INTERACTION ERROR BASED VIEWPOINT ESTIMATION FOR CONTINUOUS PARALLAX ERROR CORRECTION ON INTERACTIVE SCREENS

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ABSTRACT

Many interactive screens suffer from the incoherence between image plane and interaction plane. The resulting gap causes parallax errors that hinder a precise interaction with the system. For many reasons, this gap cannot be physically reduced any further, while a software correction is still missing. Thus, this paper introduces an observation model for a continuous automatic recalibration controller of the touch sensitive surface.

First, we show that the overall interaction error stems partly from the parallax error, which depends on the changing viewpoint of the user. Hence, a static calibration cannot overcome this error. Being not directly measurable, a continuously adapting correction controller sets the appropriate correction parameter based on updating the estimate of the user's viewpoint from the history of his interaction errors. To estimate the user's viewpoint in front of the screen based on the interaction error on the screen, we secondly investigate the correlation of the two domains from data of a user study, working on a large interactive screen with a significant gap between image plane and interaction plane. The correlation analysis shows significant differences in the interaction error stemming for different viewpoints, which allows the controller to infer the viewpoint. Finally, we model the results as a discrete observation model for the Partially Observable Markov Decision Processes (POMDP) correction controller.

KEYWORDS

User Modeling, Continuous Calibration, Parallax Distortion, Recursive Estimator

1. INTRODUCTION

Interactive screens as man-machine interfaces [1] are becoming increasingly popular [SMART® boards, Wacom® screens, Microsoft® Surface®, Apple Inc.® iPad®]. Large electronic whiteboards [2], mobile phones and Tablet PCs (e.g. [3]) enable highly intuitive operation. The direct manipulation of the screen's content with the user's finger or with tangible user interfaces [15,33] needs a good coherence between the input position and the digital content. To enable a precise interaction on such interactive screens, they need a good spatial and temporal alignment between the displayed objects and the input tracking system.

Common calibration techniques focus on eliminating static geometric distortions by a keystone correction. Being deduced from an initial calibration process, the calibration parameters correct the interaction position statically to the corresponding display coordinate. However, a spatial distance between the screen's surface and the glass pane of the tracking overlay still leads to a parallax error (Figure 1). This causes the interaction position for a specific target being dependent on the user's viewpoint. Since the user moves in front of the screen when interacting with the system, the calibration has to be continuously adapted.

A distance of centimeters between image plane and interaction plane is common for security reasons on ATMs and kiosk applications [5]. Such stability reasons to withstand the mechanical loads from touch interactions cause an offset, which creates an optical distortion in terms of a pointing error that significantly impairs the user interaction [6]. Usually, this error is avoided by enlarging the targets on the screen. This approach limits the number of targets being simultaneously shown on the screen, and impacts the usability of the application due to increasing number of menu layers and screen pages.

The parallax error is influenced by user characteristics like height, viewpoint, motion, and arm length. Thus, a static calibration depends on the specific user and results in distortions for other users during a team meeting for example. Even for the same user, the static calibration does not take into account his positional change over time, impairing the user's pointing accuracy especially on large whiteboards (see Figure 1).

Initiating a static recalibration before each user interaction can naively solve these problems. Since this is not a practicable solution, interactive whiteboard systems are only calibrated once at the beginning of the session. Here, a hidden and continuous recalibration while using the interactive system is required. Since the parallax error depends on the viewpoint of the user, which is not directly measurable, a model based correction controller uses the history of interaction errors to estimate the user's position.

Our work follows the approach in [9], which defines the basic model structure of a POMDP (Partially Observable Markov Decision Process) controller. It estimates the user's viewpoint by continuously receiving pointing errors for specific targets on the screen, and predicts the future position based on a model of the user's behavior to set up the correction parameter for the next interaction. Hence, the controller consists of a correction policy that defines the correction parameter for the estimates of the viewpoint, and three models: The process model [5] describes the user's behavior in front of the screen to predict his position; the reward model describes the effect of correction actions to the user; and the estimation model describes the correlation between interaction error on the digital surface and the actual viewpoint of the user.

Within this paper, we present the correlation between interaction error on the digital surface and the user's actual viewpoint, which we derive from a user study.

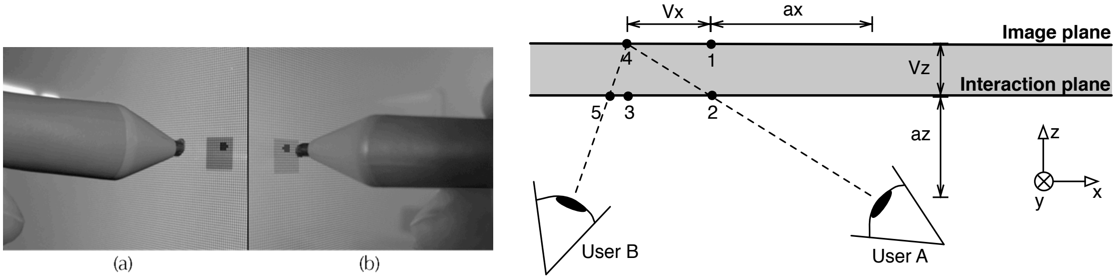
(a) (b)

Figure 1. (a) 15 mm offset, (b) 7 mm offset between the LCD's image plane and the interactive surface of the input device. (In both cases, the tip of the pen contacts the interactive surface (a 6 mm glass pane), while the dot in the gray rectangle appears in the image plane underneath.), (c) Effect of the parallax distortion on the interaction point in x-direction.

