# 11

# Improving Target Acquisitions through Utilizing Pen Pressure

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## 1. Introduction

Target selection via pointing is a fundamental task in graphical user interfaces (GUIs). A large corpus of work has been proposed to improve mouse-based pointing performance by manipulating control display (CD) parameters (Blanch et al., 2004; Grossman & Balakrishnan, 2005; Guiard et al., 2004; Kabbash & Buxton, 1995; Worden et al., 1997) in desktop environments.

Compared with mouse-based desktop GUIs, pen-based interfaces have a number of different characteristics. First, pen-based interfaces typically use absolute pointing via a direct input device (i.e., a pen), which is very different from indirect input, such as using a mouse. Second, in addition to the 2D position (x, y) values, many pen-based devices offer additional sensory properties (such as pen pressure values) that can be useful for interaction. Third, many pen-based interfaces have limited display space and input footprint. As the amount of information displayed on the screen increases, users have to select smaller targets. This is especially obvious in mobile products, such as personal digital assistants (PDAs), pen-based mobile phones, and other mobile pen-based applications. Compared with the extensive studies carried out for mouse-based pointing, more empirical studies are needed to determine how we can improve pen-input usage and efficiency.

Although previous studies have intended to exploit novel pen-based selection techniques, such as Slide Touch (Ren & Moriya, 2000), Drag-and-pop (Baudisch et al., 2003), Bubble Radar (Aliakseyeu et al., 2006) and Beam Cursor (Yin & Ren, 2006), these techniques were mostly designed for situations where targets are sparsely distributed across a display space. When targets are smaller and densely packed, the benefit of these techniques tends to be diminished or become unavailable.

Recently, an increasing amount of work has explored the use of pen pressure, which is available on pen devices (such as most Tablet PCs or Wacom tablets), as the third input dimension for interaction design (Herot & Weinzapfel, 1978; Li et al., 2005; Ramos et al., 2004; Ramos et al., 2003; Ramos & Balakrishnan, 2005), in addition to the 2D x-y coordinates. However, little attention has been paid to using pen pressure to improve target selection tasks. This study, therefore, investigates the possibility of improving the performance of target acquisition tasks for pen-based environments by taking advantage of pen pressure potentials. This chapter presents the Adaptive Hybrid Cursor, the first interaction technique that employs pen pressure for target selection. The Adaptive Hybrid Cursor can automatically adapt the selection cursor as well as the target space based on pen-pressure.

There are three fundamental elements in a selection task: a cursor, a target, and a selection background (including a void space). We explored how pen pressure can be employed to improve target acquisition tasks by varying these three elements. The background plays an important role in many applications but its use was often overlooked in previous work. For example, numerous functionalities have been designed to associate with the background in Windows and Mac desktops, from basic but important functions such as selecting and deselecting, to re-arranging desktop icons and also to more complex operations such as changing certain properties of applications. A background also serves as a visual storage space for future elements. Furthermore, group selection techniques (such as rectangular or lasso techniques) would be awkward to operate without being able to select an empty space. The famous quote from the ancient Chinese philosopher, Lao Tze, says, "the usefulness of the wheel, cup and house is actually based on their emptiness". Without the ability to select the background, many applications become difficult to use.

The Adaptive Hybrid Cursor has the following design characteristics:

(1) This technique takes advantages of pressure-sensitive input devices. Pressure is used to control the zoom ratio of interface contents. To achieve a steady zoom control by pressure, an optimal pressure mapping function is employed.

(2) This technique improves performance by manipulating all three components of target selection: the background, the target and the cursor. Such technique design allows quick and accurate small target selections, even for targets that are arranged tightly.

(3) This technique employs an adaptive strategy for target selections, in which two selection mechanisms are coupled: (i) Zooming *Cursor* method and (ii) Zooming *Target, Cursor* and *Background*. With the adaptive strategy, the best mechanism is invoked according to information on the size and layout density of a desired target.

(4) This technique provides easy cancellation by reversing the pressure value without having to use an extra mode-switch button.

In evaluations of this technique, the two selection mechanisms of this technique are thoroughly examined by formal experiments. Subjects performed 2-dimension selection tasks with different densities and sizes of targets. The researchers found that the technique indicated benefits in selecting small targets with high densities. This technique could be implemented on devices capable of sensing pressure like tablet computers or some other pen-based devices.

In this chapter, we first review the related work. Next we describe the design of our new technique. We then present the evaluation of the Adaptive Hybrid Cursor under various target acquisition conditions. We conclude with a discussion of our results and directions for future work.

## 2. Related Work

In this section, we discuss related work regarding both target selection techniques and pen pressure.

