Extension of Fitts' Law for the design of the gesture pointing interaction

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Abstract: Discrete cursor movement is caused by the malfunctions of the cursor emulation software and hardware, typically with handheld pointing devices. The predicted trajectory of the discrete cursor movement is based on the users' intention, although the cursor could eventually reach the visual target, the user's body movement might need to be adjusted frequently, which might increase total time and amplitude of the visual cursor movement and consequently impact on the physical body movement. This research aimed to investigate the effects of discrete cursor movement on human performance and validate the relationship among the discrete cursor movement, joint range of motions (ROMs) and the discomfort. Two models were designed for this experiment based on previous successful pilot studies and the result showed that relationship between the joint ROMs and the discrete cursor movement is positive, as well as the adjusted R^2 for the prediction of movement time across models.

Key words: Fitts' law, Usability, Gesture interface design.

1. Introduction

1.1 Background

This research focuses on the design and usability assessment of the tilt-based gesture interfaces for a point-and-click task within the desktop computer environment. The key function of the tilt-based gesture interface is to transfer the tilt movement of the forearm and the wrist into the cursor movement on the two-dimensional graphical user interface (2D GUI) on a real-time basis. The key component of the tilt-based gesture interface is the inertial sensor technology. This research will investigate whether the malfunctions of the hardware and software of gesture interfaces can produce the discrete cursor movement, which impacts on human performance and leads to abnormal body movements. In such a situation the actual working area and the joint ranges are lengthy and away from those that had been planned. It will be confirmed that the abnormal movement will require extra movement that will be outside the neutral posture. Eventually, the malfunction of the system will contribute to the development of discomfort in particular body regions.

Since the cursor movement is the machine output of the gesture interfaces that need to be designed, a new accuracy measure based on the calculation of the cursor movement distance and an associated model will be proposed in order to validate the continuous cursor movement. Furthermore, in order to collect the human performance data and the cursor movement distance, a graphical measurement platform has also been designed and validated, namely the Fitts' Law Generator (FLG) [1].

1.2 Aims and Objectives

The aims of this research are to investigate the effects of the discrete cursor movement on human performance based on the comparison made with two versions of the working model and, in turn, to validate that there is a relation between the discrete cursor movement, the joint ROMs and the discomfort in particular body regions. The objectives of the research are:

1. To review literature on the related background information and to develop a new accuracy measure for the cursor movement distance based on the extension of Fitts' Law and the movement behaviours;
2. To validate the proposed new accuracy measure and the associated model that could help to validate the continuous cursor movement on the 2D GUI with two versions of the tilt-based gesture interface: V1 and V2;
3. To investigate the relationship between the cursor movement and the body movement in the context of both V1 and V2, based on iterative design process;
4. To summarise the findings and original contributions to the research areas, highlight the problems that occurred during the study and identify the further research required.

2. Literature review

2.1 Critical design factors

As illustrated in Figure 1, the gesture interface aims to produce the relative cursor movement on the screen based on the reorganization of the movement states of the hand:

(1) Direction

The tilt-based gesture interface aims to transfer these relative joint ROMs in terms of relative *g forces* (+/–) in the air into the relative cursor movement direction on the screen in terms of the *relative x* and y *coordinates* (+/–), as shown in Table 1.

Table 1. The relation between the cursor movement direction and the joint motion

Cursor movement direction	Joint Motion
↑	Extension
↓	Flexion
←	Pronation
→	Supination

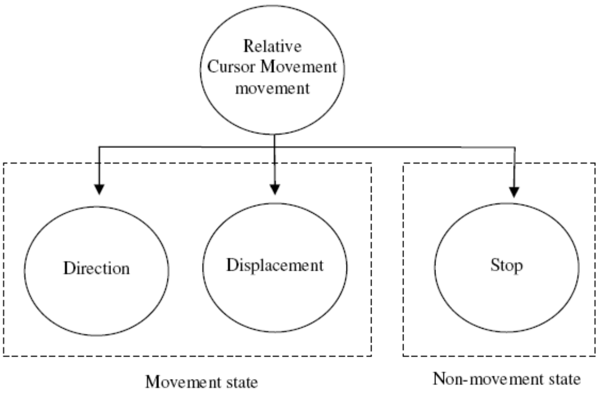

Figure.1 The relative cursor movement based on the reorganization of the movement states of the hand

(2) Displacement

In order to calculate the displacement, a double integration needs to be employed: The first integration is to get a proportional approximation of the velocity based on the acceleration given by the inertial sensor. In order to obtain the position, the integration must be performed again. The second integration gives a proportional approximation of the instantaneous position [6].