1.1 Parallax Error

The parallax error shown in Figures 1 is caused by the offset between display- and touch plane. It affects any interaction on touch sensitive surfaces due to the close spatial coupling of input and output device. The touch plane is necessary to accomplish physical robustness and security for publicly deployed systems (e.g. ticketing machines). The likelihood of missing a target increases with the screen's size and the distance between image and interaction plane Vz (Figure 1(c)). Thus, the distortion depends on the distance between viewing point and the point of interaction, as well as on the viewing angle against the perpendicular.
It is:

- Vz: Distance (offset) between image plane and interaction plane
- Vx: Resulting parallax distortion in x-direction
- ax: Distance from user to interaction point in x-direction
- az: Distance from user to interaction point in z-direction

Point 2 (Figure 1(c)) represents the interaction point of User A. Although he aims at point 4, point 1 will be registered resulting from the parallax distortion, mapped perpendicular onto the image plane. Point 5 shows the different interaction point for the same target, caused by the different viewpoint of User B. To avoid the parallax error, the user would have to interact at point 3. To reduce the effect of missing a target, the target size can be increased [21]. As a consequence, today's ticketing machines use large target areas to reduce the resulting interaction error. Due to the limited size of the displays, the number of targets is limited. This causes applications with cascaded submenu windows, which irritate the user and worsens usability [29][30].

Correcting the parallax distortion with a software controller can be easily done, once the user's viewpoint is known. The equation is:

$$V_x = \frac{V_z \cdot a_x}{a_z} \text{ (for the x-direction)}$$

Note that this equation only takes into account the geometric conditions and omits refraction indexes caused by the different optical media.

Since the offset can only be physically reduced to a certain account, an additional software correction is required in order for further increase the user's interaction accuracy.

1.2 Partially Observable Markov Decision Process

Enhancing the accuracy on interactive surfaces improves the precision of interactions, such as editing drawings and working with a widget-based user interface. A user-adaptive online re-calibration controller can overcome the parallax distortion, which depends on the user's viewpoint. Instead of tracking the viewpoint directly with high effort, the software component will use the history of interactions on the screen as evidence for the viewpoint to continuously re-calibrate the user-interface online. This problem can be formulated as Partially Observable Markov Decision Process (POMDP).

We focus on touch events from interaction on (or nearby) GUI elements that have well-defined target-points (e.g. small buttons). Comparing the offsets (from the center of these widgets) of several such interactions with a reference model of offset distributions for different viewpoints (finding of this paper) allows calculating a probability distribution over the different possible user positions relative to the screen. Conceptually, each of the possible positions represents a hypothesis. Once the software component has enough evidence supporting one of these hypotheses, it re-calibrates the interface for the corresponding viewpoint. We are hence trying to solve a sequential decision making problem.

Sequential decision making is a process (of potentially infinite steps) in which an agent at each step receives some information about the world and selects an action based on the accumulation of this information. He has to choose from a finite set of actions on how to interact with the world. In general, the information received is incomplete (hence does not allow deducting directly the actual state of the world), and the results of interactions can be uncertain. An optimal policy for such a process is a mapping of the accumulated information to action choices that maximizes the expected value of some valuation-function. A common formalization for such problems is a Partially Observable Markov Decision Process (POMDP in the following). Markov decision process models have proven to be useful in a variety of sequential planning applications where it is crucial to account for uncertainty in the process [7].

POMDPs can be described as a six tuple of States [8], a finite set of actions the agent can execute, and transition probabilities for successor states conditioned on predecessor belief state and action. The system is in one state at any point in time, which is not directly observable by the agent. This is modeled by a finite set of observations with occurrence probabilities conditioned by agent actions and system states. A reward function maps action-state pairs to values and a discount factor relates these values over different time steps.

The planner's goal is to select the optimal correction action based on previously accumulated information about the system's state. This accumulated information is represented as a probability distribution over all possible system states (referred to as the belief state of the planner/agent). Representing all information available to the agent at a point in time, a belief state fulfills the Markov Property [7]. An action choice is optimal if it results in a maximal expected value over all possible futures of the process.