### 2.1 Previous Work on Selection Techniques

Target selection tasks can be modelled by Fitts' law (Fitts, 1954; MacKenzie & Buxton, 1992). One common form of Fitts' law is $MT=a+b\log_2(A/W+1)$, which states that the time ($MT$) to acquire a target with width $W$ and distance (or amplitude) $A$ from the cursor can be predicted (where $a$ and $b$ are empirically determined constants, and the term inside the log function is called *Index of Difficulty* or *ID*). Obviously, target acquisition performance can be improved by increasing $W$, decreasing $A$, or both.

The width of a target is usually defined by the space it occupies on the screen. The *effective target width (EW)* may be defined as the analogous size of a target in motor space. In standard pointing, the effective target width matches the visual width. However, the effective width can be increased either for the cursor (Grossman & Balakrishnan, 2005; Kabbash & Buxton, 1995; Worden et al., 1997) or the target (Cockburn & Brock, 2006; McGuffin & Balakrishnan, 2002; Zhai et al., 2003) to achieve the same effect. Most previous studies have shown the effectiveness of their proposal only for single isolated target (McGuffin & Balakrishnan, 2002; Zhai et al., 2003), while they have not been shown to work well when multiple targets are present in close proximity (Cockburn & Brock, 2006; Guiard et al. 2004; McGuffin & Balakrishnan, 2002; Zhai et al., 2003). The state of the art in this category is Bubble Cursor (Grossman & Balakrishnan, 2005), a mouse-based technique that allows selection of discrete targets by using a Voronoi diagram to associate void space with nearby targets. Bubble Cursor works well even in a normal-density multiple-target environment except for the limitations mentioned in the discussion section of this paper.

There is also a large body of work that is intended to improve selection performance by decreasing A. They either bring the target much closer to the cursor such as Drag-and-pop developed by Baudisch et al. (2003), and 'vacuum filtering' introduced by Bezerianos & Balakrishnan (2005), or jump the cursor directly to the target, such as with the object pointing technique (Guiard et al. 2004). Overall, the performance of techniques aiming to decrease A is largely affected by the number of distracting targets between the starting position and the target. They tend to work well on large displays where targets are further away or in low density environments with few distracting targets. These techniques become less effective with high or normal density environments in regular or smaller size displays such as Tablet PCs or PDAs.

Some have tried to improve pointing and selection by dynamically adjusting the Control Display gain. The gain is increased on the approach to the target and decreased while inside the target thus increasing and decreasing the motor space at critical moments in the selection process. TractorBeam (Parker et al., 2005) is a hybrid point-touch technique that aids selection by expanding the cursor or the target, or by snapping to the target. Worden et al. (1997) implemented 'Sticky Icons' by decreasing the mouse control-display gain when the cursor enters the icon. Blanch et al. (2004) showed that performance could be predicted using Fitts' law, based on the resulting larger $W$ and smaller $A$ in the motor space. The common problems for these techniques occur when multiple small targets are presented in close proximity, as the intervening targets will slow the cursor down as it travels to its destination target.

An interesting special case here is a technique which is used on large displays to help reach targets that are beyond the arm's reach (Aliakseyeu et al., 2006; Baudisch et al., 2003; Bezerianos & Balakrishnan, 2005; Collomb et al., 2005 ; Nacenta et al., 2005), e.g., RadarView (Nacenta et al., 2005). However, since RadarView decreases both *A* and *W* proportionally, the *ID* is unchanged. The benefit of RadarView is only demonstrated on larger displays where users can operate on RadarView to save the extra movement required to reach a distant target i.e. one that is beyond arm's reach. Bubble Radar (Aliakseyeu et al., 2006) combines RadarView and Bubble Cursor by first placing the objects within reach, and then applying Bubble Cursor to increase selection performance. Bubble Radar also tried to address the background selection problem of Bubble Cursor by using a button switch controlled by the non-dominant hand, however, since Bubble Radar is virtually another Bubble Cursor, its advantage is likely to diminish in a high density environment.

### 2.2 Related Work on Pressure

There has been less work done on pressure than on pointing-based target acquisition characteristics. Studies on pressure can be roughly divided into two categories. One category investigates the general capabilities of humans interacting with computers using pressure. For example, Herot & Weinzapfel (1978) investigated the human ability of the finger to apply pressure and torque to a computer screen. Buxton (1990) studied the use of touch-sensitive technologies and the possibilities for interaction they suggest. Ramos et al. (2004) explored the human ability to vary pen-tip pressure as an additional channel of control information. The other category of study is where researchers build pressure enabled applications or techniques. For instance, Ramos & Balakrishnan (2003) demonstrated a system called LEAN and a set of novel interaction techniques for the fluid navigation, segmentation and annotation of digital video. Ramos & Balakrishnan (2005) designed Zlider widget. Li et al. (2005) investigated using pressure as a possible means to delimitate the input phases in pen-based interactions. Although these works opened the door to establish pressure as a research avenue, we are unaware of any work which addressed the issue of applying pressure into discrete target acquisition. We attempt to investigate this issue in this paper.

