Tangible User Interface Testing on the LambdaTable: A High Resolution Tiled LCD Tabletop

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ABSTRACT
This paper presents the LambdaTable, a tabletop display that employs tiled LCD monitors to significantly improve resolution over single display or projector systems. It supports multi-modal interaction with applications and co-present users by combining extremely high visual resolution with uniquely identified, special purpose camera tracked physical interface devices, all within a large multi-user tabletop environment. In this paper we investigate the Fitts' Law properties of this system, with particular emphasis on target acquisition across large distances. We also discuss the LambdaTable's applications for solving emerging needs within the scientific visualization and emergency response domains.

INTRODUCTION

Tiled LCD architectures are a promising new technology for tabletop display systems in the scientific visualization domain. They provide an affordable, low maintenance, high resolution alternative to projector systems that can support a variety of output media including text, imagery and relational data. However, in order to take full advantage of this technology, new forms of interaction with documents and large datasets must be developed that provide more effective methods for productivity within a tabletop environment. These interfaces must support group-based collaboration, easy access and flexible modes of interaction in order to succeed in the increasingly complex task of scientific data visualization.

The LambdaTable is the first tabletop display that combines high-resolution tiled LCD technology with multi-modal, multi-user co-present interaction using a tangible user interface system [11]. It also serves as a visualization endpoint for rendering remote high resolution datasets (500 Gigabyte to 1 Terabyte) via high bandwidth optical networks. The LambdaTable will be used to investigate new forms interaction over a shared visualization table-top environment using a variety of physical data access and manipulation tools. These tools will support alternative modalities such as querying via tracked pointing devices, manipulating data with physical handles and creating overlays with tracked lenses.

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Another goal of the LambdaTable is to fulfill an emerging need in the fields of biology, geology, and emergency response where recent advances in network infrastructure have facilitated the accumulation of massive amounts of data, but have not addressed how this data can be interactively explored and manipulated. Instead unwieldy datasets must be either divided into manageable chunks, or massively down-sampled for viewing, processes that obscure relationships among data. Two examples that highlight this challenge are wide-field, high resolution imaging in the biosciences to visualize and explore spatial relationships among multiscale components, and the use of directed graphs to visualize and explore non-spatial relationships, e.g., ontologies, genetic networks, and evolutionary trees. In both of these cases, the low resolution workspaces presented by current projector and single-display based table solutions force a trade-off between detail and breadth. The limited screen real estate also reduces the extent to which novel hybrid exploration methods, such as merging imaging data with conceptual networks, can be exploited.

Figure 1. Supporting group work with high resolution rat cerebellum imagery on the LambdaTable.

In this paper we focus on providing a preliminary validation of our system's tangible user interface tracking module by performing a series of target acquisition tests. Our goal is to evaluate the usability of our system so that we can begin extending it for more complex functionality. By testing the information capacity [3] of our subjects while using the interface, we will investigate possible sources of interference, including camera processing latency, camera resolution, and the large interaction area. Based on these results we will discuss the future of the table and current research efforts that target emerging challenges for interactive manipulation of large high resolution visualizations.

2. Related Work

Two areas of research are important to the work presented here: the application of Fitts' Law to HCI, and table interface systems including tangible user interfaces.

Fitts' Law has been the subject of nearly one thousand published works over the last fifty years[1]. The summary of much of this work has appeared in a series of publications in the International Journal of Human Computer Studies [20, 24, 25]. These works, along with a recent ISO standard for non-keyboard input devices [7] have made considerable progress in developing a standard approach to applying Fitts Law to computer interface devices. The work in this paper adheres to the standard and recommendations presented by Soukoreff [20] wherever possible. Few studies have evaluated the Fitts' properties of large scale direct-interaction table displays. A Fitts' comparison study between the HI-Space tabletop hand tracking system and a trackball [12] supported the claim that direct mediated user interfaces outperformed indirect interfaces. A study by Parker et al. tested a hybrid touch and pointing stylus on a large table display, and found that touch was faster than point for small distant targets, but users consistently preferred point over touch interaction [13]. No Fitts' studies to date have addressed direct interaction with tracked physical interface devices or interaction on a tiled LCD table.