To model the parallax-correcting problem as a POMDP, the 6 tuple is defined as follows [9]: The system's actions are the application of different adjustments to the parallax correction (or not). Its observations are the user interactions measured by the hardware's sensors for specific GUI elements, while (domain) states (S) represent the different possible distortion errors caused by the user's viewpoint, which are not directly observable. The transition model describes the resulting distortion error after applying a correction action with respect to the current distortion error. The observation model probabilistically relates interaction observations to distortion errors. Finally, the reward model defines rewards for adjustments depending on the actual distortion.

2. RELATED WORK

Common calibration mechanisms for displays were initially driven to establish the geometrical alignment between display and tracking system. An approach of how to adapt the projector calibration to the projection surface is shown in [10] and [11]. However, theses systems do not consider the influence of the user's changing viewpoint on the parallax error.

Today, interactive systems use flat screens instead of projectors. Although the compact design reduces the geometric distortions, the tracking system and the display system still have to be aligned. So far, the calibration is done in a dedicated process before using the system, in which the user has to hit a certain set of targets. The measured pointing errors are transferred into a static correction matrix, which is used to transform touch-coordinates to system coordinates [12]. Obviously, the parallax error cannot be corrected with such a fixed calibration if the user moves in front of the screen while using the system.

Reducing the offset between interaction plane and display plane is an effective approach to reduce the pointing error. As such reductions can only be reached by modifying the underlying hardware, they are naturally limited by the employed technology. A protective glass for example is necessary as it provides physical robustness of the interactive system, which is important for large interactive screens in public areas.

In order to further decrease the parallax error, only software solutions can be applied. Kent et al. [13] introduced a non-linear correction, which takes into account the tracking system's noise while Hong- Ping et al. [14] presented a learning calibration method based on back-propagation neuronal networks. Migge et al. [9] presented a general framework for a model predictive controller that increases the interaction accuracy by a user-adaptive online recalibration. Although they propose the problem as POMDP in general, the paper lacks of detailed analysis of the model parameterization. In [5], the process model is deduced from an empirical study, which models the user's movement in front of the screen.

Further studies investigated the effect of the target size on the interaction quality of touch sensitive surfaces. The ISO standard 9241-9 recommends the target size to be at least equal to the width of the index finger [19]. Jin et al. [28] investigated the target size and spacing on interactive surfaces for elderly. Other studies found that a larger target sizes led to better performance on a touch based numeric keypad [21, 22, 23, 25, 26, 27]. However, the literature lacks of analyzing the correlation between the interaction error and the user's viewpoint in front of the screen, enabling to estimate the viewpoint and correct the parallax error.

The hand-eye coordination can be evaluated with the Pegboard Test [20]. It is designed to motor dexterity and coordination of assembly line workers. Since the test is realized on a hardware board, it does not cover the task of interacting on an interactive screen. Fitts' Law [18] measures the difficulty of a given interaction task. Since the tests were designed for small displays, and due to the fact that we do not want a specific task to influence the user's interaction behavior, we do not apply this method.

3. CONTRIBUTION

In this section, we introduce the observation model for a POMDP controller to improve the pointing accuracy on interactive screens by correcting the parallax error. As we will show, the error stems from the viewpoint, which is not directly measurable. This interaction error (observation) is used to estimate the viewpoint (system state).

A common widget-based graphical user interface (GUI) provides a set of elements (e.g. buttons), whose events indicate the viewpoint. These so-called targets provide a reference point to measure (observe) the pointing error as the distance between target and interaction (touch) point. As Figure 2 (c) shows, the interaction error in principle depends geometrically on the viewpoint. Since the ability to hit small areas on the screen also depends on the user's dexterity, the measurements contain uncertainty. This uncertainty is described in the observation model. It expresses the correlation between the actual viewpoint and the resulting pointing accuracy (given as observation) as a discrete conditional probability distribution. It models the probability of an occurring pointing error (observation) for each viewpoint position relative to the target. Instead of observing the viewpoint directly, the controller uses the history of the resulting pointing error to estimate the viewpoint.

In order to set up the model realistically, we ran a user study monitoring the user interacting on a large screen with a significant offset between interaction and image plane, causing a parallax distortion based interaction error. We measured the viewpoint of the user, the target, and the interaction position as three-dimensional (3D) data and analyzed the interaction error and the viewpoint relative to the target position. Based on the viewpoint relative to the target and the target's position on the screen, the correction controller can estimate the user's viewpoint in front of the screen.

We measure the interaction error of the test setup with its offset between interaction and display plane. Next, we show that the interaction error is partly biased by the parallax error: We compare the absolute pointing error, given by the offset between target and actual interaction position, with the offset from the assumed interaction position, given on the straight line between target and viewpoint. In preparation for the discrete observation model, we discretize the viewpoint space into 5 segments representing discrete system states. For each state, we show the discriminability of the observations, which is necessary to vice versa deduce the viewpoint from the interaction. Finally, we discretize the interaction space into a set of observations, and express the observation model as discrete probability distributions over the observations for each state.

