Free-Space Pointing with Constrained Hand Movements

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Abstract
Research on pointing devices has shown that rate control is appropriate for isometric and elastic devices but not effective when input control is purely isotonic. Human hand has been generally considered as an isotonic device. Therefore, pointing devices that are directly controlled by hand movements (e.g., the mouse) are based on position rather than rate control. In this work, we study the relevance of rate control in low-resolution input. Taking into account elastic properties of the human wrist, this work explores designs that mix position and rate control when input is handled by constrained hand movements.

Keywords
Free-space pointing, hand movements, low-resolution input, position control, rate control, elastic devices

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces – Input devices and strategies, Theories and methods, Evaluation/methodology

General Terms
Design, Experimentation, Human Factors, Theory

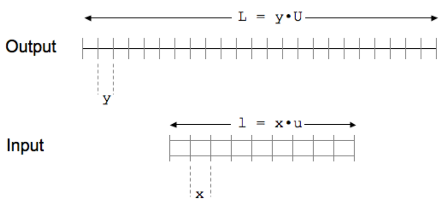

figure 1. Input and output resolutions. The output resolution unit *y* is normally 1 pixel. When u < U, we cannot visit every pixel in the output with absolute pointing.

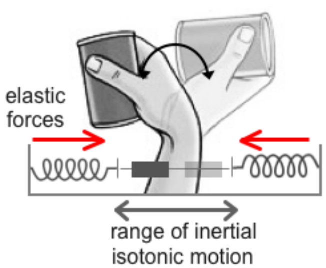

figure 2. Modeling wrist rotations (extensions and flexions) as a mix of elastic and isotonic movements. Elastic forces develop as the hand moves towards its sides.

Introduction

Technology becomes more and more ubiquitous and a variety of handheld devices, such as Wii Remotes, start becoming widely available. Researchers and designers have been envisioning scenarios that move user interaction beyond desktop computers. For example, Vogel and Balakrishnan [11] studied techniques for freehand pointing in front of high-resolution displays. Other work [2] has explored the use of mobile phones as pointing devices. In such scenarios, user interaction does not rely on the presence of specialized input devices and sophisticated motion tracking systems. Hence, interaction with high-resolution information can be difficult. Low input resolution, hand tremor and spatial constraints are common problems that restrict movement and hinder pointing precision. In this case, *absolute* pointing techniques, such as ray casting, are problematic, resulting in high error rates [9, 11].

Several solutions have tried to deal with the problem by balancing between absolute and *relative* pointing. "Clutching" is a common recalibration mechanism that repositions the frame of reference of absolute pointing. Despite its simplicity, it requires explicit mode transitions. Such transitions are generally slow. Their activation relies on additional buttons or gesture recognition algorithms [11] and competes with the activation of other actions, for example, target selections. Similar problems apply to techniques that combine clutching with ray-casting pointing [11].

This paper presents our ongoing work on pointing techniques. Based on the observation that hand movements occur within a limited range around a neutral position, we investigate rate control as an alternative solution. We also explore transitions from absolute to relative pointing that do not require explicit mode switching.

Input Resolution

The role of input resolution (or input accuracy) has been previously discussed [4] in the context of pointing performance. However, its effect has not been studied in a systematic way. Here, we define as input unit the minimum input distance *x* (see figure 1) that is (1) recognized by an input device and (2) accurately controlled by the user, if taking into account hand precision and tremor. This definition allows us to study pointing performance with respect to input resolution. The ratio between output and input resolution determines the maximum Control-Display gain that we can apply without sacrificing precision. In this work, we are interested in scenarios in which output resolution is much higher than input resolution ($U >> u$).

Hand Movement and Rate Control

Research in biomechanics [7, 8] has indicated that although hand movement is purely *isotonic* (isotonic = equal tone or force) around its central position, elastic torques develop as movement extends beyond a certain range. Previous work in HCI [1] has examined pointing performance in different parts of the human hand but has not considered the role of their natural elastic properties. Our hypothesis is that rate control could be appropriate in situations where hand movement becomes stiff and elastic due to the hand's physical constraints (see figure 2). In this case, self-centering develops naturally towards the neutral position of the hand.