## 3. Adaptive Hybrid Cursor Design

A few previous studies have shown that a reasonable manipulation of targets, cursors and context can enhance target acquisition. However, the tradeoff between the "original" state of these three elements and the "manipulation" state needs to be considered in technical design. Our approach is to employ pen-pressure which is an available parameter in some pen based devices and can be used to easily produce a continuous value or a discrete state. Pen-pressure has the potential to affect selection implementation. Based on this idea we designed the Adaptive Hybrid Cursor technique.

Adaptive Hybrid Cursor includes two states. It first determines whether it should zoom its contexts (target and background) and/or cursor according to the initial location of the cursor and the information regarding the position of targets. If the condition is not suited to the adaptive strategy, Adaptive Hybrid Cursor initiates the Zoom Cursor technique described in Section 3.1 (see Fig. 1). If the condition satisfies the adaptive strategy criteria, Adaptive Hybrid Cursor begins to zoom the targets, the cursor and background based on the pressure described in Section 3.2 (see Fig. 2).

### 3.1 Zoom Cursor Technique (State 1)

One possibly fruitful direction open to the examination of pressure-enhanced target acquisition is to use pen pressure to enlarge the cursor size. Based on this intuition, we designed Zoom Cursor, a technique that allows a user to enlarge the cursor size by pressing the pen tip harder on a tablet or a touch-sensitive screen (see Fig. 1).

As determined in previous studies (Barrett et al., 1996), the degree of pen pressure perceived by human users is not consistent with that sensed by digital instruments. For example, at a low spectrum of pen pressure, the sensed pressure value increases much faster than users would expect. Previous work has used a sigmoid transfer function to achieve the effects produced by pressure. In our experiments we also employed the sigmoid transfer function. The application of pressure is comprised of an initial "dead zone", slow response at low pressure levels (too sensitive for users to distinguish and control), smooth transitions at median pressure levels and quick responses at high pressure levels (users often confirm pre-selection by imposing heavy pressure on a pen-tip). We employed a piecewise linear function to approximate the pressure mapping.

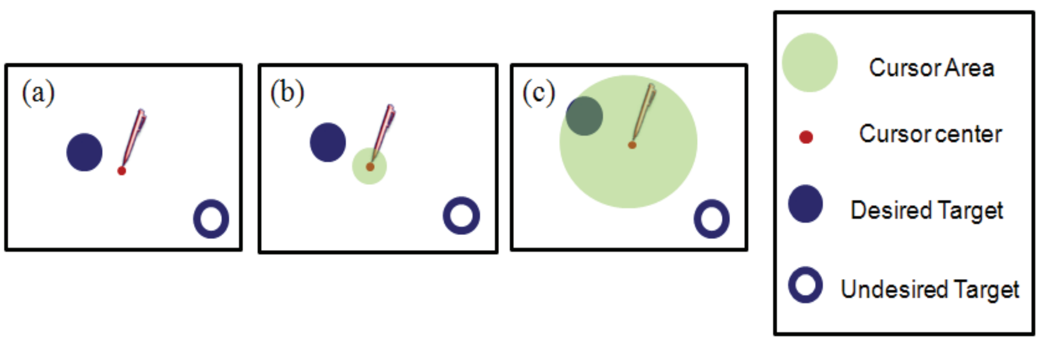


Fig. 1. The process of selecting a target with Adaptive Hybrid Cursor in State 1: the adaptive hybrid cursor employs the Zoom Cursor technique which changes the size of the cursor when targets are big in a low density environment. (a) the pen-tip lands on the screen; (b) pressure value is used to zoom the cursor. (c) pressure and location of the cursor are adjusted to make the zoomed cursor interact with the desired target. The desired target is selected by quickly lifting the pen-tip. Note that the same legend is used for Fig. 2.

If pressure causes the cursor to become too large, then more than one target might be included, and this may confuse the user. To overcome this problem, a basic principle should be specified so that when enlarging the cursor, only one target will be included at one time. Therefore, a maximum size for the cursor should be determined according to the current position of the cursor and the layout of targets. This will help to ensure that an enlarged cursor cannot include more than one target. Note that the maximum size of the cursor is dynamically changed based on the proximity of surrounding targets. We follow the algorithm used to set the radius of the cursor in Bubble Cursor. We also use a circular-shaped cursor and we allow only one target to be selected each time.