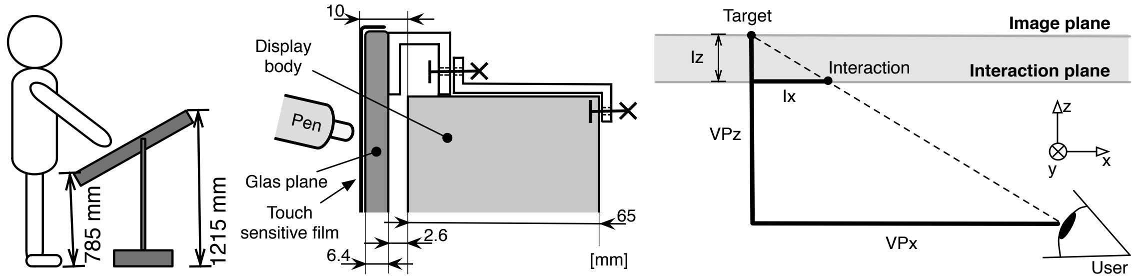

Figure 2. (a) Schematic measurement setup with test person (b) Assembly of the tracking system on top of the display. (c) Linear dependency between relative viewpoint (VPx) and interaction error (Ix).

3.1 Experiment Design

In order to model the user's interaction behavior realistically, the probabilistic model is deduced from empirical data collected in a user study. We measured the touch position on the interaction plane, the target position on the image plane, and the user's viewpoint position in front of the screen as 3D data, while the user executed a simple interaction task on a large interactive system.

3.1.1 Participants

The average age of the 13 male and 4 female participants was 31.05, their median age was 29, and the average (median) height was 1790 (1840) mm. Four test persons were left-handed and 8 wore glasses.

3.1.2 Task

As shown in Figure 2 (a), the user's task is to stand in front of the digital whiteboard, trying to hit a button that appears at random positions on the screen. Due to [19] we defined a realistic but small and symmetric target of 13 x 12 mm (15 x 15 pixels) to motivate the user to hit the target's center (see Figure 3 (c)). After each interaction, the button moves to the next position, regardless of whether the user hits the target or not. The user is encouraged to move freely in front of the screen during the task. The typical task duration (measurement acquisition time) is 5 minutes to avoid fatigue. The user's viewpoint is not only biased by his characteristics (height and arm length), it also depends on the position of the button element on the screen.

3.1.3 Interactive System

We used a 50-inch plasma display (Pioneer PDP-502 MXE) with a resistive touch-sensitive overlay (SMART Technologies) mounted on top of the display. The display's resolution of 1280 x 768 pixels and its effective size of 1098.2 x 620.5 mm result in a pixel pitch of 0.858 x 0.808 mm. Each pixel is implemented as a square arranged set of cells for each primary color, with a distance of less than 0.2 mm. The front glass is divided into a front glass substrate, a dielectric layer, and a protective layer to stabilize the monitor and to shield the high voltage. We assume the thickness of the front glass between 3-5 mm.

The tracking system is a touch sensitive film stretched on a 6 mm glass plane, which is mounted 2.6 mm in front of the display plane (Figure 2 (b)). Hence, the overall offset between interaction plane and display plane is 10 mm. The resistive system is capable of tracking a set of passive tangible user interfaces [15] like pens and an eraser, as well as the user's finger. The tracking position is forwarded to the operating system as standard pointing device coordinates. The tracking system was statically calibrated with 6 sampling points. To avoid the influence of a changing viewpoint relative to the target, the calibration is done orthogonally by hand. This implies an inherent static error of the tracking system.

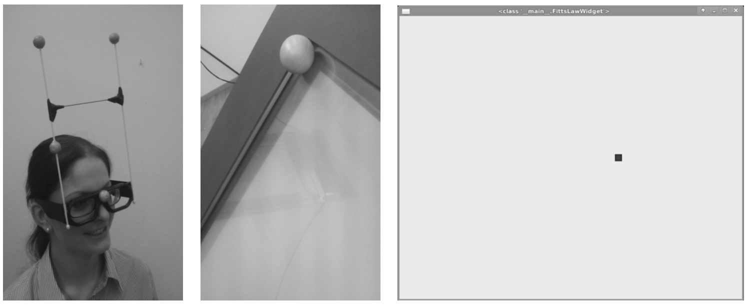

Figure 3. (a) Head tracking module, (b) passive marker on the interactive screen, (c) Interaction application.

3.1.4 Tracking System

We used the Qualisys Motion Tracking System with 4 Oqus 300 cameras to continuously track the position of the user's head and of the interactive screen. Each camera emits infrared light, which is reflected by marker balls. After calibrating the tracking system with an error standard deviation of 0.87 mm, the Qualisys tracking software provides 3D positions of the markers' centers. Together with the touch sensitive overlay on the screen, the overall setup provides the 3D coordinates of the viewpoint, the interaction point, and the target point relative to the upper left corner of the display. The viewpoint body consists of 4 markers applied to glasses the user has to wear during the tests. It was also possible to wear additional correcting glasses (Figure 3 (a)). The position of the user's viewpoint is unequivocally defined by the position of the ball, which is mounted next to his nose.

