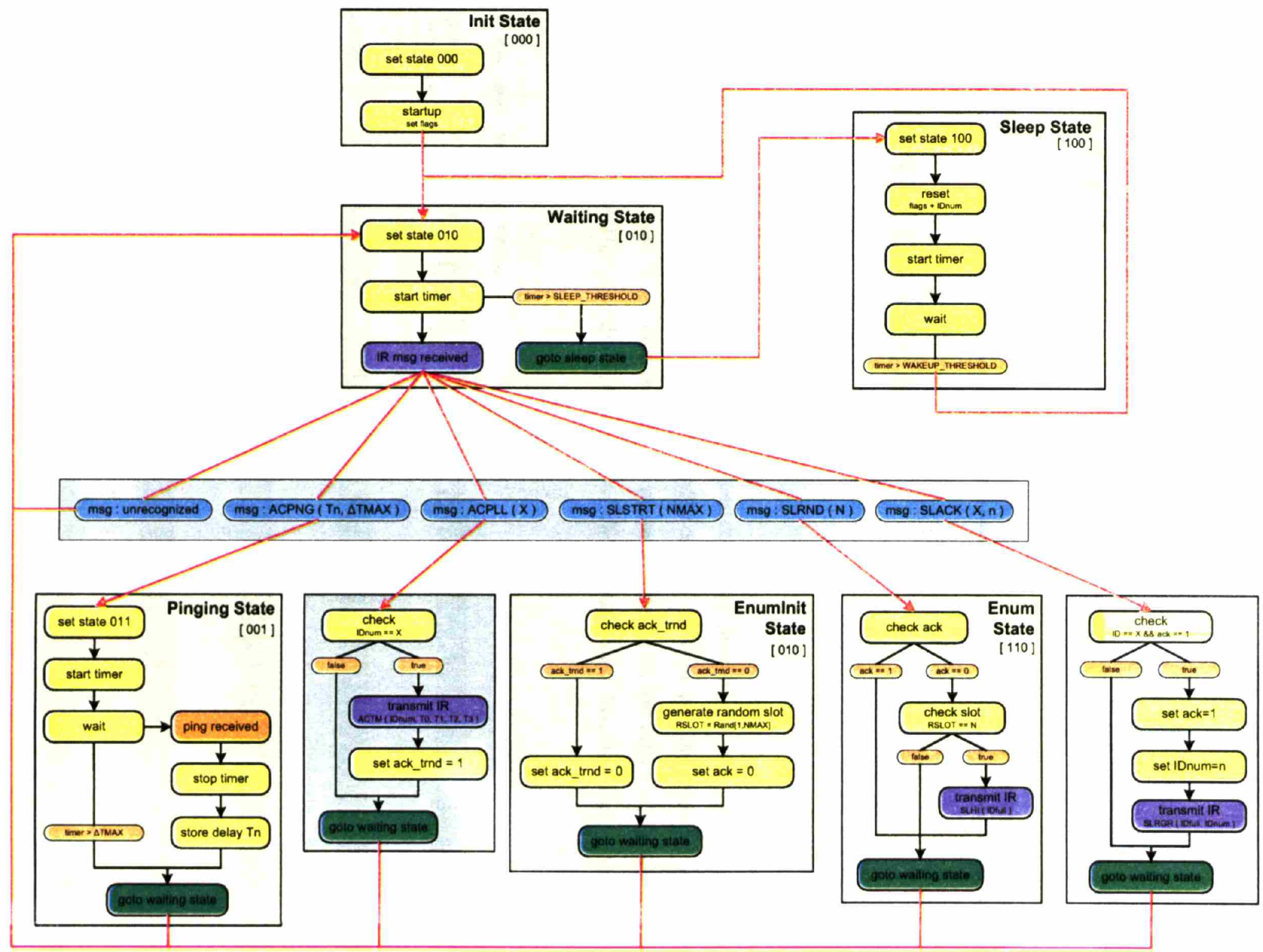