To describe the algorithm in an environment with targets *T1, T2, ..., Tn* we used the following definitions:

*Minimum Distance i (MinDi)*: The length of the shortest line connecting the center of the Zoom Cursor and any point on the border of *Ti*.
*Maximum Distance i (MaxDi)*: The length of the longest line connecting the center of Zoom Cursor and any point on the border of *Ti*.
A simplified version of the algorithm is as follows:
*Calculate the Minimum Distance to each target: MinD1, MinD2,…, MinDn*
*Calculate the Maximum Distance to each target: MaxD1, MaxD2,…, MaxDn*
*Set maximum radius of Zoom Cursor = the second minimum value (MinD1, MinD2,…, MinDn, and MaxD1, MaxD2,…, MaxDn)*
After a desired target is included by the enlarged cursor the target selection is achieved by the "quick release" manner (Ramos et al., 2004).

### 3.2 Zooming Target, Cursor and Background (State 2)

Using direct pointing, the selection speed has an upper limit due to human limitations such that selecting a 10 cm wide object which is within 10 cm of the human user will take less than a second, while a target which is 10 meters away will take at least several seconds to reach. Thus Bubble Radar uses RadarView to bring the targets within arm's reach so that Bubble Cursor can be subsequently easily applied for actual target selection.
Similarly, if the targets are too small and densely packed, it becomes more difficult for the user to visually locate the target. In such cases, enlarging the workspace has the effect of simultaneously increasing *A* and *W* and thus making target acquisition easier. Based on this hypothesis, we decided to enlarge the entire workspace when the target size is smaller than 1.8 mm (about 6 pixels in our experimental setup). (Ren & Moriya's study indicated that 1.80 mm is "the smallest maximum size" (Ren & Moriya, 2000)), or *EW/W* value is less than 2 where *EW* is the effective width. Here, we define *EW/W* as the density of targets, i.e. the amount of void space immediately surrounding a target. The result of pilot studies showed that the selection technique that zooms cursor, target and background at the same time could not show significant advantages above Bubble Cursor when the value of *EW/W* is more than 2. We defined an environment where the *EW/W* ratio was less than or equal to 1.5 as a high density environment, and, when the *EW/W* ratio was greater than 1.5 and less than or equal to 2, we called it a normal density environment. When the *EW/W* value was equal to or greater than 3, this was called a low density environment. High density environments are common in today's applications (e.g., a word processor or a monthly calendar viewer). Fig.2 is an illustrated walkthrough of the technique in State 2.

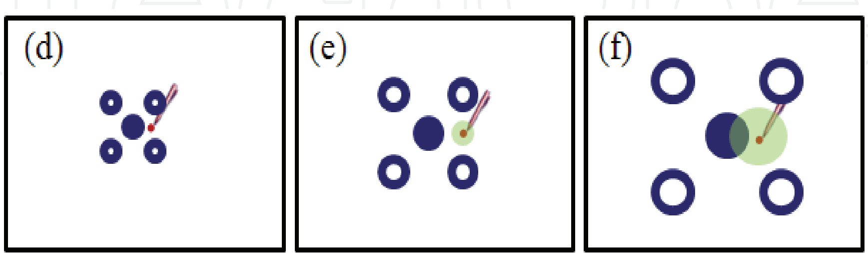


Fig. 2. The process of selecting a target with Adaptive Hybrid Cursor in State 2: Adaptive Hybrid Cursor is able to vary the size of targets, cursor and background simultaneously by pressure when approaching small targets and/or small *EW/W*. (d) the pen-tip lands on the screen; (e) using pressure value to zoom in the targets, the cursor and the background. (f) adjusting pressure and location of the cursor to make the zoomed cursor interact with the desired target. The desired target is selected by quickly lifting the pen-tip.

The maximum zoom ratio is 3 in our current design. The zoom ratio is controlled by the mapped pressure value. At the same time, Adaptive Hybrid Cursor also uses pressure and the "updated" location information of targets to zoom the cursor size according to the principles of Zoom Cursor. When the desired target was interacted by the cursor, the target selection was achieved by the "quick release" motion (Ramos et al., 2004).
The trigger for the enlargement is pen pressure which dynamically adapts the maximum zoom size of the cursor based on the zoomed surroundings, i.e., the cursor should cover no more than one object at a time.

## 4. Experiment

To evaluate the performance of Adaptive Hybrid Cursor, we conducted a quantitative experiment to compare it with Bubble Cursor and with the traditional technique, the regular cursor (the regular pointing selection in graphical user interfaces) as a baseline. First, Bubble Cursor, which is the current state of the art, has been shown to be the fastest desktop pointing technique. Second, Aliakseyeu et al. (2006) showed that Bubble Radar combined the benefits of Bubble Cursor in a pen-based situation. However, neither Bubble Radar nor Bubble Cursor experiments included very small targets (i.e. less than 1.6 mm). We, therefore, designed the same *EW/W* (1.33, 2, 3) ratios as for Bubble Cursor but with smaller targets (4 pixels). We wondered if Bubble Cursor offered the same advantage in smaller target situations in pen-based environments. Third, Adaptive Hybrid Cursor also employs the effective width of targets just as with Bubble Cursor, targets being allocated effective regions according to a Voronoi diagram.