Previous table-interaction studies have explored issues such as personal and shared space management, orientation, territory, and document passing [2, 5, 8, 9, 18, 19]. Numerous table implementations focused on touch technology have been presented, including the multi-touch SmartSkin [16], TouchTable [1], and multi-user DiamondTouch [2] systems. Table systems that employ camera tracking include the Digital Desk [23], the InfoTable [17] and HI-Space.

In 1995, Fitzmaurice, Ishii and Buxton introduced the notion of Tangible User Interfaces with their study on graspable bricks [4]. Ullmer and Ishii followed that research with the development of the metaDesk [21], a tabletop display that used physical icons, handles and instruments to manipulate a map application. A number of other projects from Ishii's Tangible Media group at the MIT Media Laboratory also employ physical objects on a table to explore new methods for human computer interaction [14, 15, 22].

Figure 2. Two tracked tangible devices; an orientable compass rose and a direct pointing device.

3. Table Setup

Currently, two configurations for the LambdaTable have been implemented, a 5x3 tile display and a 2x2 tile display used for initial testing, including the Fitts' test described here. The larger display has a maximum resolution of 1600 x 1200 per tile, creating an overall resolution of 8000 x 3600 pixels. This display is 38 in. by 78 in. and can comfortably fit 15 users around its perimeter. Currently, most projector based table systems offer no more than 1200x1600 total screen real-estate. The LambdaTable makes much more visual data available to users.

The term *mullion* describes the physical borders created by the enclosure of a monitor. In order to support the illusion of a single continuous display we create a virtual frame buffer that includes the pixels that would reside beneath the mullions. These virtual pixels are accounted for by mapping the actual individual frame buffers to appropriate regions in the virtual screen space. A simple cursor image is drawn on the virtual screen at the location of the tracked mouse to assist the user in determining the location of the active point with respect to the physical device.

[1] Estimate based on number of citations reported by Google Scholar on 15 May 2006. (scholar.google.com).

The Fitts' experiment table (Figure 3) consisted of four LCD panels in a horizontal quad arrangement with a plexiglass working surface. A single camera mounted at the ceiling, approximately 7 ft above the table, tracked the motion of the mouse pointing device. The camera and displays of the Fitts' table were driven by an Intel Pentium4 3 GHZ machine with 2GB ram and two NVIDIA Quatro 3000 graphics cards.

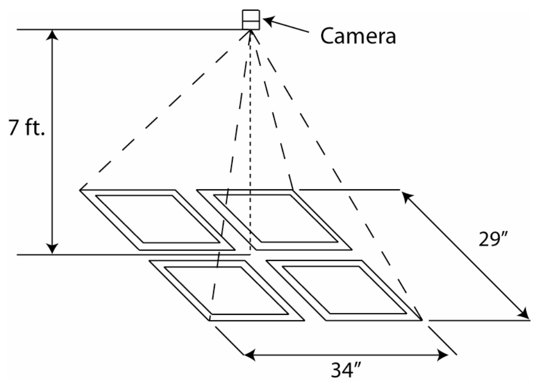

Figure 3. The smaller table implementation for conducting a Fitts' test.

3. Tangible User Interface Implementation

The LambdaTable's user interface system was designed to meet three primary requirements: to work within the constraints of a tiled LCD table environment, to support multiple co-present users by enabling separate input channels per user and separate environments for each user, and to support multi-modal input via variations of the tracked physical input modality.

Tracking user interactions above an LCD table requires a different approach than those employed previously on table systems. Methods that employ cameras behind the display are inappropriate [6, 21], as are systems that use an opaque touch sensitive screen [2] or electromagnetic tracking surface [14]. Large scale transparent touch sensitive surfaces are currently unavailable and it is impractical to tile touch screens due to the large borders required to house the sensing electronics. In addition, no transparent touch-screen technology exists that supports unique identifiers for multiple users, and can be mounted above the tiled monitors.

