Hands-free interface for seamless pointing between physical and virtual objects

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***Abstract*—To support natural communication by bedridden persons with upper limb disabilities, we propose a hands-free pointing system that enables seamless indication of physical and virtual objects. An "air-pillow interface," developed by the authors, measures head motions to control a cursor on a PC display and the direction of a laser pointer on a pan-tilt actuator near the user's head. The user moves the cursor with the head motion interface, and when the cursor reaches the end of the display, the laser pointer continues tracking head movements in the real world. We experimentally confirm the validity of the proposed method and evaluate the operating performance by throughput values with regard to pointing ability. And also we investigate angular displacement of the head to confirm the advantage of the proposed method over the conventional technology.**

Keywords—hands-free interface; head motion; laser pointer

I. Introduction

In recent years, there has been increased research on hands-free input interfaces that use head movements to allow gesture support for persons with upper limb disabilities [1–7]. Such head-operated interfaces are primarily developed to deliver input to a PC, with four directions of head movement tracked to allow mouse-like operations, such as movement, clicking, and drag-and-drop.

However, bedridden patients are surrounded by many objects other than a PC, such as medical equipment, electrical appliances, household goods, and food, and it will often be necessary to indicate these objects in communications with caregivers (or, in the future, caregiving support robots). In recent years there have been many attempts to apply laser pointers to indication of such physical objects [8–10]. It is often difficult to use words alone to quickly and accurately specify a single object from within a cluttered living environment, but laser pointers allow direct specification of a single object, making them a promising method of gesturing to caregivers.

Within this context, the present research proposes a hands-free interface that allows seamless transitional pointing between a PC display and the real world. Here, "seamless" refers to the lack of an information processing–type border between the virtual world of the PC and that of the real world, allowing objects in each to be treated similarly. Figure 1 shows a conceptual image of this, in the form of an association between a PC display object and a physical object, with a seamless drag-and-drop operation being performed between the pairs. There are multiple objects representing drinks (*a*, *b*) and household objects (*c*, *d*) on the PC display, and multiple cups (*A*, *B*) and drinks (*C*, *D*) in the real world. Operation ① is a gesture that represents pouring drink object *a* from the PC display into the real cup *B*. Operation ② represents putting the real drink object *C* into the onscreen refrigerator object *d*.

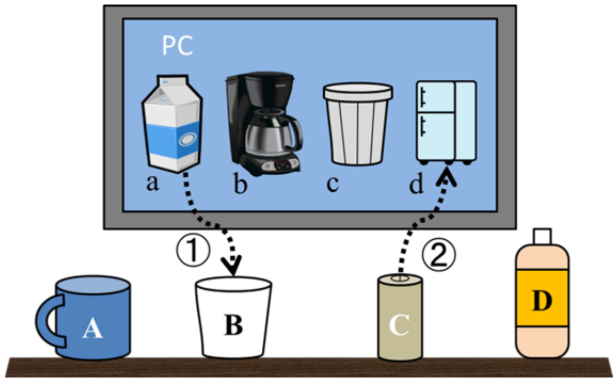


Fig. 1. Conceptual image of seamless drag-and-drop operations between a PC and the real world

As this example demonstrates, creating seamless associations that allow GUI-like manipulations between objects in the real world and the virtual world of the PC can allow for easily performing detailed gestures that tie together such objects to communicate with caregivers and caregiving robots. This paper investigates a method of pointing for virtual objects within a PC and physical objects in the real world. Such pointing will be one of the most fundamental operations for realizing an ideal interface in caregiving situations of the near future. Specifically, we propose a pointing system that combines a head-operated interface (the "pillow interface" [7]) developed by the authors with a laser pointer mounted on a pan-tilt actuator to allow access to both virtual and real-world objects.

The remainder of this paper is organized as follows. Section 2 describes a survey of related research and discusses the novelty and usefulness of our proposal. Section 3 describes the proposed method and its employment in a test system. Section 4 presents and discusses the results of evaluation testing. Finally, Section 5 presents our conclusions and areas for future research.

