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LONG PAPER

Hands-free interaction with a computer and other technologies

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Abstract Hands-free interaction with technology is a dream for any person with limitations in the use of his/her arms and hands. This paper describes two new original low-cost hands-free computer peripheries—I4Control® and Magic Key, which use movements of the user's eye or nose as an actuator of a computer cursor. Both systems emulate the PC mouse and thereby mediate direct access to any mouse-controlled computer application. Functionality of the presented systems is compared to that of PC mouse using one of the usability tests recommended by the ISO 9241 methodology. The data obtained as a result of testing a group of ten unimpaired novice users indicated that the users' performance improves over time of usage of the system, but the process is rather slow. The paper describes several easy to use toy-applications intended to improve the user's confidence in working with the considered devices. One of these applications demonstrates that I4Control® can be employed to control home appliances or a wheelchair.

Keywords Mouse emulation and control · Eye tracking · Environment control

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1 Introduction

There are a number of situations where a person cannot use his/her hands as an actuator for handling simple everyday tools (e.g., to write with pencil), to control his/her environment (e.g., to switch a light or a TV on/off) or even to take advantage of different sophisticated assistive technologies. A computer is a typical example of a technical system a person needs to work with to take full advantage of modern information society or of services offered, e.g., in a computer-controlled smart home [5, 32]. This paper describes two low-cost solutions, I4Control® [7] and Magic Key [8], which have been designed, produced and tested by authors of the paper recently. First, the principles of both systems are reviewed. The next section explains the methodology used for testing both considered systems and presents some obtained results. The last section describes several handy software tools or toy applications designed for easy operation with I4Control®. They are intended to support improvement of user's skills through challenging activities—the user who works with them gradually improves his/her skills and thus gains confidence in using alternative access to a computer. In the conclusions, some problems are discussed related to the plans to employ the considered systems for control of some home appliances, various toys or tools.

In Europe, there are more than 500,000 people who must rely on alternative access to computer due to their impairment [4]. For some, this may be a temporary problem (e.g., after a severe operation) while for others this is a long lasting condition. In both cases, they have to rely on help and support 24 h a day. A number of different alternative access solutions is being studied, designed and produced by current technology. They range from ready-to-be-used systems with voice input

[33] up to preliminary experiments with direct brain–computer interaction [30]. Experiments in gaze-based man–machine communication are not at all new, they started some 25 years ago [29] and their research agenda is still busy [1, 25]. A respectable list of eye trackers for eye movement research, analysis and evaluation can be found on the web page of the EU project Communication through Gaze Interaction (COGAIN) [15]. Overall, it is still rare to find a regular user of gaze-based computer interaction systems. This situation is not surprising—the prohibitive price of most technical tools, which can serve as gaze-based hands-free computer peripherals, causes the main problem. These systems are currently being produced in three categories: very precise expensive medical systems designed for detailed research studies of various types of eye movements, e.g., in ophthalmology or neurology (price level: 100 thousands of EURO), systems of medium complexity identifying the precise position the user is looking at the computer screen, used primarily by some professional care institutions (price level: thousands of EURO) and just a few low-cost systems (e.g., HandiEye, NaturalPoint, Nouse or Quali-Eye) standing at hundreds of EURO. Only the systems of the last category have the potential for being applied in homes of people with motor disabilities. The intention underlying this paper is to enhance the current offer for routine usage. The described systems apply movements of head or of eyes as pointing devices so that they benefit people lacking the possibility to operate a computer using hands.

To ensure universal access and to extend the existing offer to people with limitations in the use of their arms and hands, it is essential to meet their real needs and make-up for their constraints [6]. Both presented systems can be characterised as new computer peripherals obeying common design principles which have been set with respect to the requirements of the target users to provide them with easy access and utilization of any computer application. Each of the considered systems meets the following criteria:

- C1. It can be used by anyone, even by a person with hearing impairment who cannot move hands or arms at all, and who must rely on movement of his/her head or eyes only.
- C2. It is a low-cost, easy to install and mobile (i.e., lightweight) solution requiring no special equipment for its implementation.
- C3. It is so intuitive that one can master it quickly without any need for preliminary training and memorization.
- C4. It applies computer control as similar as possible to that used by an average user who controls his/her arm movements.
- C5. It provides direct access to any computer application without having to configure it.

There is a clear and natural rationale for the choice of these criteria: all of them try to offer immediate direct access to current technology for users with functional limitations. The aim of the criteria **C1** and **C2** is to pull down the objective economic and physical barriers and to ensure that the users in need can be accompanied by the system everywhere they can benefit from its existence. The criteria **C3** and **C4** try to break down subjective barriers of the potential users, by minimizing the time a person needs to learn to efficiently utilize the system (this parameter is later referred to as *take-up time*). Meeting these criteria is most important to prevent occurrence of psychological restraints, which might cause negative attitude of the user towards the system. Even though the criterion **C5** seems to be of purely technical character, it has far-reaching consequences. It ensures universal access and a long-term perspective to the users. A tool meeting the criterion **C5** warrants that the user is not limited to the software tools specially developed for him/her—on the contrary, the user can be sure that he/she can take advantage and utilize any existing or future computer program he/she is interested in.

Obviously, the intended system has to be tailored to the needs of its target user. That is why the criterion **C1** has to be considered in more detail and two different scenarios have to be foreseen depending on the ability of the user:

- C1a. If the user is able to move his/her head, human–computer interaction can utilize the head position and its change as an important source of information.
- C1b. In the opposite case, the communication means are significantly more restricted, as the will of the user has to be mediated through position of his/her eyes only.

The Magic Key system has been constructed with criterion **C1a** in mind, while I4Control® can be applied in both considered scenarios. The Magic Key system derives benefit from the fact that its user is free to choose his/her head position and can use the nose as a pointer. The construction of this solution has the important benefit that it is totally independent from its user in the sense expressed by the last criterion.

C6. The user has no electrical or mechanical appliance attached to him/her.

The system I4Control® [17] looks like a tiny add-on to ordinary glasses (see Fig. 8). With respect to **C6**, I4Control® takes a complementary approach to that of Magic Key, and it represents a step towards the creation of wearable technologies for persons with functional limitations. The last important distinction between both considered solutions stems from the way they process their input signals. Magic Key [18] uses for that purpose the processor of the controlled computer as described in Sect. 2, while I4Control® can rely also on an external processing unit (as described in Sect. 3). This approach proves most useful in the case of home appliances control, as mentioned in the Sects. 3.3 and 3.4.