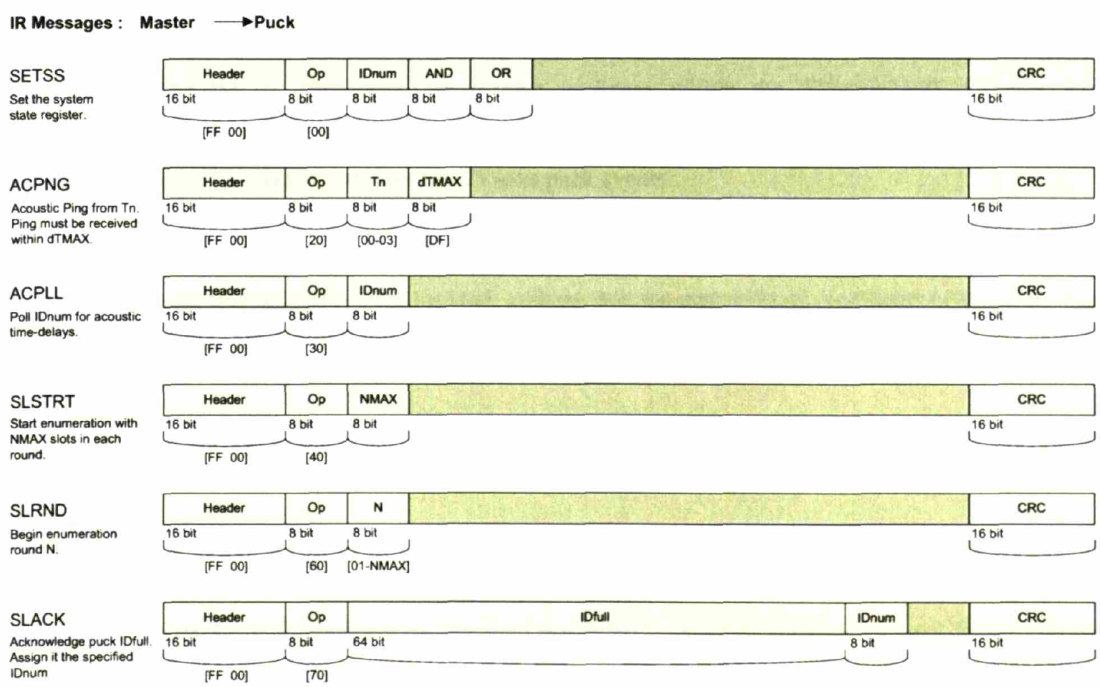