To meet the special design requirements of our system we have implemented a camera tracking system for tangible user interface devices on the table's surface. The system employs cameras mounted overhead to track objects that are identified by a unique pattern of embedded infrared LEDs. Any number of devices can be tracked simultaneously, as long as each pattern is unique. Currently, "mouse" and "puck" style interface devices have been built using arrangements of three LEDs to indicate position orientation and identity, and two as indicators for the mouse buttons. The main drawback to this implementation is that the LEDs may be occluded by the user's hand. Alternatives to LED patterns are being investigated, such as IR illuminators and reflective markers.

A real-time software computer vision system resides on a separate PC to track the infrared LEDs and deliver the position and orientation of tabletop devices via a UDP stream to the table application. The tracking system uses the Pipelined Vision Class Library [10] (PVClib) to capture frames from the camera and passes them through a sequence of image processing elements. The primary vision workflow involves segmenting, feature extraction, conversion to a graph representation and applying a graph subset search algorithm to discover predefined patterns in the image. We use two Pointgrey Flea cameras, with resolution of 640x480 and a frame-rate of 30 frames per second. The system is capable of operating at 29 frames per second with very low latency on a 3 GHZ Pentium4 PC with 2 GB of ram.

5. Fitts' Test Procedure

The focus of our Fitts' investigation was to provide a preliminary validation of the usability of our interface design. For that reason we focused on a subset of the ISO standard that included a performance test and analysis [7]. Our primary interests were to identify aspects of capturing, tracking and graphical display that might create departures from the expected behavior of a pointing device. Potential sources of interference included latency and refresh speed of the drawn cursor, mullion interaction with the drawn cursor, capture resolution of the camera, and unconventionally large target amplitudes. We implemented a discrete task, two dimensional version of the Fitts' test similar to that employed by Parker [13]. Targets were arranged radially about a central home point, which was located in the lower left corner of the display in order to achieve the widest range of indices of difficulty. Circular targets were chosen to avoid complications regarding the width and height of the target [3]. The targets were generated by varying three different criteria: size, angle from the horizontal, and distance along the axis defined by the angle.

	0 deg.	45 deg.	90 deg.
Near	7.58	8.6	4.07
Medium	14.45	17.84	10.46
Far	22.03	26.39	14.53

Table 1. Distances of taragets from the home point at each angle. (Inches)

Three target sizes were used: one, two, and four inches. On each axis there were three different distances, chosen to prevent any part of the targets from being occluded by the mullions (Figure 4). Because of the layout of the angles, and the sizes and aspect ratios of the LCD monitors, the distances from the home point were unique for each angle. This created nine distances, shown in Table 1. Given the nine distances and three target sizes, a total of 27 possible targets were generated for each trial.

Twenty four subjects participated in the study. No constraints on age, gender, race, or handedness were imposed. Eight of the 24 subjects were female, and one was left-handed. The rest were male, right-handed subjects. The subjects stood in front of the lower left LCD monitor of the table, so that the table spanned forward and to the right. Subjects engaged in an unstructured learning period prior to the start of the test to become familiar with the responsiveness, latency and sensitivity of the system.

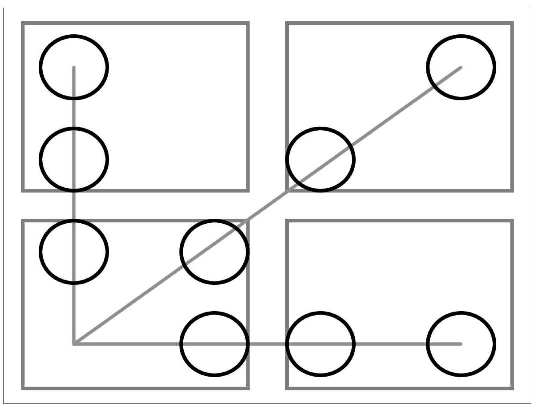

Figure 4. Each target was positioned in one of 9 different locations, no targets were occluded by mullions.