Both systems rely on recent advances in image processing and in gaze-based interaction, see [1] for their present state of the art. Even though their technical solutions are based on different principles, they share many features as a result of the fact that both of them emulate the computer mouse and offer several choices for indicating a click. In their default setting, keeping the eye closed for a predefined period of time **t1** indicates the click, but alternative choices can be applied (for more details see Sects. 2.1 and 3.3). Emulation of a computer mouse seems to be a natural solution in order to meet the criterion **C5**. Simultaneously, it allows applying the same control philosophy of the mainstream applications. Meeting the criteria **C3** and **C4** becomes a simple consequence of this design decision under these circumstances. This is a fine example of a case when a good technical decision can resolve also problems of subjective or psychological nature.

2 The Magic Key: system description

The Magic Key uses an ordinary webcam, adapted to this application. The webcam is installed below the monitor and aiming at the user's face, as illustrated in Fig. 1. The camera has to be below the user's face so that the nostrils are visible. This setting is advantageous for good detection of the state of eyes (closed vs. open eyes). For face and eyes illumination an infrared light is used, with wavelength of 840 nm and power of 0.5 W. The application uses DirectX technology to acquire real-time images of the user's face. These images have 640 × 480 resolution and are taken with frequency of 30 Hz. The application Magic Key, even in background, processes them in real time. The computer recommended to achieve good performance of the system is supposed to have at least 2.4 GHz CPU, but Magic Key can manage also with less. The functionality of this system has been demonstrated on a portable computer, namely Compaq nx9030, CPU Pentium M at 1.7 GHz: here the Magic Key consumes about 25% of CPU time, while the remaining 75% can be dedicated to the user's applications.

The first processing phase consists of the automatic tracking of the user's nose, which will always be the central reference point in the user's face. Figure 2 shows a small dark point in the nose that Magic Key places into the image. To indicate the considered spot clearly, a red arrow is added artificially to this image—it points to the dark point.

Once the coordinates of the user's nose have been established in the image system, the position of the nose is projected onto the monitor coordinate system and the mouse cursor is then moved into this new place. A direct

Fig. 1 Magic Key equipment

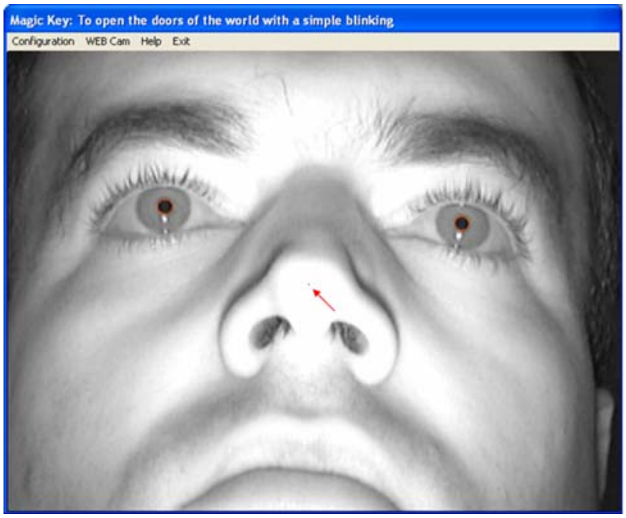

Fig. 2 Image processed by Magic Key

mapping system of coordinates is employed, using a proprietary algorithm the description of which is outside of the scope of this paper. This approach always implies the use of the absolute coordinates of the nose position, and no comparison to the previous image is applied. This increases the robustness of the system, since during such a comparison a systematic error can be introduced. Moreover, the resulting behaviour of the system is very natural: when the user is turned to the right the cursor is on the right and when the user is turned to the left the cursor is on the left. Most often, the horizontal movements of the user's face in the processed image are restricted to an interval of 100 pixels, while the vertical movements to 50 pixels. It is important to mention that in spite of this limitation and the fact that the processed data are obtained from an ordinary adapted webcam with a 640 × 480 resolution, the Magic Key algorithms mentioned above make it possible to place the cursor at the exact desired pixel on the screen, also using a monitor with a graphic resolution of 1,280 × 1,024 (see the Fig. 3).

The Magic Key always applies direct pointing, and this solution provides good results even for fine resolution. This is one of its key features, which distinguishes it from other seemingly similar systems, e.g., Nouse [11, 19] and

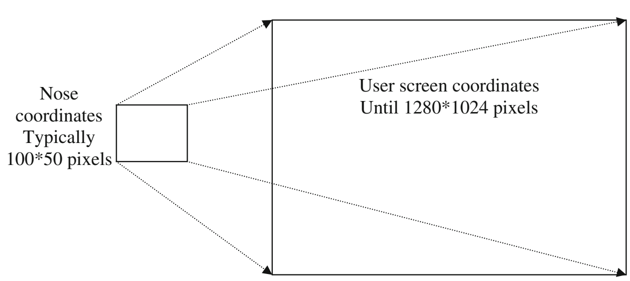

Fig. 3 Coordinates mapping

Camera Mouse [2]. Nouse switches between direct pointing and joystick mode for fine resolution. There are at least two significant differences between the Camera Mouse and Magic Key, namely:

- The Camera Mouse sets much higher requirements on the user's assistant during the calibration mode than Magic Key.
- The set of control signals utilized in Camera Mouse is significantly restricted, because the system does not evaluate information about the user's eyes (it has to stick to "dwell" time signals because blinks cannot be recognized).

Another helpful feature of Magic Key is the fact that the mouse position always responds to movement of the head in real-time. It is equally important to mention that Magic Key exhibits high stability of mouse movements even if the users have small spasms in the head.

After the nose reference is calculated, Magic Key has to find the eyes of the user (see Fig. 2), since blinking of the eyes signifies pressing the mouse buttons. When the eye is closed a button is pressed, when the eye is open the button is released. It is possible to configure the right or the left eye as that one which activates the main button of the mouse, and use or not the other eye for the secondary button. Configuration for individual users is described in the next section. Table 1 shows the possible direct click kinds as related to the user's capacities for blinking.

The only situation when the user cannot use all possible kinds of direct clicks—namely the secondary or auxiliary click, occurs when he/she cannot close one eye while keeping the other eye open simultaneously.

Magic Key offers as one of its options to use dwell time for clicking. When dwell time is applied, a small window with three icons is permanently present on the top of the screen. These three icons represent possible modifications of the next click when selected, namely secondary click, double click and "drag and drop". This window can be used in combination with blinking too. In this case, the user selects an eye configuration for the main click and uses the icons in the window to change the click type. The usage of these icons, with dwell time or blinking, represents an indirect mode for clicking: there is no single control signal ensuring for example a secondary click. Instead, the user has to click twice - first, to select the type of the next click, and second, to perform the desired click.