Figure B.2: Puck firmware state diagram

Appendix C

C. Message Format

The following diagrams illustrate the messages currently implemented by the TViews table system. Messages are transmitted between the master control board in the table and the pucks on its surface via infrared (IR). Messages are transmitted between the master control board and the PC inside the table via the RS-232 serial protocol. Note that the SLRGR and ACTM messages sent from the puck to master are also forwarded on to the PC.



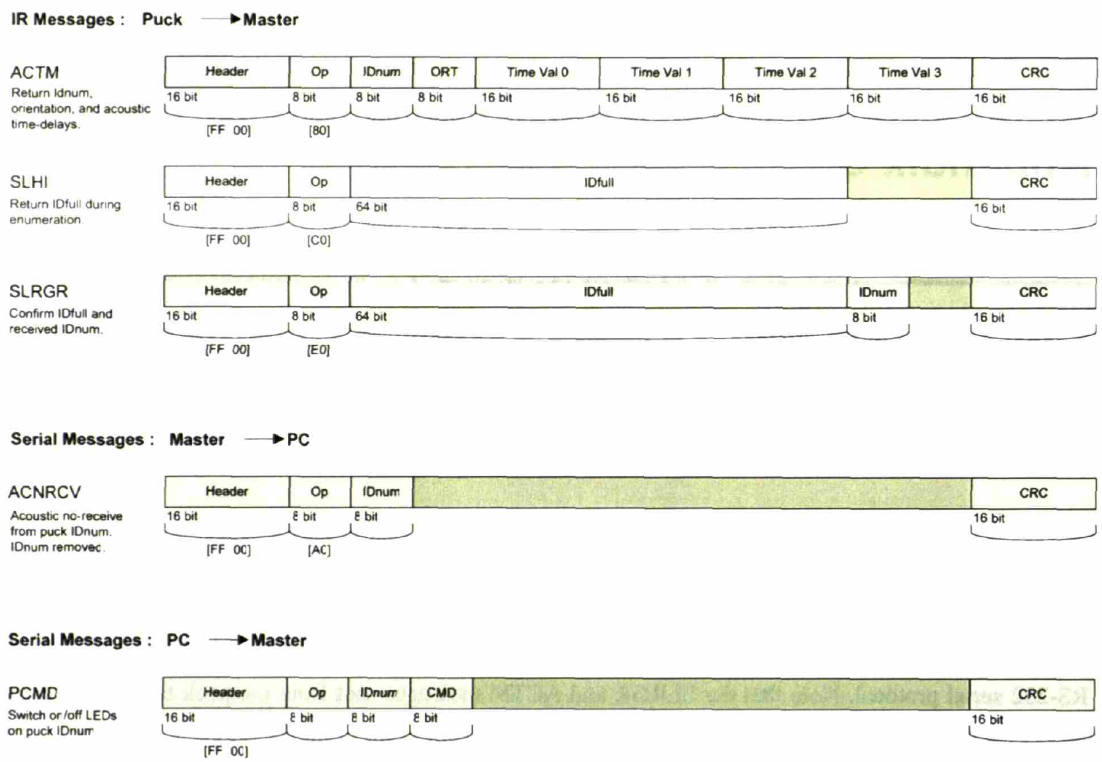


Figure C.1: TViews system messages

Appendix D

D. TViews API Specification

The TViews API (application programming interface) classes are packaged in an archive named `tviews.jar`. This appendix provides a description of the classes that are accessible to application developers as well as step-by-step instructions for developing applications using the TViews API.

D.1 API Description

The classes accessible to developers are in two packages within the TViews API: `tviews` and `tviews.tev`. The `tviews` package provides classes for managing the TViews pucks. The `tviews.tev` package provides a class and an interface for TViews puck events.

The `tviews.TObject` class is used to represent the pucks on the table. It stores the full 64-bit puck ID, a shortened 16-bit ID number that is used for puck updates, and the current (x,y) coordinate of the puck. The following methods are provided to access this information.

```
public byte    getIDNum ()
public short[] getIDFull()
public double  getX     ()
public double  getY     ()
```

The `tviews.TObjManager` class keeps track of the pucks that are currently on the table, and sends update events about the pucks to all applications that have registered themselves TViews listeners. In the current implementation, each application that runs on the TViews table needs to create a `TObjManager` and add itself as an event listener to receive puck updates. Eventually, the object management should be done at the level of the operating system within the table. The following methods are provided for developers to add/remove their application as a `TEventListener`.

```
public void addTEventListener(TEventListener tevListener)
public void removeTEventListener(TEventListener tevListener)
```

The `tviews.tev.TEvent` class extends `java.util.EventObject` and provides information about the type of puck event fired. The event types are as follows:

```
public static final int TOBJ_ADDED
public static final int TOBJ_REMOVED
public static final int TOBJ_UPDATED
public static final int TOBJ_BUTTON_PRESSED
```

The following methods can be used to find out details about the type of event fired. In particular, the getClickCount method can be used to discover whether a button pressed event was a single or double press.

```
public int getTEvType   ()
public int getClickCount()
```

Finally, the `tviews.tev.TEventListener` interface extends the `java.util.EventListener` interface. Classes that wish to receive events from the TViews table need to implement this interface and provide the following methods.

```
public void tobjAdded        (TEvent tev);
public void tobjRemoved      (TEvent tev);
public void tobjUpdated      (TEvent tev);
public void tobjButtonPressed(TEvent tev);
public void packetReceived   (TEvent tev, byte[] packet);
```

D.2 Usage Instructions

The following step-by-step instructions describe how an application developer can begin developing a new application for the TViews table.