### 4.1 Participants

Twelve subjects (11 male and 1 female) all with previous experience using computers were tested for the experiment. The average age was 24.9 years. All subjects used the pen in the right hand. All subjects had normal or a "corrected to normal" vision, with no color blindness.

### 4.2 Apparatus

The experiment was conducted on a Wacom Cintiq21UX, 43.2x32.4cm interactive LCD tablet display with a resolution of 1600 x 1200 pixels (1 pixel = 0.27 mm), using a wireless pen with a pressure sensitive isometric tip. The pen provides 1024 levels of pressure, and has a binary button on its barrel. The tablet's active area was mapped on the display's visual area in an absolute mode. The experimental software ran on a 3.2GHz P4 PC running Windows XP. The experiment software was implemented in Java 1.5.

### 4.3 Procedure

Following the protocol (Grossman & Balakrishnan, 2005), we also used a reciprocal pointing task in which subjects were required to select two fixed targets back and forth in succession, but, to simulate a more realistic two dimensional pointing environment, we changed the protocol into a multi-directional reciprocal pointing task which included reciprocal horizontal, vertical and diagonal movements. The targets were drawn as solid circles, and were located at various distances from each other along four directional axes. The goal

target, the one intended to be selected, was colored green. When a goal target had been selected, it changed color to red which was an indication that the user now had to select the next goal target. Four red circles were placed around each goal target to control the *EW/W* ratio (Fig. 3).
Subjects were instructed to select the two goal targets alternately. They were told to emphasize both accuracy and speed. When the subject correctly selected the target, he/she heard a beep sound and the targets swapped colors, which was an indication of a new trial. At the start of the each experiment, subjects were given a warm-up block to familiarize themselves with the task and the conditions.

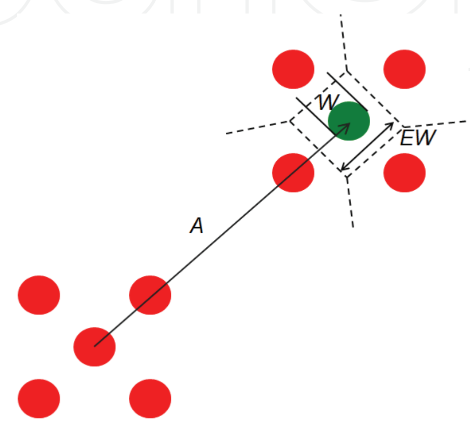


Fig. 3. Experimental setup. The solid red circle that is surrounded by four targets is the start target (as well as one of the two reciprocating goal targets), the green target is the initial goal target. The four circles around each of the start and goal targets are distracters.

### 4.4 Design

A within-subject design was used. The independent variables were: selection techniques *ST*, amplitude *A* (288, 576, 864 pixels), width *W* (4, 6, 12, 36 pixels), *EW/W* ratios (high = 1.33, normal = 2, low density = 3), and direction *DR* (horizontal, vertical, 2 diagonals). A full crossed design resulted in 432 combinations of *ST, A, W, EW/W*, and *DR*. The order of techniques was counterbalanced using a 3 x 3 Latin-Square.
Each participant performed the entire experiment in one session of approximately 60 minutes at one sitting, including breaks corresponding to changes in selection technique. The session consisted of nine blocks of trials completed for each technique. In each block, subjects completed trial sets for each of the 144 combinations of *A, W, EW/W, DR* appearing in random order. A trial set consisted of 3 effective attempts (4 attempts in total, but the first attempt was the starting point so that it was discarded. Note we had 3 *EW/W* ratios (high = 1.33, normal = 2, low density = 3), as previously defined in Section 3.2, so we could assess the results from different density environments.
In summary, the design of the experiment was as follows:

12 subjects x
3 techniques (Adaptive Hybrid Cursor, Bubble Cursor, Regular Cursor) x
4 target widths (4, 6, 12, 36 pixels) x
3 amplitudes (288, 576, 864 pixels) x
3 *EW/W* (high = 1.33, normal = 2, low density = 3) x
4 directions (horizontal, vertical, 2 diagonals)x
3 effective attempts (4 trials total, but the first trial is discarded due to the same starting point) x

3 blocks
= 46656 total effective selection attempts

After they finished testing each technique, the subjects were asked to fill in a questionnaire which consisted of three questions regarding "selection difficulty", "fatigue", and "overall usability" on 1-to-7 scale (1=lowest preference, and 7 =highest preference). These questions were made by referring to ISO9241-9 (2000)).