For eye tracking, a proprietary algorithm based on the Hough Transform [21] for the calculation of circles was developed: it introduces an important group of changes resulting in substantial decrease of processing time, but also in considerable increase in eye tracking efficiency. At this point it is important to mention that poor eye tracking would lead to numerous false mouse clicks, and

Table 1 Possible kinds of direct clicks with blinking

User's capacities for blinking			Possible kind of clicks			
Both eyes separately	One single eye	Both eyes together	Simple click	Double click	Drag and drop	Secondary click
Yes			Yes	Yes	Yes	Yes
No	Yes		Yes	Yes	Yes	Yes
No	No	Yes	Yes	Yes	Yes	No

therefore to a malfunction of the application. This can happen, for example, if the eyes are not completely open, and therefore not in the shape of a perfect circle. In situations with high level of natural light illumination Magic Key has some problems to detect the eyes. To solve this problem, the feature to be detected by Magic Key can be changed: instead of the pupil the reflex light of the infrared spot can be detected, which is highly visible since the infrared illumination is at high level even under these conditions.

2.1 Configuration process

Although Magic Key is a generic application, adaptable to any user, it has to be adjusted for the individual user during an initial personalization process. The system needs to know its user, namely some characteristic features of his/her face, e.g., the distance between his/her nostrils and their size, the same for eyes, brightness of the eyes and nose. Magic Key provides a simple and functional interface for the user's assistant who is in charge of configuring Magic Key (see Fig. 4).

After adjusting horizontal and vertical sensitivity, which is related to the degree of head movements, one has to choose one of the three available options for the main click and for secondary click. If dwell time is selected, its necessary parameters have to be specified, namely the minimal dwell time and the size of space on the screen which corresponds to a fixed position (maximal difference specifies the distance that mouse can cover in pixels without spoiling a click generation). The user's assistant can also decide if Magic Key must detect the pupil or the light reflex, and if Magic Key has to show the top window with the three icons for changing the clicks types (this is done by selecting the box *Auto click* in the lower right corner). The *Manual Configuration* facility provides access to some more parameters, which do not need modification so often. This is the case, e.g., of the minimal period of time for which an eye has to be closed to indicate that this act should be interpreted as a signal "to click". This solves the problem of involuntary blinking, which happens more or less frequently to everyone. In the default setting, the click is performed when the user closes his/her eye for at least 10/30 s = 333 ms (i.e., if ten successive images with the eye closed are registered at the processing speed of 30 images per second).

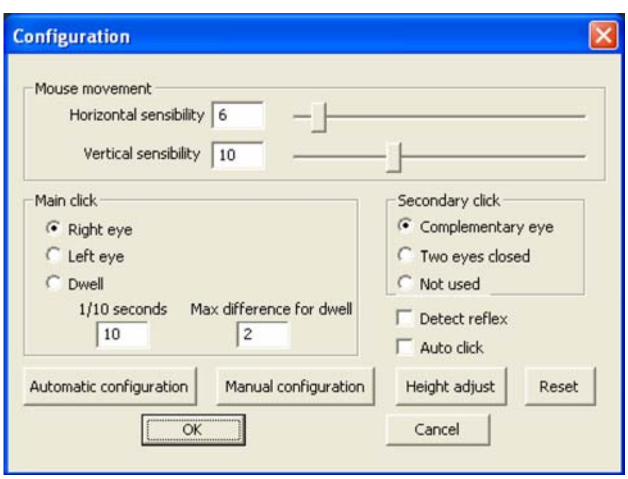

Fig. 4 User assistant's interface

Dragging can be achieved in three ways. The first way is to close the eye, and keep it closed during the whole dragging period. This simple solution is applied in the default setting. Its disadvantage is that it reduces the user's resources for keeping track of what he/she is doing (only one eye remains available). This might be, in some cases, a problem. The second solution implies keeping an eye closed for a period of time just long enough for the button to remain depressed. Later, when the eye is open again, the button remains depressed as long as no other signal for click is given. This approach allows the user to follow the activity using both eyes, while the button remains depressed. Finally, if *Auto click* is enabled, dragging can be performed by selecting the corresponding icon in the top window. The initial configuration is concluded by switching to the *Automatic Configuration*, which takes about 15 s during which Magic Key fetches the main necessary parameters, corresponding to the user's face and actual light conditions, automatically. When this process is finished, Magic Key becomes very tolerant to natural fluctuations in the levels of illumination. Moreover, the obtained data will remain in memory for future use, thus establishing a profile for each user.

2.2 Practical results

The computer used to perform these tests was equipped with an Intel Core 2 Duo at 1.582 GHz. Using advanced digital image processing techniques, alongside with other simpler and well-known ones [9], has delivered excellent results, thus diminishing the need for more expensive and complex equipment, such as high-definition cameras, whose market price is higher than the webcam used. On the other hand, the efficient manner in which the proprietary algorithms were developed and implemented, making use of, in the most critical parts of the code, a lower level implementation in order to take full advantage of the existing SIMD technologies from Intel processors [22], prevented the application from compromising the overall performance of the computer, thereby almost completely maintaining the performance of the remaining applications. The average percentage of CPU usage in the process of image acquisition and processing of the 30 images per second remains around 10% of total CPU time, as shown in right the part of Fig. 5.

It is worth comparing this performance to that achieved by the Nouse system on the same computer (see the left part of the Fig. 5). Magic Key needs less than 30% of the CPU time used by Nouse. Moreover, an important feature of the Nouse system is that it catches the user's nose only. The input of Magic Key is much more complex, as it recognizes the user's nose and both his/her eyes, and some of their modifiable features can be involved in indicating all the types of direct mouse clicks in an easily and natural way.

Magic Key has been tested with three very different users under real-life conditions. This experience proved that Magic Key is reliable and highly adaptable to individualised conditions of different users: neither wearing glasses nor limited head movement in one direction represent an obstacle. Two of the involved users wear glasses, and they were able to work with Magic Key without any problems. One user had a car accident resulting in breaking the spine near the head. She has a tracheotomy that limits the vertical head movements. She was a computer user before the accident. Another user has cerebral paralysis and his horizontal head movements are very limited. Since he is still able to move his fingers slightly, he uses a tracker ball for computer access. He tested Magic Key as a potential system for the future since his finger movements tend to be reduced. Finally, the third user had an infection in the spine that impedes any movement in the arms and legs. Before testing Magic Key this user worked with the Tracker Pro System [20].

All the three users find blinking to be easy and they seem to prefer this choice to the dwell time option. It was observed that even the third user, who was trained with a dwell system, used often blinking in the preference test performed with Magic Key and the virtual keyboard. In this setting the user could press the key where the mouse is positioned at either by blinking or by dwelling. All the users claim that this "mixed solution" suits them best, since they can use simultaneously the dwell and blinking system.

The pictures in Fig. 6 show two Magic Key users. The first user is writing in MS-Word with a virtual keyboard.