(3) Stop

In order to recognize the non-movement state of the hand, it is necessary to restore the acceleration (*g force per sec*) when the hand is in the neutral posture prior to the use of the interface, namely the initial acceleration.

Generally speaking, there are three problems with the inertial sensor system: the drift noise, nonlinear effects caused by gravity and peak noise. The current studies did not mention the effect of the peak noise on the cursor displacement and did not propose a method of error compensation to deal with this noise. As a result, without elimination of the peak noise with the inertial sensor, an error in the displacement determination occurs resulting in discrete cursor movement on the screen [2, 8].

2.2. Human Performance Model

There have been many theories and practices of human-computer interaction developed for studying human-centred performance. One famous theory is Fitts' Law. Early in 1954, Fitts introduced the mathematical relationship between speed, accuracy, amplitude of movement and target size for upper extremity tasks, which can be expressed by a simple linear regression equation as shown in Eq. (1) [3]:

$$MT = a + b \times ID \tag{1}$$

$$ID = \log_2(2 \times D / W) \tag{2}$$

where *ID* is the index of difficulty proposed by Fitts, *D* is the distance between targets, *W* is the target width, *MT* is the movement time and parameters *a* and *b* are calculated on the basis of a simple linear regression. As expected, movement time for hard tasks is longer than for easy tasks.

$$ID_e = \log_2(D/\mathrm{W} + 1) \quad (3)$$

In fact, Fitts' ID in Eq. (2) was extended from the Shannon formulation of *ID* shown in Eq. (3). It provides a better fit with observations and is truer to the information theorem on which Fitts' Law is based. Also, a negative *ID* value is not possible with this formulation. Moreover, MacKenzie recommended the use of the effective target width, W_e, instead of the nominal target width, *W*, to measure actual performance of either devices or tasks [7]:

$$W_e = 4.133 \times S.D. \quad (4)$$

$$ID_e = \log_2(D/W_e + 1) \quad (5)$$

where *S.D.* is the standard deviation of the endpoint over the target region, and ID_e is the effective index of difficulty. Recently, the ID_e model in Eq. (5) has been standardized in ISO 9241 as a design and testing guideline and as the specification for non-keyboard input devices (NKIDs), e.g. mouse, trackball, joystick, indirect touch panel and direct touch screen. In particular, Soukoreff and MacKenzie recommended that regression analysis on both *MT* and ID_e should indicate an adjusted R^2 value, which is ideally over 0.9 when testing on a normal mouse with a one-dimensional graphic user interface (1D GUI) [4, 7].

2.3. New Accuracy Measure: Cursor Movement Distance

In 2001, MacKenzie *et al.* proposed the use of cursor movement behaviours to explain natural human body motion in a two-dimensional environment. For instance, in order to perform a pointing task efficiently, an individual may suffer if movement control is difficult thus causing several attempts at target-entry before selection and an inability to match the cursor movement between targets onto a straight line. As expected, the cursor movement distance for hard tasks is longer than that for easy tasks, and could be influenced by a product itself. In this study, the cursor movement distance is defined as the '*Two-dimensional cursor movement distance captured during a trial*' [5]:

$$D_e = \sum_{i=1}^{n} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \quad (6)$$

where x_{i-1} and y_{i-1} are the coordinates of the start point and x_i and y_i those of the end point, *n* is the number of times coordinate data are captured between the start point and the end point, and D_e is the cursor movement distance calculated by the sum of the micro-distances between the coordinates of the start point and those of the end point, namely, in general terms, the '*Effective Target Distance*'. In particular, *n* is subject to the rate of data-capture of the testing platform, which is measured in *Hz* (times per second), which, ideally, should be as high as possible. Technically, capturing the coordinate data from start point to endpoint is a continuous process. Unlike movement time or the standard deviation of the endpoint, D_e is based on a single measurement per trial, which can be demonstrated in Figure 2.

