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Design and Development of a Low-Cost Eye Tracking System for the Rehabilitation of the Completely Locked-In Patient

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Abstract **– This article describes the design and development process of an eye tracking-based computer system that benefits from the intact ocular motor control of the completely locked-in patient to provide him or her with an alternative means of communication. A completely locked-in patient is an individual who has lost all types of motor control and communication ability with people in his or her environment. This developed system uses a head-mounted web camera to capture real-time images of the patient's eye. These images are then passed to a program, developed using Matlab®, which processes them and computes the coordinates of the pupil position. The program then sends commands to an interactive JAVA™-based interface, which provides the patient with a matrix of pictograms representing the most essential daily communication activities. When a pictogram is activated (clicked), the system plays back an audible statement, recorded in any language, reflecting the desired activity. Ten healthy adult volunteers, free from any musculoskeletal or neurological disorders, participated in the validation of the system. Validation results revealed a system accuracy of 96.11 ± 5.58 % and repeatability of 94.44 ± 2.51 %. The rehabilitative system developed in this project offers the locked-in patient, of any social class, the ability of simple yet effective communication. The advantages of this system over existing systems are low cost, low processing power, ease of operation, little training requirements, minimal disturbance to the patient, and ease of customization to any mother tongue.**

Keywords **– Locked-in patient, brain-computer interface, eye tracking, rehabilitation engineering.**

I. INTRODUCTION

In certain classes of neurological disorders where the central nervous system has been subjected to severe irreversible damage, conventional methods of treatment often turn out to be ineffective. Such disorders include, but are not limited to, cerebral palsy, cerebral aneurysm, traumatic brain injury, stroke, apraxia, and aphasia. In some severe cases, more than one disorder might strike the same patient and make him or her completely locked-in; i.e., cognitively intact, but unable to move or communicate [1]. Globally, there are regions where the completely locked-in patients are doomed to social rejection, specifically when conventional rehabilitation methods fail to alleviate the severity of the handicaps in these disabled individuals. For instance, in the absence of motor control, it is virtually impossible to use sign language or common input devices to interface with a computer system in order to communicate through spelling or expression-building software [2].

Brain-Computer Interface (BCI) methods for the rehabilitation of patients with neural disorders, similar to those previously enumerated, have been extensively reported in the literature. BCI systems are mainly categorized according to the utilized input technique. Commonly reported techniques include electromyography (EMG), electroencephalography (EEG), electrooculography (EOG) [3], eye tracking [2][4-9], and other custom designed input devices [10-11]. The decision about which input technique to be used depends on the specific case being studied [1].

In order to be functionally effective, the use of EMG-based BCI requires that the patient be able to control at least one-to-three distinct muscles. While, the head-mounted tilt sensor method [10] can be used only if the patient has the volitional ability of rotating his or her head. Accordingly, these two methods are precluded from consideration since locked-in patients do not possess any discernible movements or EMG activity. Subsequently, BCI methods employing eye tracking, EEG, or EOG remain feasible for applications involving locked-in patients [1]. Nevertheless, EEG systems are expensive, sophisticated, cumbersome, and require extensive training; while EOG data suffer from a lack of accuracy at the extreme position of the pupil; particularly, small angle displacements (less than 2°) are difficult to record whereas large eye movements (greater than 30°) do not produce bioelectric amplitudes that are strictly proportional to eye position [12]. As a result, eye-tracking systems would be more adequate for such applications and are easier to setup.

This article describes the design and development of a low-cost eye tracking-based brain-computer interface system for the rehabilitation of the completely locked-in patient having an intact ocular motor control to serve as an alternative means of communication. The developed system has been designed according to the following specifications: low cost, low processing power, ease of operation, little training

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II. MATERIALS AND METHODS

A. Hardware Description

A commercial webcam was used in order to reduce the overall cost of the system. A Genius® (KYE Systems Corp., Chung, Taipei Hsien, Taiwan, ROC) webcam was found suitable in terms of resolution, light sensitivity, and acceptable cost. The external packaging of the camera was reshaped, thus substantially reducing its weight and undesired volume in order for it to be mounted on the patient's head. The altered design produced a headset consisting of a simple mechanical framework with the camera lens separated five centimeter away from the patient's eye. The webcam was connected to a notebook computer via a regular USB 2.0 port. The computer used in the development and testing of this system was a Toshiba Satellite™ M70-122 (Toshiba America, Inc., New York, NY USA) notebook with a 1.73 GHz Centrino™ (Intel, Santa Clara, CA, USA) processor, 512 MB of RAM and a 15 in. widescreen. Figure 1 shows the hardware setup and the optimal position of the patient's head relative to the computer screen.

Figure 1. Hardware setup and optimal position of the patient relative to the screen.