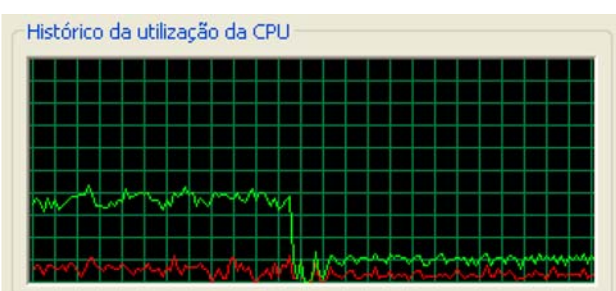

Fig. 5 CPU usage for Nouse, *left side*, and Magic Key, *right side* (from Windows Task Manager)

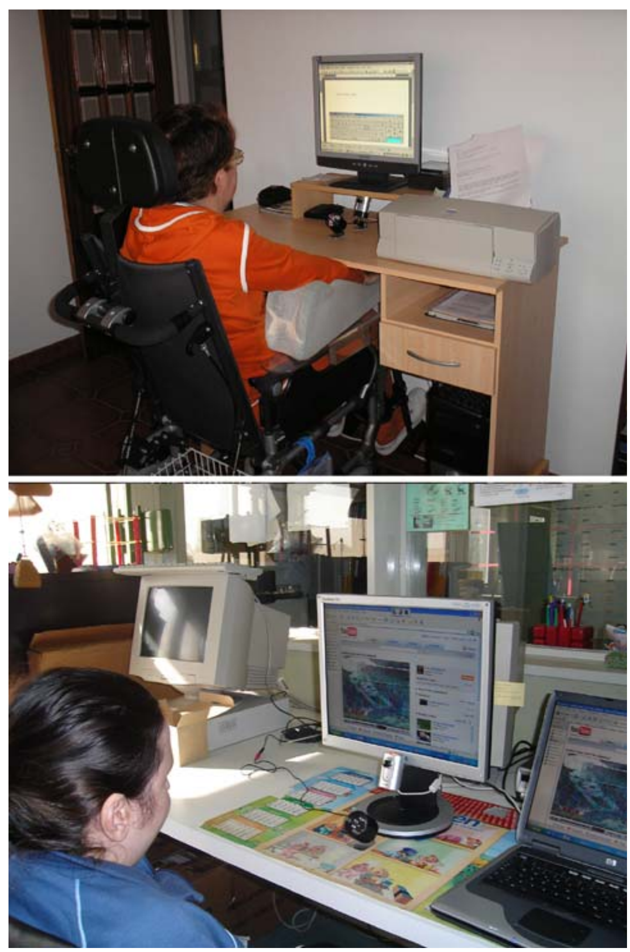

Fig. 6 Magic Key users

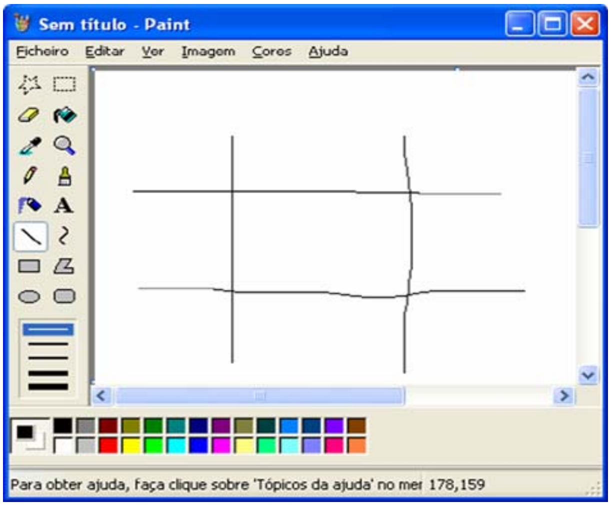

Fig. 7 Paint application

The second one uses the web to see a video clip. The picture in Fig. 7 depicts two horizontal and two vertical lines made in the Paint application. One of the horizontal and one of the vertical lines were drawn with the traditional mouse, by keeping the button pressed throughout the drawing. The remaining two lines were drawn using this application, by keeping the eye closed throughout its drawing. The left line and the top line were drawn with Magic Key. These lines show the high stability and precision of the Magic Key.

It is perfectly possible to start a Power Point presentation using Magic Key and to navigate through several slides. The same holds for any game application controlled by a PC mouse, like Solitaire or Minesweeper or for internet access, which is a favourite task of all the three users.

3 The system I4Control®

The I4Control® system [7] uses a small camera mounted on a spectacle frame to monitor the user's eye (see Fig. 8). At first glance, I4Control® looks similar to VisionKey [16], but there are several significant differences between the two systems: the set of control signals applied by I4Control® is much richer than that of VisionKey, and the prices of the two systems belong to different categories. I4Control® takes videooculograms (VOG) of the user's eye and transmits the corresponding analogue PAL signal for further processing to the external control unit (Fig. 9).

The obtained data is evaluated to estimate the deviation of the user's pupil from its *normal steady position*: left–right, up–down. The specific position of the camera is selected with the ultimate intention to decrease demands on the technical parameters of the used camera and on the

Fig. 8 The I4Control® system

complexity and time requirements of the applied image processing algorithms. The chosen position of the camera brings the following advantages:

- whatever the user is doing, the fixed camera remains targeted straight at the user's eye and fully focused without the need of any adjustment,
- the minimal resolution of 300 × 200 pixels provides an image of satisfactory quality for intended purposes,
- there is no need to implement algorithms for eye recognition in a complex scene, because the resulting image covers no more than the small area beside the eye itself.

These features allow reducing the price of the resulting system. To secure its good performance independently of external light conditions, the camera is complemented by an infrared source, which sheds light on the observed scene. If this source (situated close to the camera) is switched on, its intensity is adapted automatically to the quality of illumination of the environment.

The *external control unit* processes the obtained video signal in order to detect the actual pupil position. First, the signal is digitised in the digitising block, which is constituted of an A/D converter with brightness feedback. The processor uses the method of histogram tresholding and other types of filtration (e.g., cubic filter) for the detection of the pupil's position. The resulting information about the position of the pupil is compared to the stable position defined during the calibration process described in Sect. 3.1. The system outputs the control signals [Δx, Δy] for change of the *x*- and *y*-coordinates of the mouse cursor on the screen. In other words, it defines the direction of