According to Casiez and Vogel [3], rate control performs well even for low stiffness values, as long as self-centering is present. Besides, they found that performance decreases by only 15% when stiffness becomes zero, i.e., when movement is purely isotonic. This difference is considerably lower than the performance decrease (50%) reported by Zhai [12].

This could be explained by the fact that Zhai tested more complex tasks that involve multiple degrees of freedom. However, we suspect that there is an additional reason. Zhai examined free-range movements of the arm. In this case, natural self-centering mechanisms are weak or totally absent. On the other hand, Casiez and Vogel examined isotonic hand movement within a small range (3 - 16 cm), involving less muscle groups and possibly, a stronger self-centering mechanism.

Focusing on natural wrist movements, we hypothesize that the hand operates as an isotonic device within a limited range in which elastic forces are not present, but it becomes elastic towards its extreme positions. Motivated by previous work [5, 6] that combines rate and position control in specialized devices, our current research investigates how this approach could extend to pointing with constrained hand movements.

Pointing Techniques

We have explored three pointing techniques that balance between precision and long-distance pointing.

Rate Control

Elastic devices map forces to output velocities. A force F applied to an input device can be written as a function of its displacement d from its zero position by using Hook's law: $F = - k \cdot d$. Similarly, the output velocity v can be expressed as a function $v = f(d)$, where f maps input displacements to output velocities.

Casiez and Vogel [3] have tested linear functions, while earlier work [10] has also tested non-linear parabolic functions. When input resolution is low, the function has to be carefully selected so that the lowest velocity $v_{min} = f(x)$, which corresponds to the displacement of a single input unit, enables precise target selections. We have experimented with both linear and parabolic functions and found that the latter ones allow for more effective transitions between high precision and speed.

Mixed Control

We have explored mixed-control designs, balancing between high precision afforded by position control and smooth long-distance movement afforded by rate control. Our approach is based on existing techniques [5, 6] but does not assume the availability of specialized elastic devices.

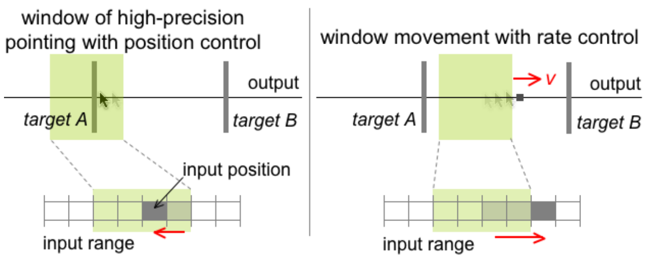

figure 3. Mixed control with a movable window

As shown in figure 3, we divide the input range into three areas. The central area is reserved for absolute pointing. The portion of the display that corresponds to movements within this area is communicated to the user as a framed (or colored) window. The side input areas allow the user to reposition this window by controlling its velocity. As a result, pointing takes place in two different stages. First, the user rotates the hand out if its central area to bring the window around the target. Then, the hand returns towards the central area to point to the target within the window's boundaries. For simplicity, we assume that the two side areas have the same size in units.

Clearly, the input resolution *u* determines the maximum size of the window. Dividing the input range into areas has not an easy solution though. Larger central areas result in larger windows, increasing the active width of rate-controlled pointing. Yet, pointing is not necessarily faster as a shorter range is reserved for rate control. Besides, absolute pointing involves longer distances in this case.

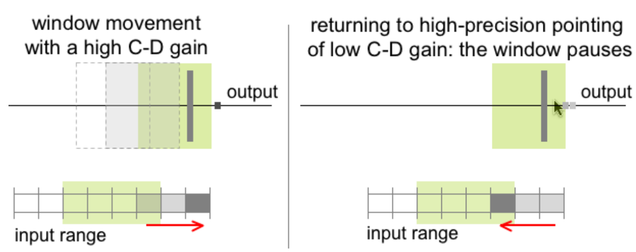

figure 4. Position control with a movable window

Position Control
We have designed a similar window-based technique that applies position control to move the window of absolute pointing (see figure 4). In more detail, a movement of the hand out of its central area translates the window to the left or to the right by using a high control-display gain. When the hand starts moving towards its central area, the window pauses, allowing the user to recalibrate the task. As with clutching mechanisms, the user may have to repeat multiple forward and backward movements before reaching a target. The number of such movements depends on the target's distance, the input resolution, the size of the central input area, and selected control gains.