Each target acquisition cycle consisted of three stages. First the subject placed the tracked mouse cursor at the home point. After a one-second wait period a target appeared in one of the predefined positions. The user then moved the device over the target and pressed the left button. A target acquisition attempt was considered an error if the user pressed the mouse button outside the target area. The total number of errors for a target acquisition was N - 1, where N was the number of clicks the user required for a successful acquisition. Each subject participated in two trials consisting of a randomized sequence of all possible combinations of target size and position. Fifty four data points were collected per subject, generating an overall total of 1296 data points.

7. Results and Analysis

Index of difficulty was computed using the Shannon formulation of Fitts' Law [20].

$$\text{(Eq 1.)}\quad T = K_0 + K \log_2(D / S + 1.0)$$

Because of the limited number of trials collected per index of difficulty for each subject, it was not meaningful to define outliers in terms of standard deviations from the mean. Instead, outliers were informally identified as measurements that fell well outside the general shape of the data when visually inspected. Based on this criterion, less than 2% appeared to be outliers. Two approaches were attempted to reduce the percentage of outliers: removal of particular subjects who were unnecessarily methodical (according to written notes taken by the examiner during the trials), and the uniform exclusion of the first trial to eliminate potential learning effects. However, neither strategy significantly affected the ratio of outliers to valid data. Because the focus of this study was not to acquire a quantitative assessment for comparison, it was decided that 2% was a tolerable error rate, and all data were included in the analysis.

A least squares regression was employed to determine the data's conformance to Fitts' Law. The index of difficulty of each of the 27 targets was plotted against the average time to target for each target and a linear fit was determined. The line has a slope of K=238.88, intercepting at K_0=425.21, R^2=0.919 (Figure 13). Due to the lack of sufficient data points per index of difficulty, we were unable to perform the correction for error suggested in Soukeroff [20]. This limits, to some extent, the accuracy of our data at lower indices of difficulty and may have resulted in a lower R^2 value.

A repeated-measures analysis of variance was performed on target acquisition time and number of error clicks in order to determine whether interactions with the independent variables existed. Time to target varied significantly with target distance (Figure 5): $F_{2,23}$=24.916 ($p<0.01$) along the horizontal axis, $F_{2,23}$=36.910 ($p<0.01$) along the diagonal axis, and $F_{2,23}$=36.924 ($p<0.01$) along the vertical axis. The number of error clicks did not vary significantly with target distance (Figure 10): $F_{2,23}$=0.439 (p=0.645) on the horizontal, $F_{2,23}$=1.510 (p=0.201) on the diagonal, or $F_{2,23}$=0.100 (p=0.905) on the vertical. Movement time varied significantly with target size (Figure 7), $F_{2,23}$=96.367 ($p<0.01$), as did error rate (Figure 8), $F_{2,23}$=8.147 ($p<0.01$).