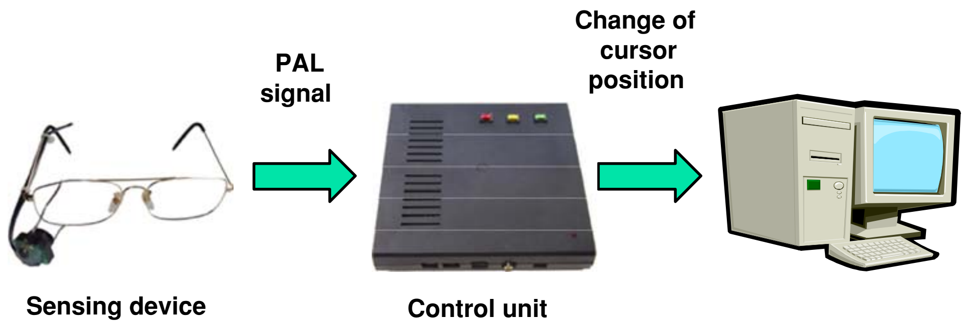

Fig. 9 The basic building blocks of I4Control®

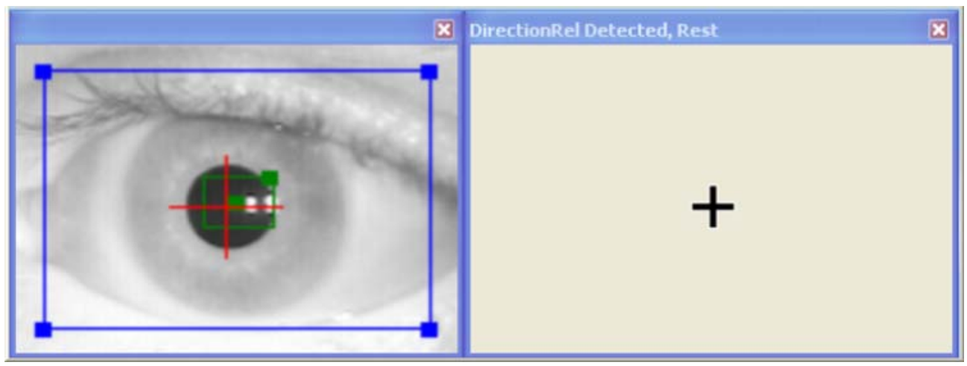

Fig. 10 I4Control® calibration process

movement of the computer cursor, which is computed from the difference between the actual pupil position and the steady pupil position in the processed videooculogram. The final task of the processor is to control the USB bus ensuring smooth communication with the PC.

Similar to Magic Key, the I4Control® system emulates the PC mouse and the click or double-click can be indicated by blinks of different length. The corresponding time parameters can be set with respect to the needs of individual users. The system allows introducing alternative choices for control signals—this feature is described in the last paragraph of this section.

The I4Control® system is as easy to install as any standard computer equipment (e.g., TV/FM card)—and the *set-up time* is very low. Its user can utilize the software keyboard included in a common operating system and she/he can write a message, send an e-mail or browse web pages without a single touch of any physical object.

The control signal for the PC cursor is derived just from the position of the user's pupil—this is the only type of movement the user has to be able to accomplish. Consequently, the I4Control® system is well suited for fully immobile users. The user who is able to move his/her head can use this ability to emphasise his/her intentions. Here, one can rely on the *oculocephalic reflex*, an "involuntary" movement of an eye which maintains gaze direction in response to neck rotation, and provides natural synchronization between locomotion of eyes and head: whenever a person is moving the head in one direction, his/her eyes go "automatically" to the other side. Thanks to this reflex, the user can manifest the intention to send the PC cursor "down" by raising his/her head, etc.

3.1 Calibration

The necessary precondition for the proper functioning of the I4Control® system is its calibration (see Fig. 10), i.e., the definition of two relevant user-specific sections of the camera image, namely:

- the part **p1** containing the full picture of user's eye and selecting the cut which has to be processed (the cut delimited by the larger blue rectangle) and
- the steady position **p2** of the user's pupil, which appears inside the smaller green rectangle.

The corresponding areas depend on the position of the camera with respect to the user's eye—that is why these sections should be identified for each user individually. They depend on his/her facial features, as well as on the spectacle frame used. The results of the calibration process are stored in the memory of the system as *user profile*, which can be read-in whenever needed. Consequently, it is enough to run the calibration for each user just once. The user can afterwards reuse his/her profile and start working with the system immediately after setting the spectacle frame on his/her nose.

The calibration is done manually by an assistant (or support worker) who switches the calibration mode of the control on by a dedicated switch (see Fig. 9, the green switch) and selects the size of the appropriate cut for both upper mentioned parts—this is ensured with the help of a simple computer program running on the screen in this mode (see Fig. 10). Part **p2** representing the steady position corresponds to a rectangle inside the image of the user's pupil, which is taken when the user is facing directly the computer screen and is observing its central section. The selection of parts **p1** and **p2** is confirmed by pressing the red switch on the control panel.

3.2 Routine function

The I4Control® system can be characterized as an indirect pointing device, as it does not move the PC cursor directly to the place the user is looking at. It applies the same incremental principle as a joystick and it influences the direction in which the PC cursor moves. This direction is determined by the deviation of the pupil from its steady position **p2** as set during the calibration process (see Fig. 11). The system first evaluates the actual position of the observed eye and compares it with the steady position to decide what actions have to be taken. As long as the eye is outside of the steady position, the system continues transmitting control signals for movement in the corresponding direction. The flow of these signals stops as soon as

- the eye returns back into the steady position or
- if the system identifies that the eye remained closed for a predefined period of time **t1** (or **t2**): this act is interpreted as a signal for click (or double click).

3.3 Alternative choices for I4Control® control signals

In the default setting, the user's pupil displacement from the stable (central) position defines the direction of the cursor movement and selection of the item under the current position of the cursor is confirmed by closing the eye for a predefined period of time. However, this does not have to be the best solution for everyone. For example, the potential user of the technology may lack some of the required abilities (e.g., he/she cannot move the pupil in a certain direction). The default setting can be easily changed during the configuration phase of the system by the user's assistant in a special dialog window for personal configuration of the keys—see Fig. 12. This window is divided into three sections:

In the left part of the upper groupbox (*Directions*) there is a list of the types of pupil movements which can be distinguished by the system. The task of the configuration process is to map the movements the user can perform to the requested keys of the computer, i.e., to choose from the drop-down menu the proper activity. If a certain faculty is not available, the choice should be "…". For example, after closing the configuration dialog from the Fig. 12, the user will confirm the choice (that is "apply click" or "select Enter") by looking down.

The interpretation of the act "the eye is closed for specific period **t1**" is specified in the groupbox *Switches*. Here, the choices are taken from the same drop-down menu as the one used in the section *Directions*. The I4Control® introduces two switches which are distinguished by the corresponding time periods **t1** and **t2,** the length of which can be set in a subsequent dialog window as well.

In the groupbox *Repeat* one can choose the mode and the speed of the cursor movement. The repeat function is enabled in Fig. 12—that means that the cursor will move in the selected direction by the speed corresponding to five clicks of the appropriate key per second. If the repeat function is switched off, a change of gaze direction is interpreted as a single click to the appropriate key.