II. RELATED RESEARCH

Here, we introduce the main research on head-operated interfaces. Nunshita et al. [1] proposed a system in which three ultrasonic transmitters are attached to a user's head, thereby providing 3D coordinates to determine head tilt and thus to control movement of a cursor. Nakazawa et al. [2] instead used a head-mounted gyrosensor to determine head tilt and move a mouse and used mouth movements to change between movement and click modes. Aida et al. [3] used 3D motion sensors that employed gyrosensors and similar devices, measured head operations that accompanied voice commands, and proposed a system for assisting indication of intent by voice commands. Kubota et al. [4] proposed a system that uses cameras to monitor eyes and controls cursor positioning control through head tilts. Itoh [5] proposed a system that realizes PC cursor control through camera tracking of a point illuminated by a head-mounted laser pointer and evaluated the system by using CT with *Throughput* as an objective index. Tsukada and Seki [6] proposed a similar method, in which a point illuminated by a laser pointer was directly linked to a cursor position. Nakamura et al. [7] used an inflated pillow to develop a head-operated interface (below, a "pillow interface") for PC operation.

We next describe previous research related to using laser pointers for object specification. Kemp et al. [8] constructed a system in which a wheelchair-bound patient uses a laser pointer to illuminate an object, and a robot fetches the indicated object. Takahashi et al. [9] developed a system in which a ceiling-mounted laser pointer illuminates daily necessity items, which are fetched by a robot. Lim et al. [10] developed an interface that allows cervical spine injury patients to use a head-mounted laser to deliver commands to an arm robot.

Each of the above-mentioned previous studies employs methods that treat objects in the PC differently from objects in the real world and do not allow access to both in the manner of the system described in this paper. References [5] and [6], in particular, are pioneering research closely related to the present research, in that they use a head-operated laser pointer to perform GUI operations on a PC. These studies describe operation of only the PC, however, and do not include the concept of allowing pointing to both virtual and real-world objects, as described here. Also, as will be shown in the experiment in Section 4, the method proposed here has significant merit in that it allows pointing by means of head movements within a very limited range.

III. THE PROPOSED METHOD

A. Basic concepts

Figure 2 shows a conceptual image of the proposed system. The basic method is that a head-operated interface measures user head movements and uses those signals to control a PC cursor, with an actuator amplifying the amplitude to perform laser pointing. Doing so is expected to translate user head movements even within a restricted range to pointing operations in a wide real world.

Specifically, during operations within the PC display, the head-operated interface is used to perform normal PC operations, as when using a mouse. Immediately upon the cursor reaching the edge of the screen, the actuator-mounted laser pointer continues pointing, as if the cursor had jumped off of the PC display into the real world. The user then performs real-world pointing by visually confirming that the pointer is illuminating a real-world object. Conversely, when pointing moves from the real world back to the PC display, control immediately returns to the cursor, and normal PC operations resume.

B. Implementation of the proposed method on a test system

We developed an experimental system to investigate the fundamental applicability of the proposed method (Fig. 3). In the system, a pillow interface [7] affixed to a reclining bed is linked to a pan-tilt actuator with two degrees of freedom installed near the user's head. The user uses the pillow interface to operate the cursor and perform click and drag GUI operations; the laser pointer is used outside the realm of the PC to perform real-world pointing. The discussion below describes details of the linkage.

1) Method of linkage with the pillow interface

We begin with a simple overview of the previously developed pillow interface [7]. The pillow interface is an air-inflated pillow that can be manipulated by head operations (Fig. 4(a)). Four rectangular air bladder units are arranged in a grid pattern, and an air pressure sensor measures the air pressure in each bladder to detect the *xyz* direction of load from the user's head. The head load can then be converted into mouse movement and click operations. This head-operated