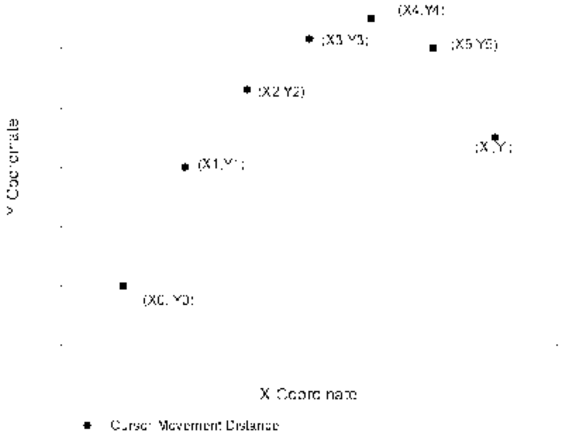

Figure. 2 Cursor Movement Distance D_e

ID_{e2} is further proposed by using D_e instead of D, as shown in Eq. (7).

$$ID_{e2} = \log_2(D_e / W_e + 1) \quad (7)$$

ID_{e2} could be used to explain *why* some devices, tasks or people are more efficient than others and is vital to the expansion of the theoretical knowledge base concerning the measurement of performance of natural human body motion.

3. Hypothesis

H1: The movement time *MT* across the models (i.e. *ID*, ID_e and ID_{e2}) is predictable with the working model V2 (R^2>0.1);

H2: The human performance with the working model V2 is significantly better than with the V1 ($p<0.05$);

4. Trial Protocol

4.1. Subject selection

As can be seen in Table 2, a total of one hundred Taiwanese students in Transworld University in Taiwan volunteered in the pre-test. The participants consisted of fifty-two females, age range from 17 to 32 years, and forty-eight males, age range from 18 to 32 years. The average weekly PC usage reported by females was 31.2 hours per week, and by males was 35.4.

In the post-test, a total of forty-three Taiwanese students volunteered, who attended the previous session with the working model V1 volunteered. The participants consisted of twenty-seven females, age range from 18 to 25 years, and sixteen males, age range from 18 to 23 years. The average weekly PC usage reported by females was 32 hours per week, and by males was 37. All participants used their preferred right hand to perform the tasks, and reported over six years' experience with PCs. None of the participants reported uncorrected visual problems or physical limitations that would inhibit their use of the input device. None of them had previous experience of using gesture interfaces.

Table 2. Subject background

Gender	Mean age (y.)	Age range (y.)	Mean mouse experience (y.)
female (n=52)	20.2	17~ 32	8.2
male (n=48)	21.2	18~32	7.8

Table 3. Target conditions

Factors	Levels
Graphic target width (mm) (2)	45, 30
Graphic target distance (mm) (2)	45, 90
Angle of approach (8)	0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°

4.2. Testing apparatus

The experiments were conducted in a laboratory in Transworld University in Taiwan, based on following instrument:

- An Acer® Aspire laptop PC with a mobile Pentium 1.4GHz CPU, 768MB of RAM, 17” 16:9 wide-screen LCD monitors.
- A standard two-button optic mouse with 800 dpi, manufactured by Logitech®.
- Fitts’ Law Generator (FLG): A graphic-based measurement platform was designed and validated in an earlier study [1].
- A five-scale subjective questionnaire, digital camera, pen and paper.
- Working models (V1 and V2).
- The data analysis was performed using SPSS version 13 and Excel 2003.

4.3. Experimental Procedure

The design case study was iterative design process, based on the pre-/post-experiment design. Both tests used the same 2 × 2 × 8 repeated-measure factorial design for the objective measurement of human performance, as illustrated in Table 3. In the pre-test, the engineering working model V1 was tested with one hundred participants. In the post-test, the engineering working model V2 was tested with forty-three participants randomly selected from the same population. There was a time lapse of one month of between the two tests to allow for the design of the working model V2.

The direct observation was employed: in the pre-test, the operational gestures of the arm and hand were captured by a digital camera located to the right hand side of each participant. As regards, if participants changed the gesture at each learning block, a photo was taken and the observation note was taken using pen and paper. In the post-test, a digital video recorder (DV) was used to record the posture of the right arm of each participant. The post-video analysis is undertaken after the experiment: if any posture changes at each learning block, a still photo is then taken from the video. Once the experiment was completed, participants were asked to fill out the subjective questionnaire and were encouraged to write down open-ended comments about the design failures of the engineering working model and the experiment design. In addition, the experimental procedure was under the control of FLG, thus the process bias could be reduced.

5. Selected results and analysis

5.1. Fitness-of-models (*H1 test*)

> *H1: The movement time MT across the new models (i.e. ID, ID_e and ID_{e2}) is predictable with both the mouse and the V2. ($R^2 > 0.1$).*

As can be seen in Table 4, the linear regression analysis indicates the different predicted R^2 values across different models (*ID*, ID_e, ID_{e2}) with the mouse and the working models V1 and V2. For the mouse and V2, there is a linear relation between the movement time *MT* and the models ($R^2 > 0.12$). Thus, the hypothesis *H1* is accepted.