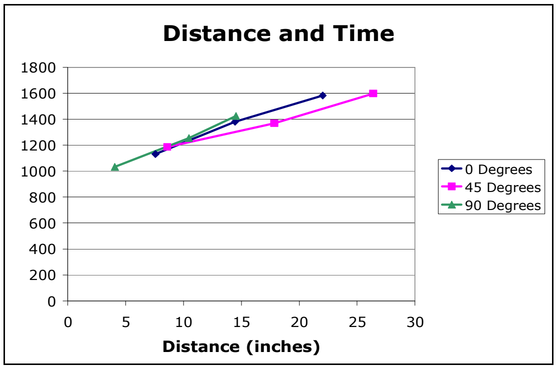

Figure 5. Distance versus Time

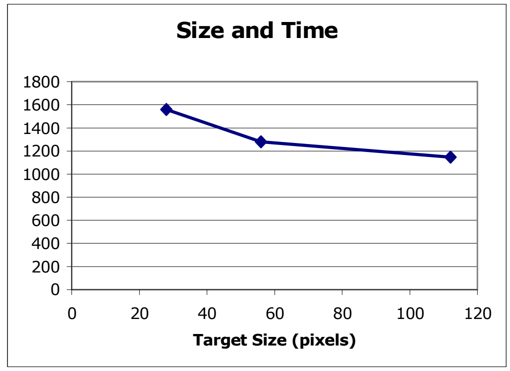

Figure 7. Decrease in acquisition time due to target size

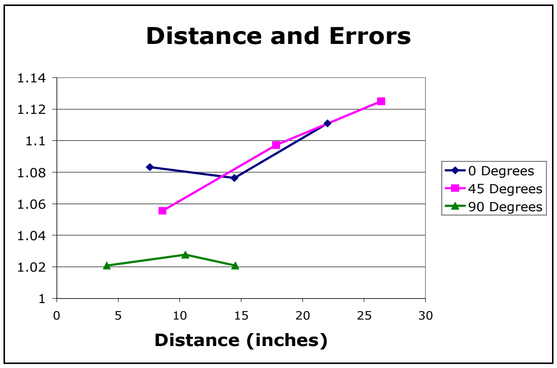

Figure 6. Distance versus Number of Clicks

Figure 8. Decrease in number of clicks due to target size

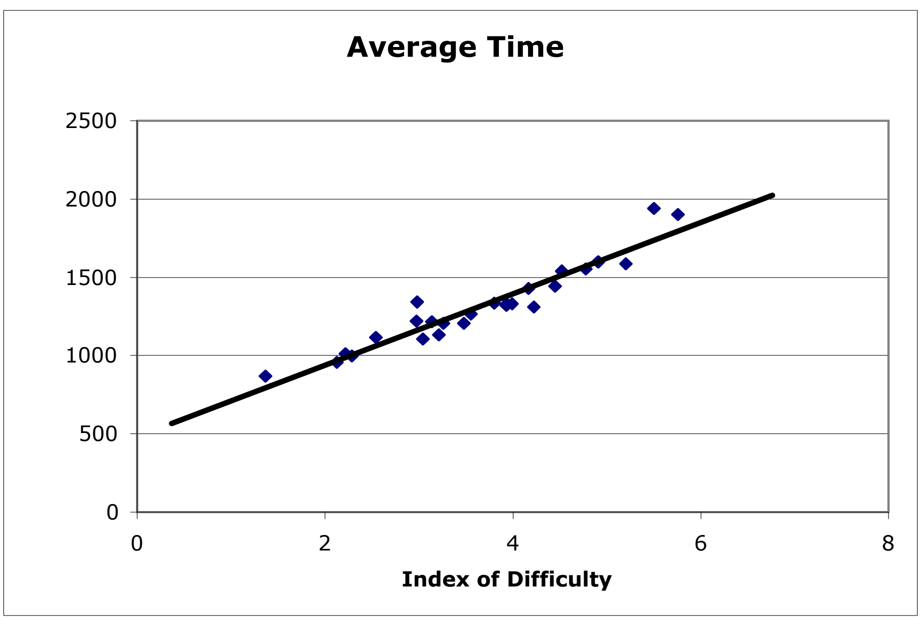

Figure 9. Linear regression with R^2 = 0.92

9. Discussion

The most important result of the analysis was the good fit of the linear regression on the data. This fit is further supported by the fact that all samples were incorporated in the analysis, including outliers. One drawback of the experimental setup is that reaction time was not explicitly measured and accounted for as recommended by Soukoreff [20]. According to this paper, the time for a target acquisition can be partitioned into *reaction time*, or the time required to respond to a new event, *homing time*, or the time required to grasp the mouse or input device, *movement time*, and *dwell time*, or the time required for the system to recognize that the target was acquired. In our system, homing time not significant because the subjects' hands were always on the input device, eliminating homing time, and dwell time was minimal because a button press was used rather than a dwell period to indicate target acquisition. However, reaction time was not measured. Despite this, the linear regression intercept was still close to zero. If we had accounted for reaction time, we could expect an even smaller intercept.