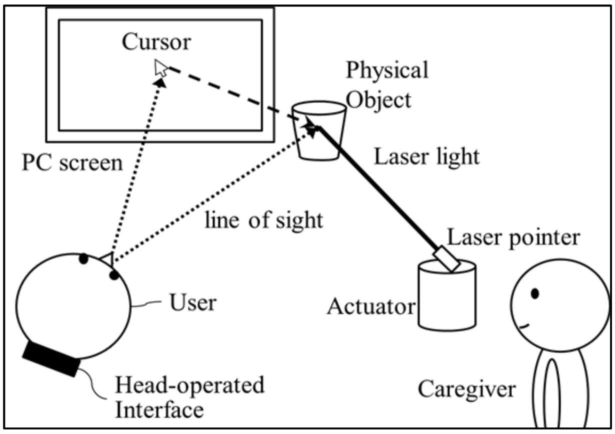


Fig. 2. A conceptual image of the proposed system

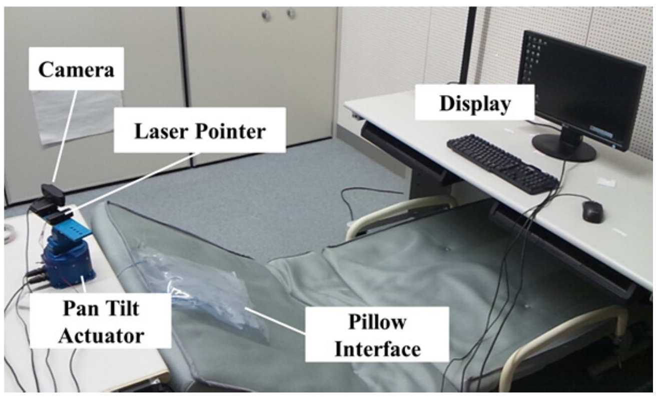
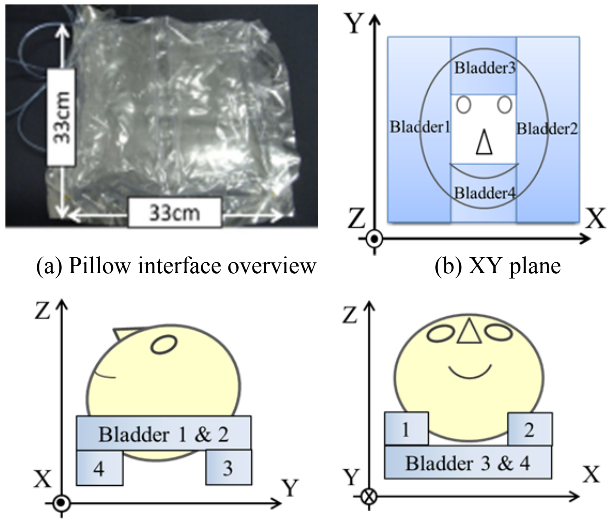


Fig. 3. An overview of the experimental system



(a) Pillow interface overview (b) XY plane

(c) YZ plane (d) XZ plane

Fig. 4. Pillow interface configuration

interface was employed in this study for the reasons described below.

- Non-invasive design, with no need for sensors or markers on the head or face
- Capability for normal use as a pillow from a reclining position on a bed
- Force-input design that allows for operation over a restricted range of head movements

We next give a detailed description of the method used to realize cursor movement. The air pressure of the respective air bladders is p_i (i=1,2,3,4), and these pressures are used to measure changes in position. For example, when the x-directional head load increases, as shown in Figs. 4(b)–(d), p_2 increases and p_1 decreases, while p_3 and p_4 remain unchanged. In contrast, when the y-directional head load increases, p_3 increases and p_4 decreases, while p_1 and p_2 remain unchanged. The mouse cursor display position $\boldsymbol{c} = (x, y)^T$ can thus be obtained as

$$\boldsymbol{f} = \begin{pmatrix} f_x \\ f_y \end{pmatrix} = \begin{pmatrix} s_x(p_2 - p_1) \\ s_y(p_3 - p_4) \end{pmatrix} \quad (1)$$

$$\boldsymbol{c} = \int \boldsymbol{f} dt \ , \quad (2)$$

thus allowing cursor operation according to the direction of head load. Here, S_x, S_y are positive dimensional constants related to operational sensitivity; these can be adjusted according to user preference. When there is no change in head load, the integral effect is used to maintain the immediately previous cursor position. When the value from (2) exceeds the number of display pixels, the calculation is continued as if the display extends out into the real world, and the value is passed to the pan-tilt actuator to realize pointing in the real world. The following section provides details of the method used for actuator control.