Step 1. Import the tviews libraries.

```
import tviews.*;
import tviews.tev.*;
```

Step 2. Create a class that implements the TEventListener.

```
public class MyClass implements TEventListener { ...
```

Step 3. Create an instance of a TObjManager.

```
// Declare the TObjManager as a class variable
TObjManager tom;
// Create an instance of the TObjManager in the constructor or initialization code
tom = new TObjManager();
```

Step 4. Register the class to receive TEvents from the TObjManager.

```
tom.addTEventListener(this);
```

Step 5. Implement the TEventListener methods.

```
// Since the class implements TEventListener, it needs to provide the following methods.
// These methods can call other methods based on what users do with the pucks.
public void tobjAdded (TEvent tev) {
   TObject to = (TObject) tev.getSource();
   // additional code here ...
}
public void tobjRemoved(TEvent tev) {
   TObject to = (TObject) tev.getSource();
   // additional code here ...
}
public void tobjUpdated(TEvent tev) {
   TObject to = (TObject) tev.getSource();
   // additional code here ...
}
public void tobjButtonPressed(TEvent tev) {
   TObject to = (TObject) tev.getSource();
   // additional code here ...
}
```

Step 6. Use the methods in TObject to play with incoming puck data.

```
public byte getIDNum()      // manufacturer assigned unique puck ID
public short[] getIDFull()  // ID value assigned by the table when a puck is placed on it
public double getX()        // x coordinate of the puck, use this in tobjUpdated
public double getY()        // y coordinate of the puck, use this in tobjUpdated
```

Step 7. Tip for storing pucks.

```
// It is a good idea to create a way to keep track of the pucks on the table.
// This simple class can be used to store a single puck object.
```

```
import tviews.*;
public class Puck {
   TObject tobj;
   public Puck(TObject tobj, Sprite spr) { this.tobj = tobj; }
   public TObject getTObject() { return tobj; }
}
```

Step 8. Tip for puck management.

```
// The pucks can be managed using a vector object.
// Declare a vector of pucks as a class variable.
Vector pucks;

// Create the vector in the constructor.
pucks = new Vector();

// When a puck is added (tobjAdded, add a new puck it to the pucks vector.
pucks.add(new Puck(to));

// When a puck is removed (tobjRemoved), remove it from the pucks vector.
for (Enumeration e = pucks.elements(); e.hasMoreElements();) {
   Puck p = (Puck) e.nextElement();
   if (p.getTObject().equals(to)) {
      pucks.remove(p);
      break;
   }
}
```

Appendix E

E. Table Construction

The encasing for the TViews table was built by Mark Barkus from Axis Woodworking Inc. in Somerville, Massachusetts. It is constructed in the form of a large wooden chest that is hollow on the inside (Figure E.1). The table is on wheels so that it can be easily moved around.

Figure E.1: TViews table
The TViews table at the MIT Media Laboratory is built in the form of a large wooden chest.

The tabletop opens with a hinging mechanism (shown in Figure E.2), which provides access to the electronics contained inside. The 32" LCD monitor and glass plate with acoustic transmitters are mounted into a square opening in the lid of the chest from behind, in such a way that the screen area is visible through the glass within the table's top surface. A fan in the base of the chest pulls cool air from underneath the table and directs it onto the back of the monitor through a dryer hose in order to prevent it from over-heating. Additional ventilation holes are cut into the sides of the chest immediately below the top surface (shown in Figure E.2). A power strip is contained inside the table to provide power to the PC, master control board, display and fan. A single power cord extends from the side of the table and can be plugged into a wall outlet.