Table 4. The prediction of the total movement time *MT* (ms) across models (*ID*, ID_e, ID_{e2}) among the mouse, the working model V1 and V2

Device	N*	Adjusted R^2 **			
		ID	ID_e	ID_{e2}	Predictable?
Mouse	3,689	0.43	0.41	0.48	Yes
V1	8,614	0.02	0.02	0.02	No
V2	3,879	0.15	0.12	0.15	Yes

* The error trials were excluded for the analysis.

** The linear regression analysis was applied on the adjusted data for the prediction of the movement time *MT* across models (*ID*, ID_e and ID_{e2}). The adjusted R^2 value was used since the sample size was difference among these studies.

5.2. Device difference (*H2 test*)

> *H2: The human performance with the working model V2 is significantly better than with the V1 ($P<0.01$).*

The hypothesis *H2* is based on the fact that the working model V1 had usability problems involving discrete cursor movement caused by the malfunction of the cursor emulation program, thus its human performance is likely to be poorer than with the V2, which produces a nearly continuous cursor movement by using the mouse buttons. As can be seen in Table 5, the descriptive statistics indicate that the total movement time *MT* with the V2 (1,349 ms ± 569) is 31% faster than with the V1 (1,963 ms ± 1,401). Furthermore, the Independent T test is applied on the raw material to examine the significance of the difference. As result, it indicates that the human performance with the V2 is better than with the V1 in terms of a significantly lower *error rate* ($p<0.01$), lower target re-entry *TRE* ($p<0.01$), shorter cursor movement distance D_e ($p<0.01$), shorter approaching time *AT* ($p<0.01$), shorter pointing time *PT* ($p<0.01$) and shorter total movement time, *MT*. Since all objective dependent factors gained with the V2 are significantly better than for the V1, the hypothesis *H2* is accepted. In addition, the huge *standard deviation* could be one of the reasons which causes no linear relation between the movement time *MT* and three models (adjusted R^2=0.02) with the V1.

5.3. Subjective feelings

In terms of the subjective feelings about the design, participants gave a significantly higher score for these six indicators (i.e. smoothness, effort, accuracy, speed, comfort and overall performance) with the working model V2 than with the V1. With regard to the discomfort, participants gave lower values for all body regions with the working model V2 than with the V1 and all of the discomfort levels among body regions are lower than the average (2.5). With respect to the user experience, the participants also felt more relaxed and experienced greater ease-of-use and usefulness with the V2 than with the V1. Furthermore, the Mann-Whitney U test is applied on the raw material to examine the significance of the difference. The result indicates that the subjective feeling about the smoothness is significantly better with the working model V2 (*mean* = 3.9) than with the V1 (*mean* = 3.2) ($p<0.05$). This indicates that the cursor movement with V2 is a great improvement over the V1.

Table 5. The difference of the human performance between the working model V1 and V2

Human Performance	Working models ***		Improvement	P value
	V1 (n=8,614)	V2 (n=3,879)		
E*rror Rate* (%)	14.6% ± 0.49	6.8% ± 0.29	+	<0.01**
Target Re-Entry *TRE* (%)*	12.9% ± 0.43	4.3% ± 0.23	+	<0.01**
Cursor movement distance D_e (mm)*	128 ± 116	90 ± 47	+	<0.01**
Approaching time *AT* (ms)*	2,855 ± 15,098	1,179 ± 535	+	<0.01**
Pointing time *PT* (ms)*	258 ± 279	165 ± 113	+	<0.01**
Total movement time *MT* (ms)*	1,963 ± 1,401	1,349 ± 569	+	<0.01**

* The error trials were excluded for the analysis.
** The difference between the devices is statistically significant.
*** The across + means the improvement was made.

5.4. Direct observation

When using the working models V1 and V2, various arm postures of those with a preference for right handed working can be categorized in terms of the elbow flexion angle $\theta 1$ and the wrist flexion angle $\theta 2$:

- Angle $\theta 1$: The flexion of the elbow;
- Angle $\theta 2$: The flexion of the wrist;

Based on the observation, there were three operational postures being defined, shown as follows:

- Type I: It is the neutral position where $\theta 1$ *and* $\theta 2$ *are approaching to* $0^{o.}$
- Type II: Where $\theta 1$ *and* $\theta 2 > 10^{o}$ *and* $< 30^{o.}$
- Type III: Where $\theta 1$ *and* $\theta 2 > 30^{o.}$

In the pre-test, totally, there were n = 3 learning blocks × 93 subjects = 279 cases being collected. In the post-test, participants who attended the studies with the working model V1 were invited randomly for the study with the V2. In comparison with the postures gathered from both tests, 29 cases were found to have posture photos with both the V1 and V2. As a result, 26 out of these 29 cases (nearly 90%) were found to have the neutral posture (posture Type I). Furthermore, among these 26 cases, 12 were found to have their joint ROMs reduced from the posture Type II or III with the working model V1, to the neutral posture (posture Type I) with the V2.