The target position as well as the touch position on the interactive screen is given as display coordinates. As we will discuss in more detail, the hit point and the target position on the screen are provided by the test application as two-dimensional display data. To compare this data with the 3D viewpoint position, the display data is transformed into 3D data. In order to map the display data to 3D spatial data, the display's 3D position also has to be tracked. For doing so, we equipped the display with three markers in the corners (Figure 3 (b)). Since the corresponding vectors are aligned to the display dimensions, the display coordinates can easily be transformed to special coordinates using the display's pixel pitch as dilation factor.

The tracking setup covers the working area in front of the interactive display. Since the system interaction on the interactive screen is limited by the user's arm length (between 662 and 787 (616 and 762) mm of human males (females) [16]), the tracking area is limited to two times the maximum arm length plus the display width times the arm length (distance to the display) times the user's height (between 1629 and 1841 (1510 and 1725) mm of males (females)). The tracking system captures the user's position with an update frequency of 50 Hz.

3.1.5 Data Consolidation

As described before, the tracking system provides 3D data from the user's viewpoint and the corners of the interactive screen in mm, while the test software provides the target position and the user's click position in 2D display coordinates. Thus, this different information has to be consolidated to have a single data model.

Based on the pixel pitch of the display and the 3D positions of the display corners, the logging software calculates the 3D position of the 2D display data. The display coordinates are shifted orthogonally to the display plane by the parallax offset of 10 mm with additional respect to the marker's diameter. Given theses parameters, the consolidation module queries the 3D tracking software for the markers' 3D positions, triggered by an interaction of the user within 50 mm distance of the target to ignore accidental integrations. Then, the software records the timestamp, the calculated 3D data of viewpoint, as well as target and hit point relative to the upper left corner of the display. Logging the viewpoint, the interaction point and the target on the screen separately, the setup is robust against movement of the devices.

3.2 Measurement Results

Based on the 3D measurement of the touch position on the interaction plane, the target position on the image plane and the user's viewpoint position in front of the screen, we analyze the pointing error of the hardware setup, defined as offset between interaction position and target center for the vertical and horizontal dimension according to the display. Moreover, we deduce the assumed interaction point from the target position and the viewpoint, to show the impact of the parallax error onto the overall interaction error.

In preparation of the observation model, which we shall describe next, we investigate the correlation of the viewpoint and the pointing error.

3.2.1 Pointing Error

This section contains results of the pointing error measurements. Due to the small and symmetric target, we assume that the targets are hit in the center. The first aspect is the overall pointing error, which is defined as offset between interaction point and target center. The second aspect shows the influence of the parallax distortion on the overall pointing error, measuring the offset between the actual interaction point and the assumed interaction point. The assumed interaction point is defined on the line between target and viewpoint (Figure 4), which implies not to be affected by the parallax error. Hence, the deviation of the overall pointing error (first aspect) and the offset between assumed and actual hit point (second aspect) indicates the influence of the parallax error on the overall pointing error, with respect to the specific test setup.

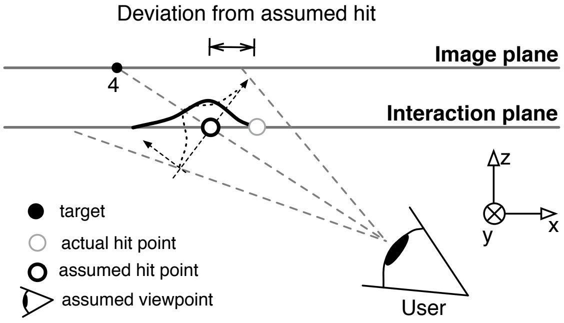

Figure 4. Schematic model of the assumed hit point.

We deduce the overall pointing error directly from the empirical data and analyze two aspects: The pointing accuracy is a measure of how well the user hits the given target [17]. It is indicated by the mean value of the measurements. The pointing precision, on the other hand, refers to the stability (variance) of the data [17], and is a measure of the quality of repeatability.

Figure 5 shows the vertical (a) and horizontal (b) click error with regard to the center of the target. The measurements show that the user did mostly click left of the target's center with a mean distance of -3 mm. 41 % of the interactions lay outside of the target area (33% left and 8% right). The standard deviation of 11 mm indicates a relatively large uncertainty in horizontal precision. The mean of -7 mm in vertical error indicates that the users mostly clicked above the target. With 10 mm, the standard deviation is similar to the horizontal values, although the target was missed in 45% of the interaction (40% above, 5% below). The histogram of the horizontal pointing error shows two clusters around -5 and 0 mm.

The horizontal deviation of the interaction position from the assumed interaction point is illustrated in Figure 5(b). It has a mean value of -1 mm and a standard deviation of 9.4 mm. Although the two domains are not significantly distinguishable (see Figure 5(c)), the deviation of the actual interaction point from the assumed touch point is lower than the overall pointing error. The vertical measurements show a mean value of -6 mm with a standard deviation of 10 mm. Since 41 % (45 %) of the horizontal (vertical) clicks lay outside the target area, 19 % of the interactions with the target area are recognized correctly.