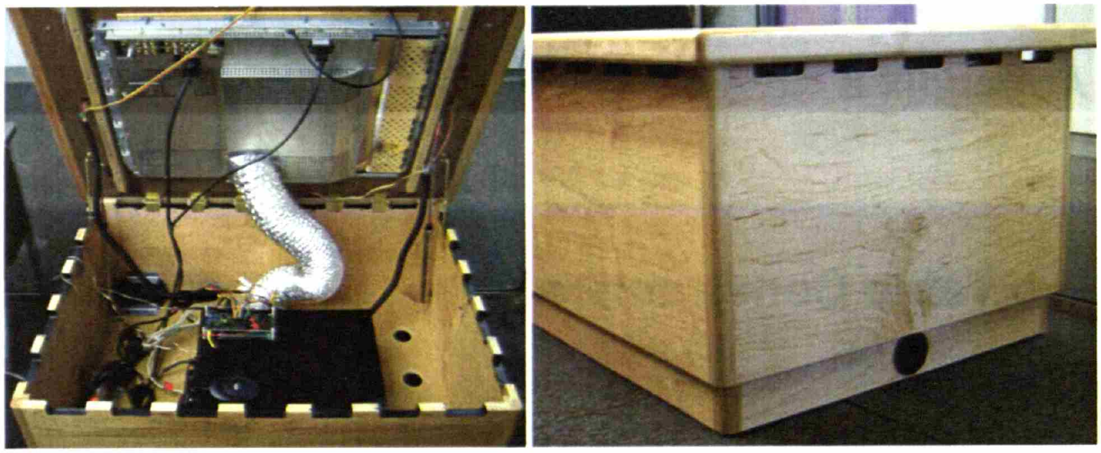


Figure E.2: Table inside and side views

The photo on the left shows the inside of the TViews table containing the PC and master control board. The LCD monitor is mounted into the hinged top surface from behind. The photo on the right shows a side view of the Table with ventilation holes just below the top surface and a hole for the power cord near the base.

The master control board inside the table communicates with the pucks via infrared transceivers that are mounted into small holes within the wooden frame around the display area, as shown in Figure E.3.

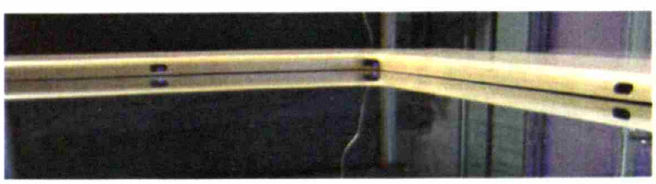


Figure E.3: IR transceivers

The infrared transceivers in the TViews table are mounted in the wooden frame around the display area.

Appendix F

F. Puck Design

The pucks were designed using a layered approach and were constructed using a combination of acrylic, brass and felt materials. The acrylic and felt layers were cut on a laser cutter, while the brass was cut on a water-jet cutter and then polished using a lathe. The brass adds weight to the puck in order to ensure that the acoustic sensor embedded in its base will make good contact with the glass surface of the table. The brass ring used in the current puck design weighs 130 grams. The lid of the puck contains a small removable icon piece with an embedded button. The icons can be customized for different applications to indicate their functionality. The circuit board is encased inside the puck, however a power switch, programming/charging connector and the infrared transceiver are accessible from the outside at the base of the puck. Felt material on the bottom provides a soft surface on which it the puck can glide. The top part of the puck is held in place by three screws, and can be removed in order access the circuit board and battery.

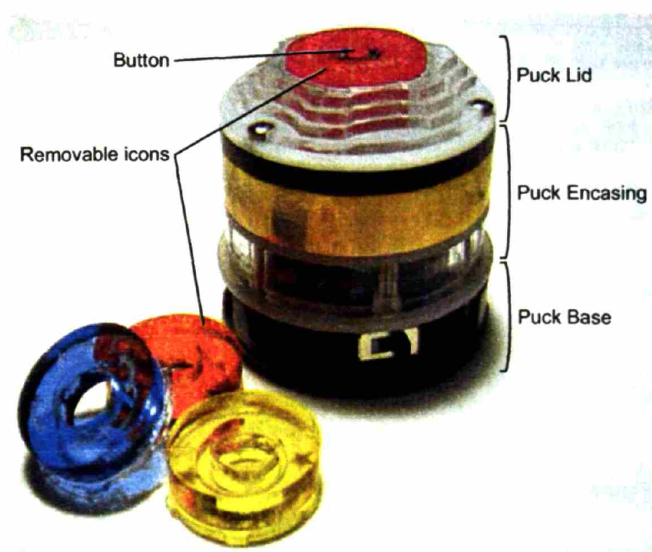


Figure F.1: Puck design

This photo shows the final puck design and several icons that can be swapped into the its lid. The lid also contains a pushbutton. The puck encasing includes a brass ring for weighting. The base consists of a sensor layer that holds the circuit board, acoustic sensor and infrared transceiver in place.

The puck base consists of three separate layers: the gliding surface made of felt, a thin acrylic base support, and the acrylic sensor layer which holds the circuit board in place. The current circuit board is a 1.3" diameter hand soldered PCB (printed circuit board). The puck encasing consists of five separate layers. Each one is ring shaped and when stacked together they form a hollow cylinder to protect the components on the top side of the circuit board and the battery. The circuit constraint is a ring that surrounds the circuit board from the outside. The lid consists of five thin acrylic layers and a removable icon piece that snaps into place. The individual layers in the base, encasing and lid are held together using an acrylic solvent cement. The figure below shows the individual layers in the puck base, encasing and lid.