### 4.5 Results

An ANOVA (analysis of variance) with repeated measures was used to analyze performance in terms of selection time, error rate, and subjective preference. Post hoc analysis was performed with Tukey's Honestly Significant Difference (HSD) test.

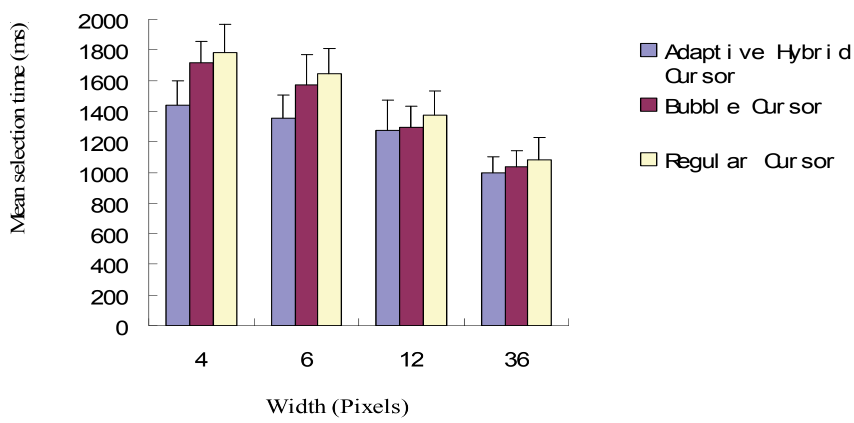


Fig. 4. Mean selection times for different sizes of targets at *EW/W* ratio=1.33.

#### 4.5.1 Selection Time

There was a significant difference in the mean selection times among the three selection techniques, $F(2,33)=13.1$, $p<.0001$. The overall mean selection times were 1129 ms for Adaptive Hybrid Cursor, 1177 ms for Bubble Cursor and 1429 ms for Regular Cursor. Tukey HSD tests showed that both Adaptive Hybrid Cursor and Bubble Cursor were significantly faster than Regular Cursor ($p<.001$). No significant difference was found between Adaptive Hybrid Cursor and Bubble Cursor. Significant interaction was not found between selection technique and block number, $F(4,99) = 0.56$, $p = .69$, which indicated the learning improvement did not significantly affect the relative performance of selection techniques.

As shown in Fig. 4, at the *EW/W* ratio value of 1.33 there was a significant difference in selection time between the three selection techniques, $F(2,33)=15.1$ and 8.9 for the target sizes of 4 and 6 respectively, all $p<.001$. For target sizes of 4, 6 Tukey HSD tests showed Adaptive Hybrid Cursor was significantly faster than Bubble Cursor and Regular Cursor ($p<.01$), however, no significant difference was found between Bubble Cursor and Regular Cursor. No significant differences were found between the three selection techniques for the target sizes of 12 and 36.

At the *EW/W* ratio values of 2 and 3, both Adaptive Hybrid Cursor and Bubble Cursor were significantly faster than Regular Cursor, $F(2,33)=8.0$, 22,9, 8.8 and 19,6 for *EW/W*=2; $F(2,33)=24.2$, 14.0, 15.2 and 20.1 for *EW/W*=3, at target sizes of 4, 6, 12 and 36, all $p<.01$. No significant differences were found between Adaptive Hybrid Cursor and Bubble Cursor in both *EW/W* ratios.

The perspective brought by Fitts' law in terms of size and distance effects provided a useful framework for our design. However, it is questionable if it is valid to parameterize our results with a Fitts' law model. Adaptive Hybrid Cursor was more complex than a typical single pointing task in Fitts' law studies because it required the user to perform multiple steps, i.e., enlarge the curser and its contents by pressure, confirm the goal target, and select the goal target. Indeed, we obtained a rather poor fit between the Fitts' law model and the actual data collected, with r2 value at 0.53 for Adaptive Hybrid Cursor, and 0.87, 0.97 for Bubble Cursor, Regular Cursor respectively (we defined *ID* as $log_2(A/EW+1)$ for Adaptive Hybrid Cursor and Bubble Cursor, while for Regular Cursor $log_2(A/W+1)$). The $r^2$ value for Adaptive Hybrid Cursor was much lower than the values for 0.95 or lower than those found in conventional one-step pointing tasks, e.g. Accot & Zhai (2002); MacKenzie & Buxton (1992). We also looked at the data of State 1 (i.e. Zoom Cursor) described in Section 3.1. We obtained a better fit with $r^2$ value at 0.87 for Zoom Cursor but still lower than the values for 0.95. This was due to the fact that users had to control the size of the cursor which they do not have to do in conventional one-step pointing. The $r^2$ value (0.87) for Bubble Cursor was lower than the values for 0.95. This may have been due to the limitations in pen-based systems mentioned in our discussion section.