3.4 Real life experience

The I4Control® system has been tested by two male students of a secondary school in the Jedlička's institute (a specialized care and educational institution dedicated to severely disadvantaged youngsters). The first student lost his arms in an accident, while the second one is suffering from muscular dystrophy. Both boys had some prior experience with a computer because some of their lectures take place in the school computer lab. Most of the students control the computers there through well-chosen dedicated peripheries which help them to overcome their constraints (e.g., a special trackball which does not have to be operated by fingers).

The I4Control® testing started by a brief introduction (5 min) offering to both students a rough explanation of

- the principles that the system applies to control a computer and
- the process of its calibration.

The next 10 min immediately after calibration represented the training period when the assistant asked each of the students to perform several simple tasks related to moving the cursor to specific predefined places on the screen. During this short period they gained confidence in working with the new peripheral and they were ready to start using it on their own.

The first boy wanted to relax and play a game—he had no problems to play the card game FreeCell, which is offered as a part of Microsoft Windows OS. The second boy used I4Control® to move through the menu of the operation system. Since he had no problems in

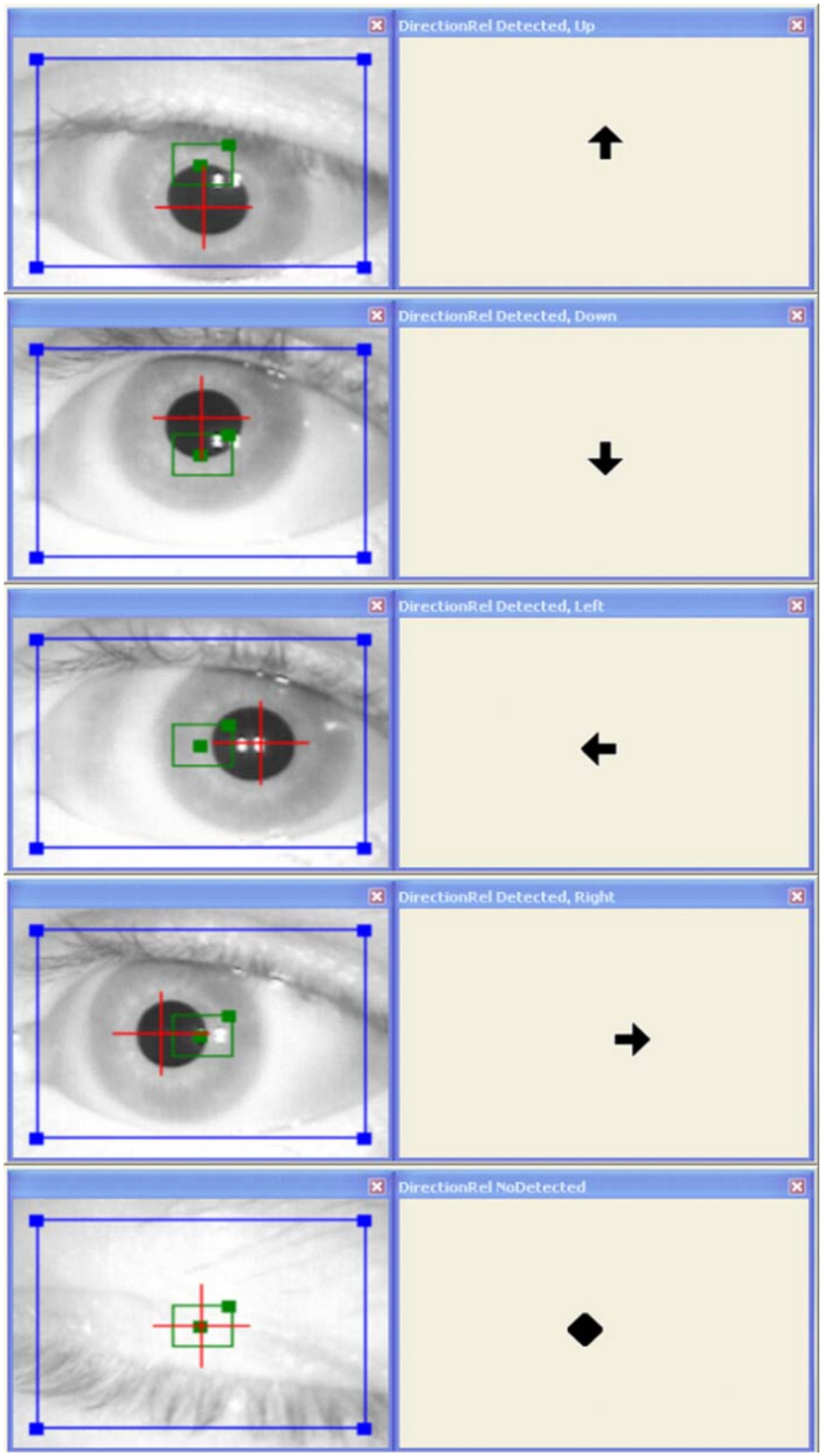

Fig. 11 Changes of pupil position and their interpretation by I4Control® in the inverse mode (choice prefered by users who can move their head): the cursor goes **a** up, **b** down, **c** left, **d** right. The last image **e** shows a closed eye—this is interpreted as a signal to click

switching between various installed applications, he decided to test his skills in drawing using a graphic editor (Fig. 13).

Finally, they were asked to write a short message using the software on-screen keyboard offered as a part of the operation system. This proved to be rather simple. The

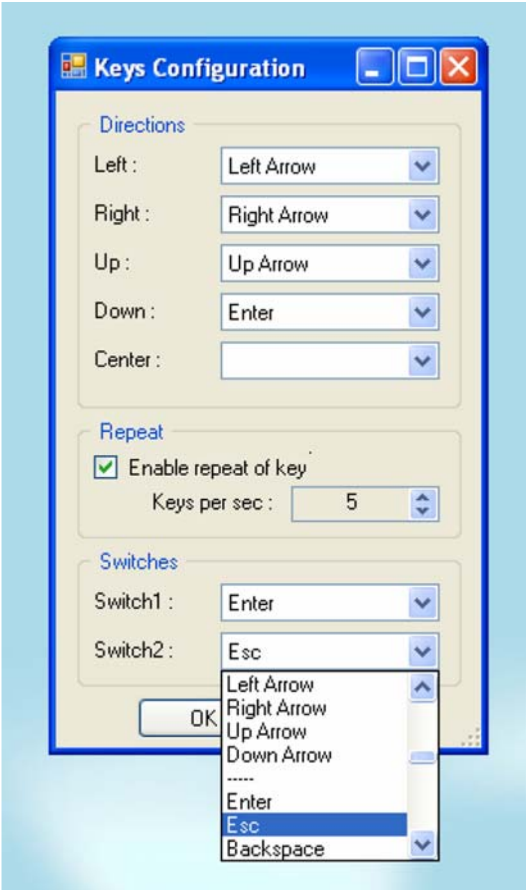

Fig. 12 I4Control® dialog window for personal configuration of the keys

Fig. 13 Testing I4Control®

second boy used this option to give a name to the file with his picture and he saved it.