B. Software Description

Images of the contour of the eye are transmitted to a Matlab® (The MathWorks, Inc., Natick, MA, USA) program. This program was implemented under Matlab® version 6.5, release 13, and consists of a series of image processing routines that are designed to locate the position of the center of the pupil. The point of gaze is localized as a pair of rectangular coordinates. The pseudocode lines shown in Figure 2 describe the algorithm that was developed to be used in this design, and that proved to be very efficient in terms of accuracy and processing speed. This algorithm is able to process around four frames per second on the previously designated computer system, a frame rate that is enough for this specific application.

```
proc locate (A: array [1..H][1..W] of double)
    for i ← 1 to (H – h) do
        for j ← 1 to (W – w) do
            for m ← i to (i + h) do
                for n ← 1 to (j + w) do
                    error ← error + A [m, n];
            if (error <= minError)
                minError ← error;
                x ← (i + h/2);
                y ← (j + h/2) ;
            error ← 0;
    return x, y;
```

Figure 2. Pseudocode of the algorithm used for the detection of the patient's pupil.

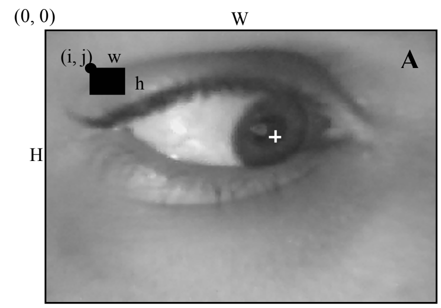

Figure 3. Illustration of how the algorithm scans the image for the darkest region that is considered to be the approximated pupil position. A = image of the eye; H = height of the image; W = width of the image; h = height of the search window; w = width of the search window.

As illustrated in Figure 3, upon the acquisition of the image (A), the program sweeps a search window (w x h) over the entire surface of the frame (W x H) and computes the degree of correlation between the search window and the corresponding area of the frame. The area that best correlates with the black window is considered to be the darkest region of the image and hence it is the approximated position of the pupil. Prior to running this pupil-allocating algorithm, the program cancels the effect of any white spot caused by reflection of light on the eye by eliminating high-intensity pixels. The coordinates of the center of this area are then passed to the next stage of processing where interpretation of the data takes place.

The second component of the software system is a graphical user interface written under the JAVA™ platform (Sun Microsystems, Inc., Santa Clara, CA, USA). This interface consists of several searchable pages, each of which encloses a (2 x 3) grid of large buttons showing a collection of pictograms. Pictograms are simple understandable images that represent basic human daily needs. As the locked-in patient focuses on a specific button, the processing program determines the point of gaze and measures the time duration that the patient spends looking at the same button. Three seconds were considered appropriate to make sure that the patient is indeed intending to execute the corresponding function. This duration can be adjusted by the computer operator.

When a clear decision is taken that a certain function has to be executed, the program fetches the corresponding wave file from the computer hard disk and plays it back to the patient's attendant through the built-in standard wave output device. The wave files can be recorded independently of the system and in any desired language. To ensure that no faulty executions are made, all buttons are initially *disabled* except for a particular button, located at the lower right corner of the screen. This button is used to activate the grid and to allow the toggling of the buttons between the *enabled* and *disabled* states. The patient can therefore choose to enable the buttons, and then request the system to execute his or her desired command. Once a function is executed, all buttons are automatically disabled, thus recovering the initial state of the program. This cycle can be repeated as long as the program is running.

Pictograms representing basic human daily needs are stored in an expandable database. Some typically used commands include: "I am Thirsty", "I am Hungry", "I Need to Go to the Toilet", and "I Want to Sleep." For instance, if the patient is trying to tell his or her nurse that he or she is feeling hot, the system might respond by playing back an audio signal: "I Am Feeling Hot, Would You Please Turn the HVAC System On!" Figure 4 shows a sample screenshot of the interface that is used by the patient.

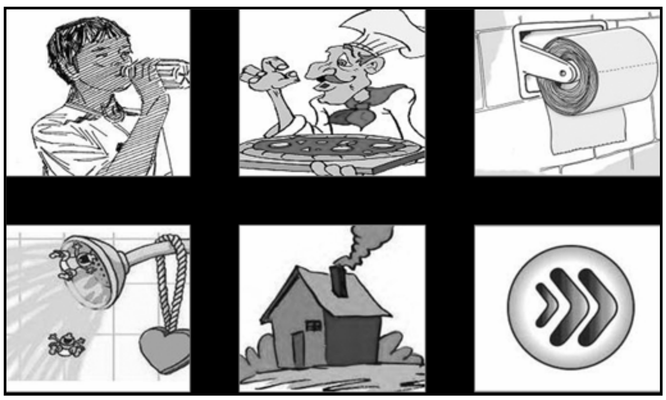

Figure 4. Screenshot of the interface enclosing a panel of buttons.

C. Calibration Process

Prior to utilizing the system, a calibration process, upon which the point of gaze will be determined, must be executed. After running the calibration program, the application generates a numerical grid of rectangular coordinates that represent six different strategic points on the screen, in concert with the six pictograms. The application sequentially displays a red disc, contrasted by a black background, through the six strategic points. The center of the disc corresponds to the geometric center of the pictogram at that specific location. The disc is 120 pixels in diameter, and remains in a predetermined position for five seconds before moving to the next location. During this time, the locked-in patient is instructed to focus on the disc so that the mean coordinates of the point of gaze are determined. Subsequently, each pictogram will be referenced with respect to the mean sampled coordinates of the point of gaze at a particular disc location.