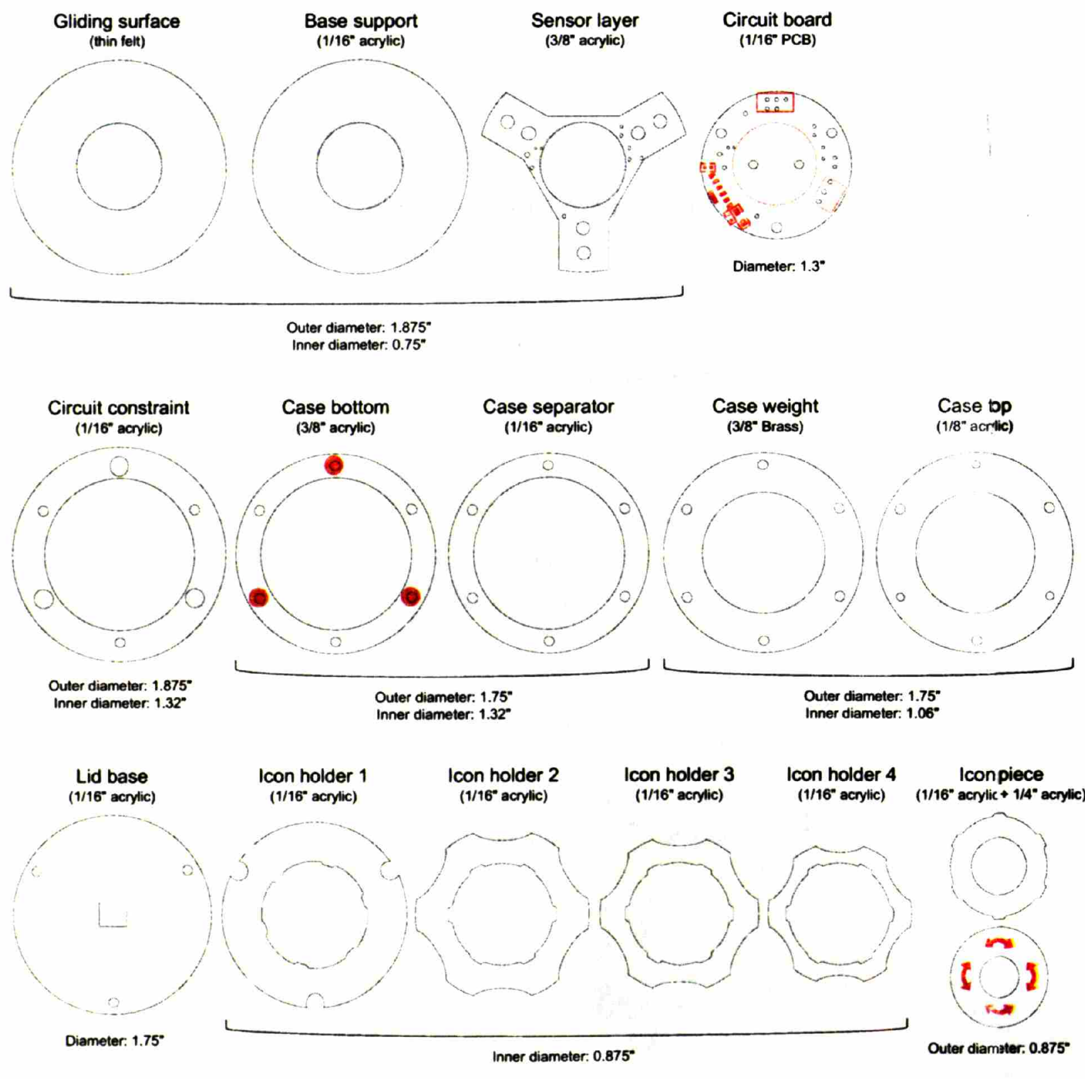


Figure F.2: Puck layers

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