The next person who tested I4Control® is a client of the Social care institution for severely challenged adults in Habrovany. He was admitted into this institution just a few years ago for severe muscular atrophy, which manifested itself and progressed in his late 40s. No signs of illness were observed earlier and he was working as a skilled worker. In the social care institution, he became a regular computer and Internet user. He takes advantage of these technologies to pursuit his favourite activity—chess playing. Currently, he operates the computer using a mouth stick, but he would like to obtain same alternative means for computer access because his gums suffer from extensive use of the mouth stick. He was eager to test I4Control® in the chess playing applications and he has done rather well, Fig. 14.

The I4Control® system has been successfully tried by numerous disabled and healthy users during various exhibitions where this system was presented. To raise the interest of public in the process of testing, several gaze controlled games have been developed (e.g., Sudoku [14], "Fifteen"), see Figs. 21, 22. By far the most appealing for the public proved to be a gaze-controlled toy car Gertie, Fig. 23. The acquired experience with more than 100 persons who tested it proved that a person can learn to "drive Gertie" in less than 5 min including the individual calibration.

All the pilot users were able to move their head and they had no involuntary eye/head movements. These users reported no problems when they were asked to browse through a text presented on the full screen (e.g., web news) and read carefully some of its parts. They were able to use their eyes both for reading and for indicating the direction in which they wanted to move the computer cursor. They considered the task rather easy because they were able to employ their head movement to follow the computer cursor—consequently, when reading they were looking straight having their eyes in the steady position. The blink-based clicking proved better than dwell-based solution when reading multimodal text, because this choice allowed the user the option to observe the considered part of screen as long as necessary without danger that his/her fixed gaze is misinterpreted by a dwell-based system as an instruction for opening a new window. Testing the system under more complex conditions remains a challenge [23] which will be addressed in future work.

4 Testing the presented systems

4.1 The method used for testing

To validate the basic properties of the systems it was decided to apply one of the tests recommended in the Annex B of the European Standard ISO 9241-9:2000 [24] for evaluation of computer pointing devices. A uniform testing environment was prepared, which is similar to that used in [28], see Fig. 15. The main goal of the experiments

Fig. 14 Playing chess and driving a toy car with I4Control®

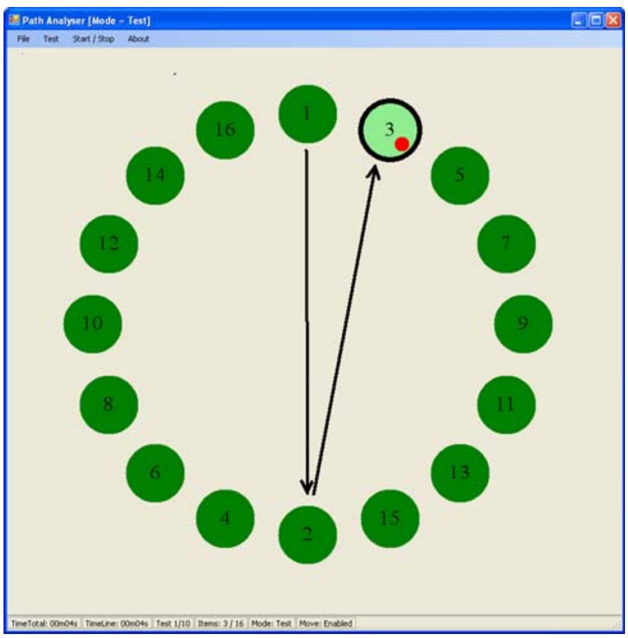

Fig. 15 The task the user had to carry out during a single trial

was to compare the accuracy of the pointing devices to the accuracy one can achieve through the mouse. The time needed to accomplish the considered task is taken as a complementary criterion only.

Ten able-bodied volunteers of the age between 20 and 35 years were recruited for these trials. The groups ensuring the testing of both devices were disjunctive. All the participants were regular PC users accustomed to the mouse, but with no prior experience with the novel devices. The tested subjects obtained no compensation for participation in the experiment described bellow.

Each of the subjects was invited to perform a series of ten trials (with the selected type of actuator). In each trial, the subject was asked to accomplish a simple task, such as “to carry out 16 target selections of the points around the circle in the Fig. 15”. Each trial began when a participant clicked on the top target in the layout circle. The next selection was targeted on the opposite side of the layout circle, and so on. The lines in Fig. 15 identify the first three selections 1–2–3. At all times, the “next” target is highlighted by a clear change of its colour. Participants were instructed to select the targets as quickly and accurately as possible. If the selection was correct, the original target lost its bright colour and the next target was automatically highlighted. If the selection missed the target, the test environment reported this error by a sound signal (beep), inviting the person to repeat the selection of the same target (which remained identified by the bright colour) again. The trial concluded as soon as the subject successfully selected all 16 points presented on the screen. This is the main difference with respect to the design of the experiment conducted in [28], where each sequence of 16 clicks was taken as the basic building block and number of errors (missed points) in this sequence of the fixed length was evaluated. On the contrary, in the experiment reported here, the number of errors made by the subjects was not of interest. The intention was to characterize the effort necessary to achieve the desired result; therefore the trial did not end before the subject selected all the 16 target points, and the measured value was “the total number of clicks the user makes in selecting all 16 targets”.

The subjects using I4Control® have been asked immediately after their series of ten trials to answer the standard Device Assessment Questionnaire provided in the Appendix C of the European Standard ISO 9241-9:2000 [24] for the evaluation of computer pointing devices, where the questions 8, 9 and 10 related to the strain in fingers, carpus and arm were replaced by questions concerning eyestrain, eye stitching and headache.

4.2 The obtained results

Each subject performed ten trials for the specified device. While 60 minutes approximately was the total time spend by one subject performing the experiment both with the mouse and with the I4Control® system during that time, the experiments with a mouse and the Magic Key took about 20 min, only. Data collection was continuous within a single trial; however, rests were allowed between the trials (the time measurement for each trial started when the user clicked the first target and concluded as soon as the 16th target was successfully selected).

The tests were running on a screen with a diagonal of 50 cm. The user was sitting at the usual distance of 80 cm from the screen and he/she was allowed to move his/her head. The circle (see Fig. 15) had the (external) diameter of 20 cm and the size (diameter) of individual target points was 28 mm. Each user was asked to run the test with the mouse first to get used to the test environment. After the mouse test has been finished, the user was invited to work with the alternative devices I4Control® or Magic Key. The calibration of the device is not included in the time taken. Overall, individual calibration proved to be very quick—it took about 1–2 min on average for each of the considered systems.