C. Pan-tilt actuator control

Cursor tracking of the pan-tilt actuator-mounted laser pointer requires knowledge of the geometric relation between the pan-tilt actuator and cursor values. First, the target coordinate ${}^{PT}\mathbf{r} = (x_{PT}, y_{PT}, z_{PT})^T$ is calculated from the target cursor position. This position is obtained from the pillow interface and the homogeneous transformation matrix ${}^{PT}\mathbf{T}_D$ between the display and the pan-tilt actuator. In the present experimental system, a camera is mounted in parallel with the laser pointer and ARToolKit [11] is used to determine the position and orientation of a visual marker affixed to the display, thereby obtaining ${}^{PT}\mathbf{T}_D$. Indicating a target point in the coordinate system of the pan-tilt actuator requires obtaining the target coordinate ${}^{L}\mathbf{r} = (x_L, y_L, z_L)^T$ as seen from the coordinate system of the laser pointer. This ${}^{L}\mathbf{r}$ value is calculated from ${}^{PT}\mathbf{r}$ and the homogeneous transformation matrix ${}^{L}\mathbf{T}_{PT}$ between the laser pointer and the pan-tilt actuator. Here, ${}^{L}\mathbf{T}_{PT}$ is calculated as

$${}^{L}\mathbf{T}_{PT} = \begin{pmatrix} \cos\theta_P & 0 & -\sin\theta_P & -p_x \\ \sin\theta_P \cos\theta_T & \cos\theta_T & \cos\theta_P \sin\theta_T & -p_y \\ \sin\theta_P \cos\theta_T & -\sin\theta_T & \cos\theta_P \cos\theta_T & -p_z \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (3)$$

where θ_P, θ_T are the operating angles of the pan-tilt actuator, and $\mathbf{p} = (p_x, p_y, p_z)^T$ is the translation component between the pan-tilt actuator and the laser pointer. ${}^{L}\mathbf{r}$ can thus be represented as

$${}^{L}\mathbf{r} = {}^{L}\mathbf{T}_{PT} \, {}^{PT}\mathbf{r} = \begin{pmatrix} x_{PT}\cos\theta_P - z_{PT}\sin\theta_P - p_x \\ A\sin\theta_T + y_{PT}\cos\theta_T - p_y \\ A\cos\theta_T + y_{PT}\sin\theta_T - p_z \end{pmatrix}, \quad (4)$$

where $A = x_{PT}\sin\theta_P + z_{PT}\cos\theta_P$.

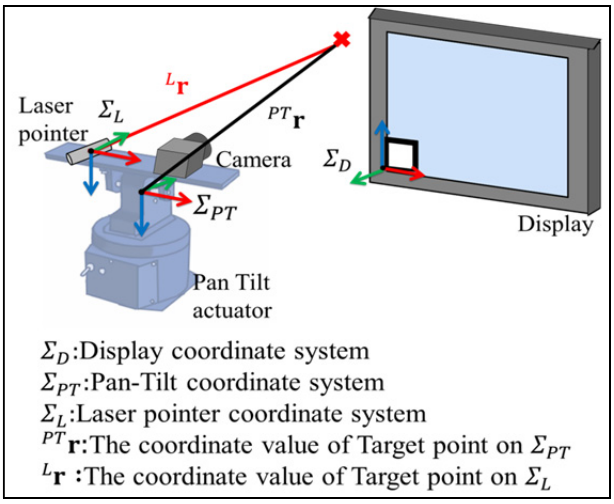


Fig. 5. Coordinate systems in the experimental system

The calculated ${}^{L}\mathbf{r}$ value is used to calculate the operating angles θ_P, θ_T of the pan-tilt actuator by (6), such that the conditions of (5) are satisfied.