If *w* units of a total of *u* input units are reserved for absolute pointing, the maximum output distance *D* that can be visited without recalibration can be computed as follows:

$$D = w \cdot gain_{low} + (u - w) \cdot gain_{high} \qquad (1)$$

Apparently, higher control gains and lower *w* values could reduce the number of clutches but could also hinder motor control and pointing precision.

Early Evaluation
We are currently working on the evaluation of the three pointing techniques. Here, we present early results from two pilot experiments.

Task and Apparatus
We tested the techniques in reciprocal 1D pointing tasks (see figure 5). We used an Ascension 3D motion tracker to detect rotations of the wrist around a vertical axis. In order to control input resolution, we discretized the rotation values measured by the magnetic tracker. The operational angle of rotations was measured at the beginning of each experimental session through a calibration procedure. Clearly, this angle varied among participants, but its range in discrete units was fixed.

Experiment 1: Rate Control and Input Resolution
The first experiment tested the three transfer functions shown in figure 6 on two low input resolutions. The functions were empirically selected prior to the

figure 5. Experimental task. The user performs reciprocal 1D pointing tasks by rotating the wrist while holding a small object. Rotations are detected by a magnetic system. Selections are activated by pushing a key on the keyboard with the non-dominant hand. Note that the hand is not externally constrained and movement is natural.

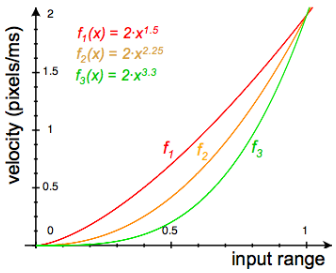

figure 6. Transfer functions tested in Experiment 1

experiment. Six healthy volunteers participated. The design was as follows:

> 6 participants x 2 low input resolutions (21 and 61 units) x 3 transfer functions x 3 blocks x 2 targets widths (8 and 16 pixels) x 3 distances (232, 464, and 928 pixels) = 648 trials in total.

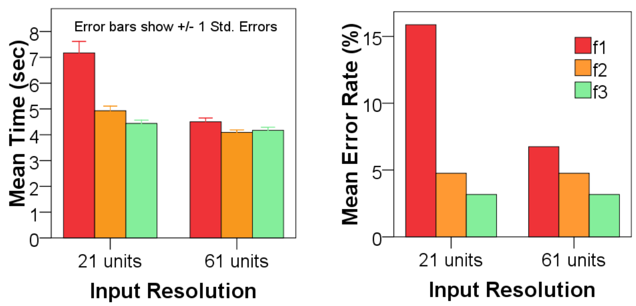

figure 7. Movement time and error rates for two low input resolutions and three parabolic transfer functions

As shown in figure 7, parabolic functions that grow slower around the neutral hand position perform better in terms of both time and errors, particularly when input resolution is low. Interestingly, pointing performance is only 10% slower when input resolution falls from 61 to 21 units, as long as an optimal transfer function is selected. Consider that if a traditional position-control mechanism was used, pointing to a target at a distance of 464 pixels would require at least 7 clutches under a 61-units input resolution and more than 20 clutches under a 21-units resolution.

Experiment 2: Pointing Techniques

The second experiment compared the three pointing techniques. The design was as follows:

> 6 participants x 3 techniques x 2 low input resolutions (61 and 241 units) x 3 blocks x 3 targets widths (8, 16 and 32 pixels) x 3 distances (250, 500, and 1000 pixels) = 973 trials in total.

For both the window-based techniques, we divided the input range (in discrete units) as follows, based on results from a pilot study:

Resolution	Left Area	Central Area	Right Area
61	12	27	12
241	60	121	60

We also tried to optimize control gains and transfer functions based on results from the first experiment and smaller informal tests.