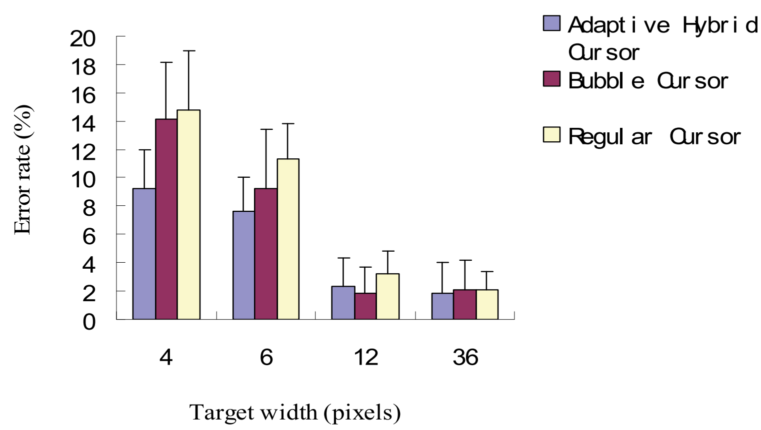


Fig. 5. Mean error rates for different sizes of targets at *EW/W* ratio=1.33.

### 4.5.2 Error Rate

There was a significant difference in overall mean error rate between the three techniques, $F(2,33)=23.4$, $p<.0001$. Tukey HSD tests showed Adaptive Hybrid Cursor was better than both Bubble Cursor and Regular Cursor ($p<.05$). Bubble Cursor was better than Regular Cursor ($p<.01$). Overall error rates were 4.2% for Adaptive Hybrid Cursor, 5.4% for Bubble Cursor, and 7.3% for Regular Cursor.

As shown in Fig. 5, at the *EW/W* ratio value of 1.33, there was a significant difference between the three selection techniques for the sizes of 4 and 6, $F(2,33)=8.1$, 4.2 $p<.05$. For target size of 4, Tukey HSD tests showed Adaptive Hybrid Cursor was better than both Bubble Cursor than Regular Cursor ($p<.05$). No significant difference was found between Bubble Cursor and Regular Cursor. For a target size of 6, Tukey HSD tests showed Adaptive Hybrid Cursor was better than Regular Cursor ($p<.05$). No other significant differences were found among the three techniques. There was no significant difference in error rate between the three selection techniques for the sizes of 12 and 36.

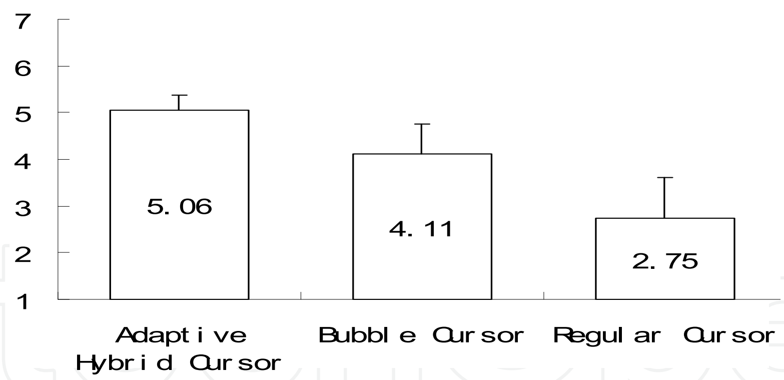

Fig. 6. Subjective ratings for the three techniques (1 = lowest preference, 7 = highest preference).

At the *EW/W* ratio value of 2, there was a significant difference between the three selection techniques for sizes 4 and 6, $F(2,33)=16.2$, 16.6 $p<.01$. For target sizes of 4 and 6, Tukey HSD tests showed both Adaptive Hybrid Cursor and Bubble Cursor were better than Regular Cursor ($p<.01$). No significant difference was found between Adaptive Hybrid Cursor and Bubble Cursor. There was no significant difference in error rate between the three selection techniques for sizes 12 and 36. The results of the *EW/W* ratio value of 3 followed trends similar to those of *EW/W*=2.

#### 4.5.3 Subjective Preference

Fig. 6 shows the subjective ratings for the three techniques. These ratings were based on the average value of the answers given by the subjects to the three questions. Significant main effects were seen between the three selection techniques, $F(2,33)=38.4$ $p<.001$. Tukey HSD tests showed Adaptive Hybrid Cursor was better than Bubble Cursor, and Bubble Cursor was better than Regular Cursor ($p<.01$). Adaptive Hybrid Cursor was the most preferred (mean = 5.06).