$$\begin{cases} x_L = 0 \\ y_L = 0 \\ z_L \geq 0 \end{cases} \tag{5}$$

$$\begin{cases} \theta_P = \tan^{-1}\left(\dfrac{z_{PT} p_x \pm x_{PT}\sqrt{x_{PT}{}^2 + z_{PT}{}^2 - p_x{}^2}}{x_{PT} p_x \mp z_{PT}\sqrt{x_{PT}{}^2 + z_{PT}{}^2 - p_x{}^2}} \right) \\ \theta_T = \tan^{-1}\left(\dfrac{A p_y \mp y_{PT}\sqrt{A^2 + y_{PT}{}^2 - p_y{}^2}}{y_{PT} p_y \pm A\sqrt{A^2 + y_{PT}{}^2 - p_y{}^2}} \right) \end{cases} \tag{6}$$

Using θ_P, θ_T from (6) as the pan-tilt actuator target angle values allows for continuous switching between pointing on the PC display and in the real world. Note that there is no need for laser illumination of the display when the PC is being operated, so the laser is turned off at such times and immediately turned on when the focus again moves to the outside world.

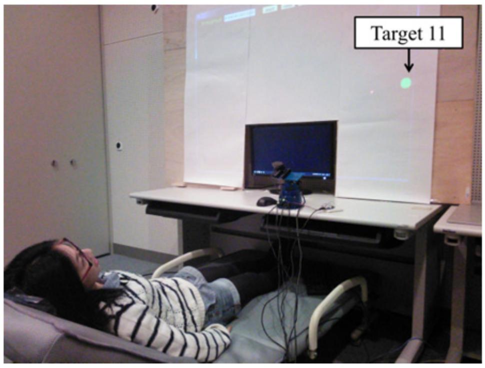
IV. Evaluation Experiment

A. Preliminary testing of pointing inside and around the PC display

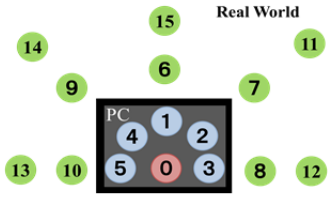
To perform quantitative evaluation of pointing performance in the real world, we evaluated operational performance obtained by multiple participants. Evaluation tasks and indices were established following the methods of [5], which examines these in detail. Participants were 10 healthy university students in their 20s.

1) Experimental methodology

Participants performed evaluation tasks from a reclining position in a bed (Fig. 6(a)). Targets for pointing were a central target (target number 0) and 15 peripheral targets inside and outside of the PC display, radially projected by a projector (Fig. 6(b)). Participants were instructed to point to the central target and a randomly displayed peripheral target as quickly as possible. Each participant performed 30 repetitions. Targets were shown one at a time, with the next target displayed immediately after the participant pointed at a target. Because the central target and peripheral targets were displayed in turn, participants repeatedly moved from the center to the periphery and then back to the center. The projector projected the targets in the arrangement shown in Fig. 6(b), and each target was a circle with radius 50 mm. A flat panel was installed along the periphery of the PC display as an extension of the display plane. The pillow interface experiment was repeated three times, and for comparison the experiment was performed once using a computer mouse to determine ideal operation by a healthy subject. The evaluation used the following equation, as per [5]:



(a) An overview



(b) Target number

Fig. 6. Throughput evaluation experiment

$$Throughput = \frac{\log_2(D/W+1)}{MT} \tag{7}$$

Here, D [mm] is the distance from the starting position to the center of the target, W [mm] is the diameter of the target, and MT [s] is the time required for the mouse cursor or laser spot light to move to the target. This value increases when farther and smaller targets can be reached in less time and allows evaluation of good pointing performance.

2) Experimental results

Table 1 lists mean values and standard deviations of the forward and return *Throughput* values for each subject using a mouse and the pillow interface. Figure 7 shows the mean values of the forward and return *Throughput* values for each target using a mouse and the pillow interface, with target numbers corresponding to those in Fig. 6(b). The values in Table 1 show that *Throughput* values are much higher for the mouse than for the pillow interface. Such differences are expected, as they are comparisons between the more familiar operation of moving a mouse with the hands and the less familiar operation of operating the pillow interface with the head. Examining the *Throughput* values by target in Fig. 7, there is a marked difference between values for targets on the PC display (targets 1–5) and those in the real world (targets 6–15). This difference is likely due to the slow tracking performance of the actuator; the cursor on the PC display is a massless object, but the actuator and laser pointer have mass, which results in a significant difference between the *Throughput* values for the types.