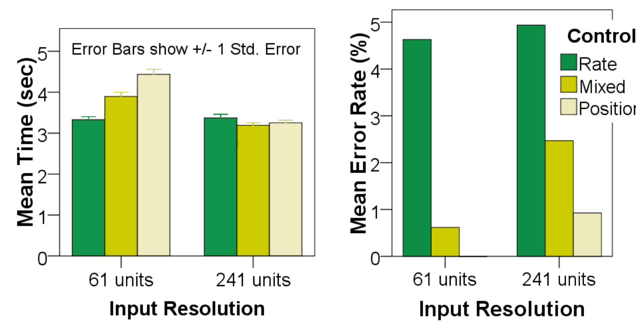

figure 8. Movement time and error rates for the three techniques under two input resolutions

Overall results are presented in figure 8. Results show that rate control suffers from higher error rates. As in our first study, the performance of this technique is not affected by input resolution. Surprisingly, the two window-based techniques perform equally well, although there is a slight but non-significant overall advantage of the mixed-control technique under the low-resolution condition. However, a more detailed analysis of the data shows that there is a significant interaction effect between techniques and distances ($F_{4,20}$=10.43, p<.001). The two techniques are equally fast for 250 and 500 pixel distances, but the mixed-control technique is 20% faster for 1000 pixel distances (p=.039, using Bonferroni's adjustment for nine pairwise comparisons). Clearly, the cost of recalibration movements required by the position-control technique becomes apparent in long distances and low input resolutions.

Conclusions and Future Work

We have explored techniques that help users acquire distant targets with constrained hand movements. Our results show that pure rate control can be effective when input resolution is low, but it results in higher error rates. Our proposed designs split input range into a central area where pointing, based on position control, is more precise and areas where pointing, based either on position or rate control, is faster. We are currently evaluating these techniques. We are also working generic models to describe user performance using the techniques and are planning to test their fit to our data. Our future goal is to assess the techniques in more complex tasks, such as two or three dimensional pointing tasks and hand movements that involve three to six degrees of freedom.

Citations

[1] Balakrishnan, R. and I.S. MacKenzie. Performance Differences in the Fingers, Wrist, and Forearm in Computer Input Control. In Proc. ACM CHI, 1997, 303-310.

[2] Ballagas, R., Rohs, M. el al, Sweep and Point & Shoot: Phonecam-Based Interactions for Large Public Displays. In Ext. Abstracts of ACM CHI, 2005, 1200-1203.

[3] Casiez, G. and D. Vogel. The effect of spring stiffness and control gain with an elastic rate-control pointing device. In Proc. ACM CHI 2008, 1709-1718.

[4] Casiez, G., D. Vogel, R. Balakrishnan, and A. Cockburn, The Impact of Control-Display Gain on User Performance in Pointing Tasks. Human-Computer Interaction, 2008. 23(3), 215-250.

[5] Casiez, G., D. Vogel, Q. Pan, and C. Chaillou. RubberEdge: reducing clutching by combining position and rate control with elastic feedback. In Proc. ACM CHI, 2007, 129-138.

[6] Dominjon, L., Lécuyer, A., Burkhardt, J.M., Andrade- Barroso, G., and Richir, S. The bubble technique: Interacting with large virtual environments using haptic devices with limited workspace. In Proc. of IEEE World Haptics, 2005, 639–640.

[7] Lehman, S.L. and B.M. Calhoun, An identified model for human wrist movements. Experimental Brain Research, 81(1), 1990, 199-208.

[8] Lemay, M. A. and P.E. Crago. A Dynamic Model for Simulating Movements of the Elbow, Forearm, and Wrist. Journal of Biomechanics, 29(10), 1996, 1319-1330.

[9] Myers, B. A., Bhatnagar, R., Nichols, J., Peck, C. H., Kong, D., Miller, R., and A. C. Long. Interacting at a Distance: Measuring the Performance of Laser Pointers and Other Devices. ACM CHI, 2002, 33-40.

[10] Rutledge, J. D., and Selker, T. Force-to-Motion Functions for Pointing. In Proc. of Interact, 1990, 701–706.

[11] Vogel, D. and R. Balakrishnan. Distant freehand pointing and clicking on very large, high resolution displays. In Proc. ACM CHI, 2005, 33-42.

[12] Zhai, S., Human Performance in Six Degree of Freedom Input Control. Ph.D. dissertation, 1995, University of Toronto.