D. System Validation

In order to quantify the overall accuracy and precision of the system, the system was tested on a population of 10 healthy adult volunteers (seven males and three females) ranging in age from 21 to 51 years (mean ± S.D. = 27.0 ± 9.5 years). Test subjects were free from any musculoskeletal or neurological disorders, and had intact ocular motor control and proper conjugate eye movement. Four of these subjects suffer from myopia.

The validation protocol consisted of performing a series of tests in a well-illuminated environment. Test subjects were asked to execute a sequence of pre-instructed tasks, designed to test all six button positions in different combinations. Each task consisted of activating a certain pictogram by gazing at it for three consecutive seconds. The allowable time limit for activating a pictogram was set to 15 seconds. Beyond that limit, the subject was considered to have failed to activate the desired button and a 'miss' was recorded for that task. The percentage of 'hits' versus 'misses' was computed at the end of each trial. The values acquired from all subjects were then averaged in order to obtain the overall system accuracy. The individual percentages of 'hits' versus 'misses' obtained from the different trials of each subject were used to calculate the overall system repeatability or precision.

It is noteworthy to mention that the system must be further tested with a population of completely locked-in patients before it can be put into clinical use.

III. RESULTS

Validation results revealed a system accuracy of 96.11 ± 5.58 % and system repeatability of 94.44 ± 2.51 %. These values represent the mean ± S.D. Figure 5 shows a graphical representation of the system accuracy and precision.

Interestingly, all four test subjects suffering from myopia showed a reduced performance while utilizing the system.

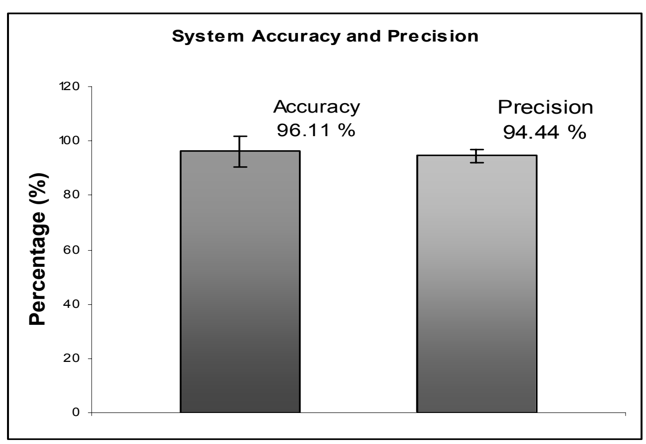

Figure 5. Mean system accuracy and precision (repeatability) with their corresponding standard deviations.

This observation suggests that poor eye-sightedness may affect system performance, and hence requires further investigation.

IV. DISCUSSION

In the course of developing this system, several questions were raised and imposed challenging constraints that were progressively solved:

1. The decision on using a head-mounted camera was based on three major disadvantages of remotely fixed cameras. First, remotely-placed cameras should have high resolution in order to get a clear image of the pupil. This would result in increased processing resources and hence would worsen system complexity. Second, to obtain the position of the pupil with a remotely placed camera, three-dimensional coordinates are required. While, the position of head-mounted camera relative to the eye is always constant, thereby reducing the number of spatial rectangular coordinates to two. Last, once the image of the eye falls outside the field of view of the remote camera, re-tracking the pupil would be difficult.

2. To reduce the effect of uncontrolled head movements relative to the screen, a semicircular headrest was mounted at the back of the wheelchair. The headrest is ergonomically designed to avoid any discomfort to the patient and would decrease the degrees of freedom in head motion.

3. During an eye blink, images captured by the camera result in correlation values that do not exceed a certain preset threshold, since areas of dark pixel concentration (i.e., the pupil) are no longer present. Such images are irrelevant for the calculation of the pupil position and are therefore discarded by the system.

4. During and following the execution of a certain function, the system disables all buttons to prevent the patient from unintentionally activating another function. Faulty executions are avoided by incorporating a confirmation step in which the patient is asked whether he or she is really wishing to execute the command. If within 15 seconds, no confirmation is received, the system aborts the execution, returns to the home page, and disables all buttons.

5. Locked-in patients are in some cases expected to show signs of limb spasticity. In such cases, it has been recommended by consulted rehabilitative practitioners that the arms and legs be constrained to the wheelchair in an extended comfortable position.

The whole system is subject to future upgrading. For instance it can be modified to be implemented on a motorized wheelchair. Modifications would allow the patient to control the movement of his or her wheelchair by simply gazing at directional buttons supplied on the screen. Moreover, expression-building add-ins can be developed to allow the completely locked-in patient to express his or her thoughts and personality. The system can further be improved by being developed as a stand-alone application. Furthermore, the system can be personalized according to each user. Colors would be easily modified and a database that includes recorded statements that fit the gender, age group, and language of the particular patient can be added.

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