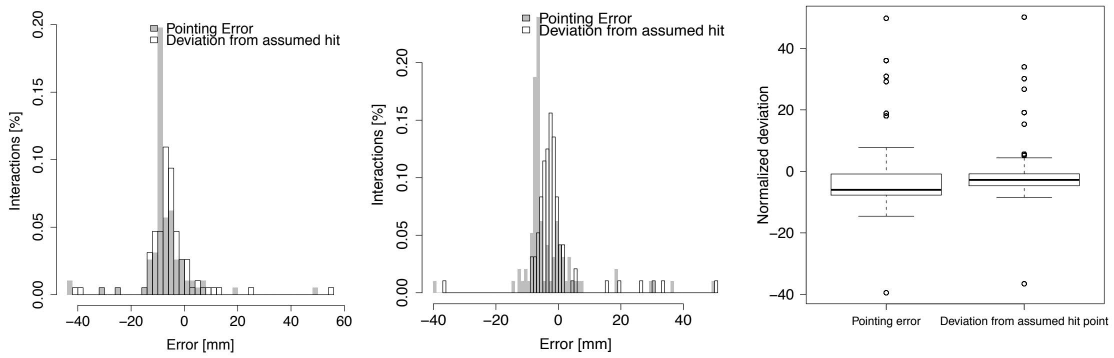

Figure 5. (a) Vertical and (b) horizontal pointing error and deviation from assumed interaction position; (c) boxplot of the horizontal deviation from the target center (pointing error) and the assumed interaction position.

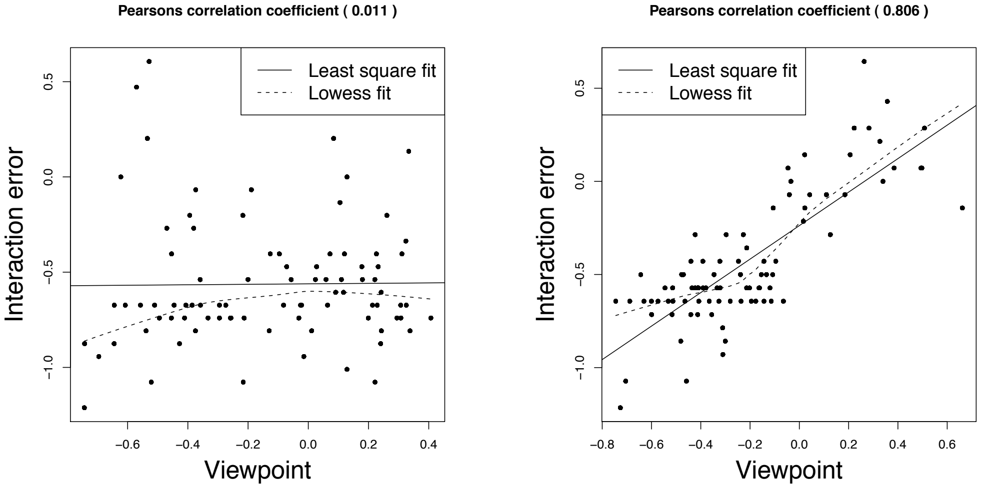

Figure 6. Normalized (a) vertical and (b) horizontal viewpoint and interaction error.

3.2.2 Correlation of Pointing Error and Viewpoint

To motivate the dependency of the interaction point and the viewpoint, which is assumed by the parallax correction controller using the pointing error as indication for the viewpoint, we analyzed the correlation between the two domains. As indicated in Figure 2 (c), we investigated the offset of the viewpoint position and the interaction position with respect the target position. We normalized the offsets with respect to the distance to the display plane and treated the horizontal and vertical dimension separately.

Figure 6 shows scatter plots (with 5505 measurements) of the relation between viewpoint and interaction error in vertical and horizontal dimension. Since Pearson's r. gives a horizontal (vertical) positive correlation coefficient of 0.806 (0.011), the horizontal data is globally positively correlated and the vertical data is not correlated. Hence, we focus on analyzing the horizontal data. The linear model Figure 6 (b) indicates that the correlation is globally biased by a factor of app. 0.3. The LOESS model [24, 34] for local regression shows an almost linear model over the entire space: The correlation is linear: The interaction occurs right (left) to the target if the user is standing right (left) of the target. The area between -0.5 and 0.0 [viewpoint] indicates a correlation of higher order with a medium correlation coefficient of 0.462.

Showing a correlation between the viewpoint position and the interaction error, the measurements motivate to deduce an observation model, which describes the probability of getting an interaction error (observation) given a viewpoint (state). This model will allow the controller to set up the parallax correction based on the viewpoint, which is inferred from the pointing errors.