Target acquisition time, and error rate both decreased (Figures 7, 8) as the target size grew, which was expected. Additionally, target acquisition time decreased as the distance decreased, which was also expected. No significant relationship could be found between the errors and target distance. One might suppose that distant targets would cause a greater number of errant clicks. The farthest targets were often at the extent of a subject's reach which, it could be hypothesized, creates a greater hand-eye coordination challenge. However, many of the subjects we observed moved more than just their arm when acquiring a target. In some cases, subjects repositioned their entire body while acquiring a target. Generally, during trials with higher index of difficulty, subjects appeared to make whatever natural adjustments were necessary to ease the task, including motions involving the wrist, arm, shoulder, torso and lower extremities.

Another relationship that was not supported by the ANOVA results from the distance-error analysis involves the mullions. It could be hypothesized that the mullions in the immediate vicinity of the middle distance targets, by interrupting the feedback provided by the graphical cursor, might create a visual obstruction or distraction that could increase error rates. In our experiment, the cursor provided important information as to the position and orientation of the device's active point. However, no significant source of variance in error rates could be identified between distance groups. This suggests that interruptions of the visual data caused by the screen borders did not create a distraction, or otherwise degrade performance during this test. This is possibly due to the accounting for virtual pixels under the mullions, which caused the cursor to move continuously between monitors. If these pixels were not accounted for, the cursor would have jumped from one screen to the next, creating a greater distraction and perhaps affecting performance.

One aspect of our system that was not explicitly tested, but which could have influenced the results, was the effect of the device's orientation. Previous research has suggested that for direct mediated interfaces, the graphical depiction of the cursor under the physical device is not necessary [12]. However, previous pointing tests with TUIs have used devices with a physical point. Our device had no such point, so the graphical representation was necessary to inform the subject where the active point was in relation to the device. Because the tracker captured rotation as well as position, the cursor could be drawn with correct orientation under the device. In effect our device required both it's physical and graphical components to generate a "complete picture." However, many subjects quickly recognized the relationship between the cursor and physical device, and used this information to anticipate the cursor's location. In some cases, subjects were able to move the device and click the button before receiving visual feedback, and still achieve a successful acquisition.

10. Future Work

During the course of the experiment a number of areas in which further research could yield improved accuracy and valuable new insights were identified. In particular a more exhaustive study with more trials per subject, subject-wise adjustment for accuracy [20] and a baseline comparison against an established large format pointing device such as a "digital whiteboard" system would be very beneficial. Additionally the impact of occlusion caused by mullions in a direct interaction tiled display environment is a largely unexplored field which warrants further investigation. However, as LCD displays continue to increase in size, and borders continue to diminish, this area will likely become less important. We have already started to build the next generation LambdaTable, which will feature much larger LCD displays, reducing the ratio of mullion to pixel space. The new design will also employ higher resolution cameras, providing another opportunity for future research-- during this study we intentionally used large targets (one inch and greater in diameter) to avoid problems that might occur as the target size approached the limits of the tracking resolution. This interaction between resolution and target size could interfere with the normal distribution of end-point scatter positions that define a target's effective index of difficulty [20]. To avoid this problem on the new table, a matrix of cameras will be employed to greatly increase the user interface tracking resolution. This higher resolution will allow us to employ smaller targets and investigate higher precision target acquisition.

11. Conclusions

This paper presented empirical evidence to support the claim that a tiled table interface behaves according to Fitts' Law. It also discussed unexpected aspects of the results; that large distances and proximity to screen borders do not have a significant impact on target acquisition error for this system. Overall, the results indicate that the tangible device tracking system on the LambdaTable and the tiled display itself couple to form a sufficiently usable interface. We also discussed some of the limitations of non-tiled display table implementations. Currently, many of these systems do not provide sufficient resolution or space to allow multiple users to work with visually detailed data such as text, graphs and high resolution imagery. We described the implementation of the LambdaTable and how its architecture and user interface address these issues.

With the validation of this user interface system, we can now begin to investigate numerous new modes of interaction with high resolution content within the tangible realm. Additionally these results will inform further development of the LambdaTable interface for porting across larger tiled displays with similar properties, and for supporting multiple users with independent input channels.

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