TABLE1. MEAN *Throughput* BY SUBJECT

Subject	Mouse		Pillow Interface	
	in	***out***	***in***	***out***
A	1.61 ±0.487	1.98 ±0.506	1.19 ±0.433	1.36 ±0.493
B	1.65 ±0.623	2.03 ±0.688	1.08 ±0.522	1.07 ±0.437
C	2.29 ±0.621	2.40 ±0.885	1.19 ±0.539	1.57 ±0.575
D	1.62 ±0.548	1.74 ±0.585	0.92 ±0.507	1.21 ±0.84
E	1.68 ±0.488	1.77 ±0.503	1.05 ±0.361	1.22 ±0.527
F	1.96 ±0.425	2.00 ±0.679	1.02 ±0.547	1.11 ±0.782
G	1.52 ±0.515	1.44 ±0.568	0.91 ±0.352	1.12 ±0.507
H	1.64 ±0.506	1.93 ±0.674	1.27 ±0.550	1.29 ±0.499
I	1.41 ±0.649	1.54 ±0.694	0.83 ±0.538	0.88 ±0.385
J	2.25 ±0.655	2.17 ±0.951	1.12 ±0.466	1.29 ±0.499

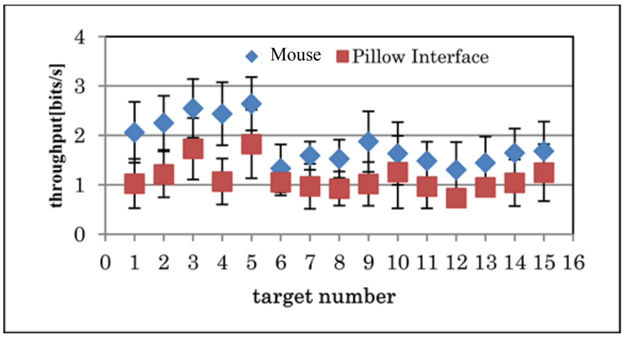


Fig. 7. *Throughput* by target

B. *Stroke evaluation experiment*

We performed an experiment to investigate stroke (vertical and horizontal angular displacement of the head) during real-world pointing. Participants were 10 healthy men and women in their 20s.

In this experiment, as in the experiment of subsection A, participants alternated between pointing at a central target directly in front of their face and peripheral targets placed in a radial arrangement at five locations 150 cm from the central target. During the experiment, an external measuring device separate from the pillow interface was used to precisely measure head stroke (vertical angle θ_x and horizontal angle θ_y). θ_x, θ_y were initialized to 0 when the head was oriented such

Fig. 8. A conventional pointing device
(eyeglasses equipped with a laser pointer)

that the central target was directly ahead. To allow comparison with the pillow interface, following the system in [5] we created a pair of eyeglasses with a centrally mounted laser pointer (Fig. 8) and performed each pointing experiment under the same conditions. When using this device, the laser pointer is directly attached to the user's head, which allows extremely direct control with no mechanical delay and makes it an ideal method for head-controlled pointing. A significant drawback, however, is that it requires the attachment of a device onto the user's face. As Fig. 9 shows, θ_x, θ_y can take positive and negative values, so $\theta_{ave}(i)(i = x, y)$ is defined as follows to evaluate the magnitude of the effective mean amplitude:

$$\theta_{ave}(i) = \sqrt{\frac{\int_0^T \theta_i^2(t)dt}{T}} \tag{8}$$

Here, T [s] is the time required to point at all targets in each experiment.