3.3 Discrete Observation Model

Motivated by the measurement results, we now present the discrete observation model for the POMDP parallax correction controller. The model describes the correlation between the interaction error and the user's viewpoint and allows the controller to infer the actual viewpoint from the interaction instead of measuring it directly (with a 3D tracking system). Motivated by the fact, that the correction can only be applied in a discrete way and the interactions are defined with respect to the discrete display coordinates, the final model is formulated as discrete conditional probability distributions over the observation space O (interaction error) given the state s (viewpoint) from the state Space S: $P(O|S=s)$.

The correction controller defines the state space as the deviation of the user's actual viewpoint to the left (respectively right) from the assumed viewpoint [9]. The line between the actual assumed viewpoint and the target position defines the expected interaction position (Figure 7). Hence, the offset between expected interaction position and target center defines the actual applied correction of the interaction, so that the interaction on the expected interaction position (O_{hit}) would be perfectly corrected to the center of the target. Interacting beside the assumed interaction point indicates a different viewpoint of the user and the controller adapts the assumed viewpoint according to the observation model. If the interaction point around a specific target is within the tolerance interval, the controller assumes that the respective target was aimed for. Therefore, it is mapped to the observation space and emits a discrete observation to the controller. Figure 7 shows three observations: O_{hit}, O_{left} and O_{right}, which are defined with respect to the inferred viewpoint. Given the actual viewpoint, which is unknown to the controller, the observation model defines the probability of the occurrence of the observation. The controller receives one of the observations and calculates a probability distribution over the viewpoint space applying the Bayes theorem to the conditional probability of the observation model. This new information is used to adapt the assumed viewpoint position and the parallax error correction for the next interaction.

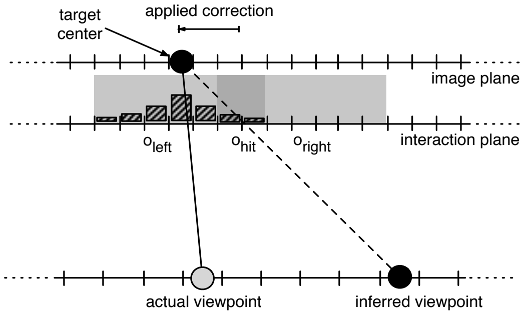

Figure 7. Observation (O) model for a given viewpoint and target (S) as discrete probability distribution $P(O|S)$.

Since the controller uses the interactions (observations) as evidence for the viewpoint (state), we investigate the discriminability of the interaction observations for each viewpoint and show a selection of the resulting conditional probability distributions for the discrete observation space.

First, we discretize the normalized horizontal state space into five intervals with equal length to distinguish between five viewpoints “far left”, ”slightly left”, ”above”, ”slightly right” and “far right” from the target’s position ([-1.0, -0.55, 0.15, 0.0, 0.15, 0.55, 1.0]). Analyzing the occurring pointing errors for each state separately, we found that the states are distinguishable by the resulting pointing error (see Figure 8(a)). The boxplots show that the areas between the first and the third quartile do not overlap. Although the measurement data does not provide sufficient data for the interval [0.55, 1.0) (user’s viewpoint on the “far left” of the target), due to the few left handed participants of the study, we assume symmetric results. The plots show an increasing variance of the data with increasing offset of the viewpoint.

Due to the significant difference of measurements for the discrete states, the interaction error can be utilized to indicate the viewpoint. As an example for the observation model, Figures 8 (b) and (c) show the discrete probability distribution of two states over five observations.

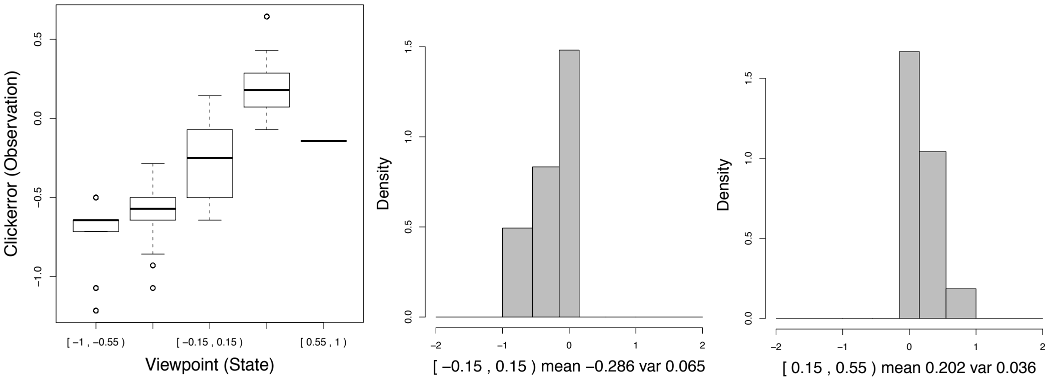

Figure 8. **(a)** Boxplots of the horizontal click error for 5 discrete viewpoint states. (b),(c) Discrete Observation model for three viewpoints as probability distribution over the observation space: P(O|S=s)

4. DISCUSSION

The measurement of the overall pointing accuracy shows a negative mean of the horizontal pointing error. As digital pens were used in the experiments, a likely explanation is the learned behavior of central Europeans to hold pens in a fashion that facilitates writing from left-to-right.