6. Discussion

This research has achieved its aims: Firstly, since the hypothesis *H1* is accepted, it is likely that the working model V2 produces a nearly continuous cursor movement because the prediction rate R^2 is approaching that of the ordinary mouse. Furthermore, the hypothesis test *H2* indicated that the human performance with the working model V2 is better than with the V1 in terms of significantly lower *error rate* (p<0.01), lower target re-entry *TRE* (p<0.01), shorter cursor movement distance D_e (p<0.01), shorter approaching time *AT* (p<0.01), shorter pointing time *PT* (p<0.01) and shorter total movement time *MT*. Also, the working model V2 is 31% faster than with the working model V1. Moreover, the subjective assessment also highlights that the participants like the V2 more than the V1 in terms of the significant enhancement of the subjective feelings.

To sum up, the research can conclude that the working model V2 produces the nearly continuous cursor movement like the ordinary mouse and that it also has the following advantages:

1. Improved quality-in-use;
2. The nearly continuous cursor movement;
3. A reduced opportunity for manual error compensation;
4. Similar cursor movement behaviour to the ordinary mouse.

Moreover, the result analysis reveals that there is a relation between the discrete cursor movement and the adjusted R^2 for the prediction of the movement time, *MT*, across models. As can be seen in Figure 4, each device obtained a range of adjusted R^2 values for the prediction of the total movement time across ID_e.

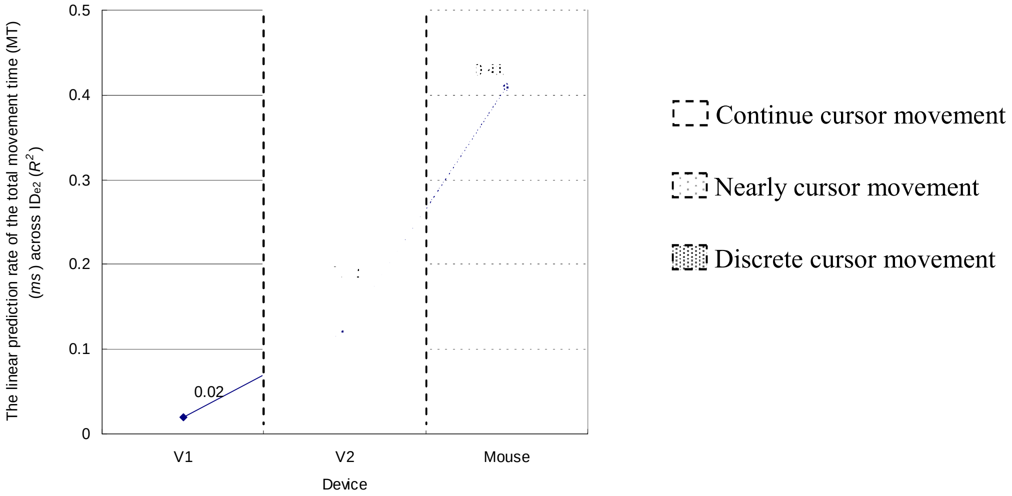

Figure.4 The prediction of the total movement time *MT* (*ms*) across ID_e with the pointing devices tested in this research.

7. Conclusion

This research validates that the working model V2 is better than the V1 because it can allow users to maintain the elbow and wrist joint ROMs in a neutral posture according to the planned working area. Moreover, by comparison with the one having continuous cursor movement (i.e. V2), the result suggests that the tilt-base gesture interfaces having discrete cursor movement (i.e. V1) can increase both elbow and wrist joint ROMs which depart from the neutral posture. Essentially, this research reveals that there is a relation between the joint ROMs, the discrete cursor movement and the adjusted R^2 for the prediction of the movement time, MT, across models. It is further suggested that a market survey and more user studies need to be done in the future in order to specify the detailed requirements of the future gesture interface for the point-and-click task, in particular for the development of a novel button activation method for a hands-free interactive gesture system.

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