## 5. Discussion

To improve the performance for selecting targets in a dense layout, we designed the Adaptive Hybrid Cursor (including Zoom Cursor), a novel interaction technique for pen-based systems, which enables users to adjust the size of the background, the targets and/or cursor the simultaneously. The Adaptive Hybrid Cursor dynamically adapts the permitted upper boundary of a zoomable selection cursor based on the current index of difficulty of a desired target. As shown in our Experiment, the Adaptive Hybrid Cursor showed advantages over other techniques in performance for small targets in a high density environment. The subjective preferences also showed that the Adaptive Hybrid Cursor was the most preferred technique among the three techniques tested.

Overall, the Adaptive Hybrid Cursor showed significant improvements in a pen-based selection task. It works well with a pen, and in expanding contexts. At the same time, it offers competitive selection performance without losing the background selection capability, and does not expand the context in groups of big targets, in normal and low-density environments. By contrast, many of the other mouse and pen-based interaction techniques have been shown to work well only in low density environments or on isolated targets .

Though Bubble Cursor is comparable to Adaptive Hybrid Cursor in high *EW/W* ratios or groups of larger targets in a high-density environment, it has several limitations compared to our technique, especially in pen-based environments. First, by maximizing utilization of empty screen space, Bubble Cursor trades-off the ability to select an important "target", the background. By contrast, our Adaptive Hybrid Cursor (including Zoom Cursor) allows the user to select the background (by applying lighter pressure). Second, Bubble Cursor lacks the undo function. Our technique provides "natural" cancellation by reversing the pressure value rather than using another mode-switch action like Bubble Radar (Aliakseyeu et al., 2006). Third, Bubble Cursor is not designed for pen-based environments and it does not guarantee continuous, incremental visual feedback of the selection cursor. During the experimental process we found that continuous feedback of Bubble Cursor may not always be available on a pen device (e.g., in tracking mode) because the pen-tip often loses communication with the induction area of the tablet when lifting or landing and feedback suddenly appears or disappears as a consequence. Though continuous feedback is not assured with the Adaptive Hybrid Cursor either, it can control the size of the cursor well by pen-tip pressure. Fourth, though Bubble Cursor allows denser target placement than many previous approaches, its performance advantage largely degrades when a target is closely surrounded by other objects. In theory, when the target's effective width (*EW*) approaches its actual width (*W*), little room can be used to improve the motor space. In fact, it has been shown that as the *EW/W* ratio changes from 3 to 1.33, the advantage of Bubble Cursor degrades (Grossman & Balakrishnan, 2005). In contrast, the Adaptive Hybrid Cursor can enlarge the targets, the background, and the cursor, according to the targets' surroundings. Fifth, neither Bubble Cursor nor Bubble Radar experiments have included very small targets. To further clarify, we also designed the same *EW/W* (1.33, 2, 3) ratios but with a smaller target (4 pixels = 1.08 mm). The experimental results showed that Bubble Cursor suffered from performance limitations in groups of small targets in high density environments.

We varied the essential parameters but we found it necessary to simplify our experimental design in some minor points. First, we set each target in each environment to the same size so that control of the target density parameters could be achieved more easily. Second, we used circular targets so that the distance between start point and destination target was constant in all four directions. Third, in Bubble Cursor's experiment, beside the circles around the target, many black-filled circles were also placed between the starting position and the final target as distracters on the mouse pathway. We omitted intermediate targets (i.e., distracter targets) for the following reasons. In indirect pointing environments, these distracters can significantly impact selection performance, since the subjects' selection pathway can't be avoided by the cursor. However, in a direct pointing pen-based environment, the user simply lifts the pen in the air to move from the starting position to the goal target where an out-of-range state is possible. This hypothesis was confirmed in pilot studies and in our Experiment. In addition, even though the distracters are placed between the start and destination targets, visual load will be similar for each of the techniques. Furthermore, the error rate for Bubble Cursor may increase because if the user selects a distracter he/she cannot perform the "undo" task with Bubble Cursor.

We explored the use of pen pressure for improving the performance of target acquisition tasks in pen-based environments. The experimental results have shown that pen pressure can be used to design more effective selection techniques for pen-based environments. The

Adaptive Hybrid Cursor takes advantage of pressure information. By using pressure, the Adaptive Hybrid Cursor (particularly the Zoom Cursor aspect of the technique) achieves in-place mode switching between background and target selection and requires no additional accessories. This is different from Bubble Radar's approach (Aliakseyeu et al., 2006) which uses an additional button to switch states (Li et al., 2005).

Our study contributes valuable empirical data for applying pressure for target selection techniques which had not been previously addressed in literature. This paper also suggests new ways to further improve target acquisition performance for small targets and high density environments. Future work includes applying a combination of strategies found in (Aliakseyeu et al., 2006; Yin & Ren, 2006) into the Adaptive Hybrid Cursor for large display environments and group selections.

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