The negative overall vertical pointing error, which means that the user tended to click above the target, could be caused by the fact, that the user's viewpoint was mostly located above the target on the screen, due to the screen setup. The histogram of the horizontal pointing error shows two clusters around -5 and 0 mm. The left cluster indicates the viewpoint to be located left of the target and hit point, and the cluster next to "no error" could be caused by the user trying to correct the parallax error.

The negative mean of the overall pointing error occurs similarly for right- as well as for left-handed people in the vertical and horizontal dimension. This indicates a system inherent error, which could be caused by a dimension-independent error within the static calibration of the tracking system or a wrong offset between interaction plane and display plane. Since the plasma display illuminates gas to plasma, the exact position varies within the cell up to 4 mm. This could also cause the high variation of the pointing error.

The variance of the vertical and horizontal pointing error and dexterity model is similar. The main difference between the vertical and the horizontal data of the pointing error is the mean value, with a distance of 4 mm. Since the dexterity model, which excludes the parallax error, shows a similar distance of 5 mm, without the influence of the parallax error. It could be affected by the different relative position of the viewpoint, under the assumption that the user's motor skills decrease for unfamiliar postures. Analyzing the corresponding data shows that the offset between interaction point and viewpoint is stable for the horizontal direction (low variance), but unstable for the vertical dimension (high variance). Our results confirm the findings in [5]: The user moves mainly in the horizontal direction when working on large interactive screens, while the distance to the screen and the vertical position is stable.

4.1 Improvement of the Parallax Error Correction

The quality of an interaction system can be quantified by counting the number of successfully recognized interactions. A correct interaction is defined as hit detection of the target, which occurs if the pointing coordinate is located within the target area. Since the user's goal in the test study was to hit the target area, we interpret every click as an intended click on the target.

In this section, we discuss the interaction improvement using a parallax correction controller without partial observeability. This imaginary perfect controller directly measures the viewpoint of the user with a 3D tracking system like we used for the user study. It shifts the interaction position by the offset between assumed interaction point and target center in order to eliminate the parallax error. Although this controller could eliminate the parallax error, it does not reduce the error that stems from the motoric skills and the motivation where to hit the area target. Thus, we can interpret the deviation of the interaction from the assumed interaction position as click error after viewpoint based parallax error correction. Moreover, the deviation between the resulting target hits indicates the potential improvement of the parallax correction with respect to the specific target (shape and size) and the interaction system. Applying this correction controller, the number of correctly detected pointing interactions would be 43% (82% in the horizontal and 53 % in the vertical dimension). This would increase the pointing quality, since the number of correctly detected interactions from the user study without the correction is only 19%.

5. CONCLUSION AND FUTURE WORK

In this paper, we derived a discrete observation model to enable a POMDP parallax correction controller to deduce the user's viewpoint from his interaction. The controller can be implemented into several applications on interactive surfaces like public kiosk applications, cashing and ticketing machines, or large digital whiteboards to eliminate the disturbing parallax error. The increased pointing accuracy allows using smaller pointing targets. This increases the usability of the system, since the number of targets on the screen increases and the number of submenus could be reduced. The main advantage of using a model-based approach is the fact that the controller overcomes the parallax error without any additional and expensive tracking hardware to directly measure the user's viewpoint.

In order to realistically model the user's interaction behavior, we derived the model from empirical data of a user study. We investigated the pointing quality on the test setup and showed the significant impact of the parallax error. Next, we showed the correlation between actual viewpoint and interaction error, which allows the controller to estimate the viewpoint based on the interaction. Since the parallax error depends on the viewpoint, the controller can continuously adapt the correction parameter on the interactive screen to eliminate the parallax error. It does not overcome the error stemming from the motoric skills and the motivation where to hit the area target.

To define an observation model, which is based on the interaction error with respect to a specific target on the screen, the controller has to be able to identify the target, which the user wants to hit. Hence, the targets must be arranged with a certain distance on the screen. We assumed that the target is hit in the center. The model could be extended considering the click positions for different targets. Thus, we will investigate the click position for several targets, which differ in size and shape. This will be deduced from a user study on an interactive screen with minimal offset between the interaction and image plane to minimize the influence of the parallax error. The resulting targeting probability distribution will be used as prior for the estimator to weight the interaction observations.

In a second step, the process model of the user's behavior [5] will be integrated into the estimator to predict the future user position, since the correction has to be done for the upcoming interaction. To set up a non-myopic correction policy with respect to the uncertainty of the estimated viewpoint, the POMDP model has to be planned out. To finally evaluate the estimating controller, we will compare it with a camera based tracking system, which observes the users viewpoint directly.

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