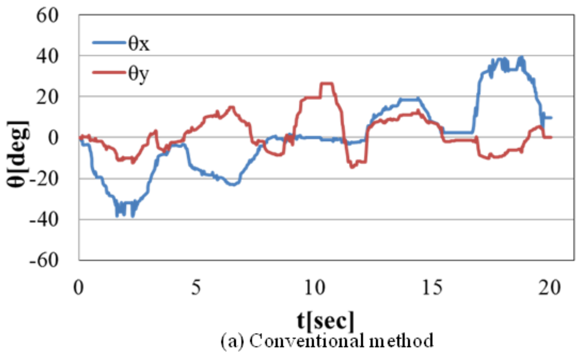
C. *Experimental results and discussion*

Table 2 shows the θ_{ave} values for the method of Fig. 8 and the proposed method. Figure 9 shows the changes in angles θ_x, θ_y during the experiment. We performed *t*-tests on the vertical and horizontal data in each system and found statistically significant ($p < 0.05$) differences for each direction. Table 2 indicates particularly noteworthy differences in the horizontal direction. The difference between the two systems is smaller in the vertical direction, but angular displacement was smaller under the present system. The reasons for this are likely that the pillow interface uses force input for device pointing, which fundamentally requires no displacement, and that the combination of head movement with changes in view direction allows for pointing over a wider range.

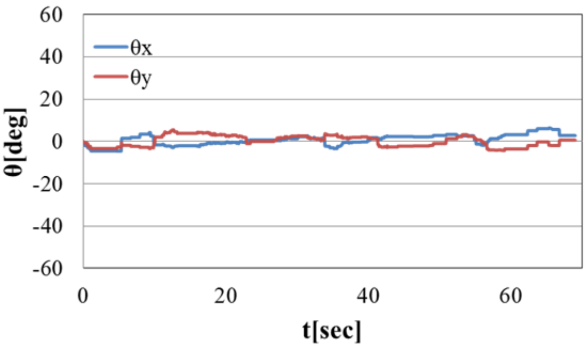
In the proposed system, the reason that the effective angular displacement is larger in the vertical direction than in the horizontal direction is likely because the angular field of vision of the human eye is smaller in the vertical direction than in the horizontal direction and thus necessitates larger head movements. Comparing the two systems, the reason why there is no significant difference in the horizontal direction in relation to the vertical direction is likely because no targets were situated below the PC display.

TABLE2. MEAN HEAD ANGLE VARIABILITY BY SUBJECT

Subject	Conventional method			Proposed method		
	time	***θx***	***θy***	***time***	***θx***	***θy***
A	20.03	18.25	9.44	69.06	2.64	2.56
B	16.70	18.95	11.67	78.05	4.30	6.52
C	8.93	22.37	8.28	68.12	7.30	8.61
D	20.73	16.42	8.53	120.47	3.24	9.05
E	14.38	15.84	10.10	83.00	4.73	6.28
F	14.39	14.41	8.40	133.18	6.54	8.40
G	13.53	17.30	12.12	121.35	2.91	9.09
H	10.64	17.95	10.86	90.76	3.03	5.70
I	12.48	19.39	14.24	75.26	6.69	7.25
J	12.01	20.14	10.47	52.72	11.13	11.29
Average	14.38	18.10	10.41	89.20	5.25	7.47



(a) Conventional method



(b) Proposed method

Fig. 10. Head movement

The above results indicate that the present system realizes access over a wide range with smaller strokes than does the system of [5].

In view of the fact that the higher average age of bedridden patients tends to limit head stroke, this result suggests the effectiveness of the proposed system. However, the proposed system is 3- to 9-fold slower than the system of [5], indicating that there is still significant room for improvement to (2).

V. CONCLUSION

We considered a system that provides seamless association of objects in a PC environment and those in the real world for gesture support for bedridden persons with upper limb disabilities, and realized such a system to investigate pointing systems, which is one of the system's most important features. We proposed a non-invasive, hands-free device capable of pointing at objects, both within the PC environment and in the real world, and performed experiments to demonstrate its fundamental effectiveness. The present study focused on technologies required for only object pointing to allow real-world drag-and-drop operations, such as those shown in Fig. 1. Realization of an actual system such as that in Fig. 1 will also require camera-based object recognition and the use of projectors or other devices for display of object icons in the real world. Further study of methods for associating the virtual and real worlds is therefore necessary, and these are left as topics for future research.

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