The developed test environment collects a range of data. In the present study, the following values are utilized for each individual user during the considered ten trials, which were accomplished first with mouse and later either with MagicKey or with I4Control®:

- number of clicks necessary to perform the full trial and to hit all 16 target points
- the length of the path followed during the trial
- total time from the first to the last click of the trial (including the delays caused by the blinks the user had to accomplish to ensure the clicks in the default setting).

The results obtained by the novice users are presented in the Fig. 16 (columns 1–10). It is interesting to compare these results with the performance of an experienced user reported in the very right column (“expert user”). The expert Magic Key user needs about 25 s to complete a single trial, his path length is about 310 cm (this value is smaller than that for the mouse user), and the number of the needed clicks is also smaller than that of the mouse user. On the other hand, the expert I4Control® user needs less than 100 s to complete a single trial, his path length is about 410 cm and the number of the needed clicks is about the same as in the case of the mouse. The significant difference in the time needed by both devices can be partially explained by the fact that performance of I4Control® is highly influenced by the used setting which can be changed according to the needs of the user (see the section Alternative choices for I4Control® control signals). The decisive parameters are

- **t1**—the length of the blinking period indicating the click
- the speed with which the cursor moves (=the number of keys per second selected in the repeat option).

The default setting was used both for the subjects and for the experienced user to obtain compatible data as presented in Fig. 16. These experiments prove that the naive users are able to handle this default setting without any problems. It has to be brought forward; however, that I4Control® can work more efficiently under the guidance of the experienced user provided the following adjustments are applied:

- the speed of cursor does not have to be constant but it can grow with the time the user is looking into the same direction
- the length of the period **t1** can be decreased from the default setting of 1 s down to 250 ms (with respect to the abilities of current user).

As expected, one can observe in Fig. 16 certain advance in naive user’s performance and slow convergence towards the characteristic values of the experienced user. If the user should rely on the alternative access tool, he/she has to gain full confidence into that solution first. And this cannot be achieved without sufficient training.

For this reason, it is important to support the users with special attractive software tools, which will motivate him/her to master the novel technology. These tools have to be designed in such a way that their control through the devices is simple—some of such tools are mentioned in the next section. As soon as the user masters the movements necessary for their control, they will have no problems to control any mouse controlled software.

It is still premature to evaluate the user’s comfort with I4Control®. Overall, the answers of ten volunteers to the Device Assessment Questionnaire seem encouraging: none complained about headache after an hour of working with the tool. Slight eyestrain or eye twitching was reported by six and three persons, respectively. Three persons complained about accuracy and four persons claimed that they would welcome an increase in speed.

5 Dedicated software applications

5.1 Message writing and web browsing

The I4Control® user can use the virtual software keyboard (offered, e.g., by Microsoft Windows version 2000 or more

Fig. 16 Results of the accomplished experiments

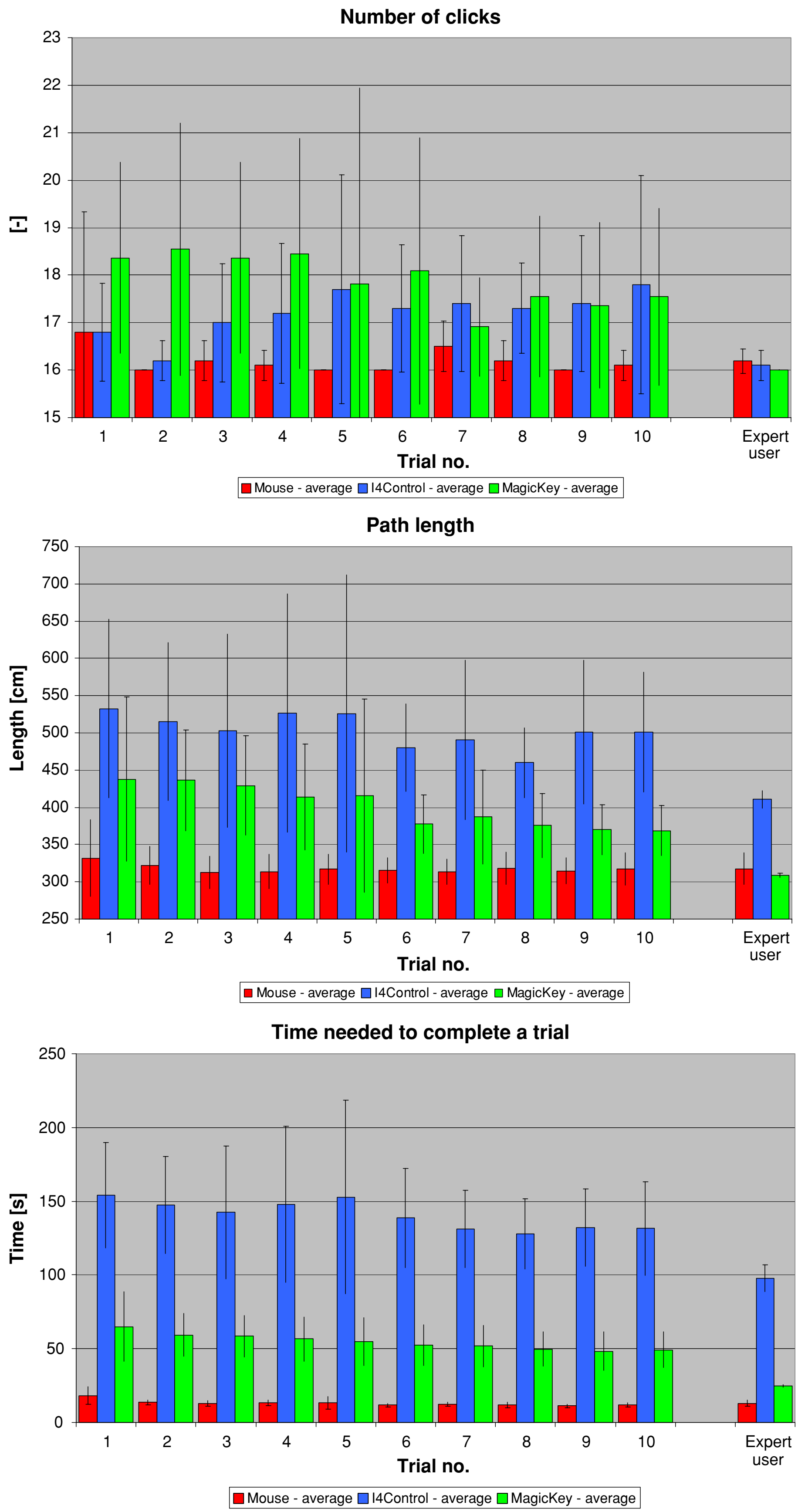

Fig. 17 Web browsing with I4Control®

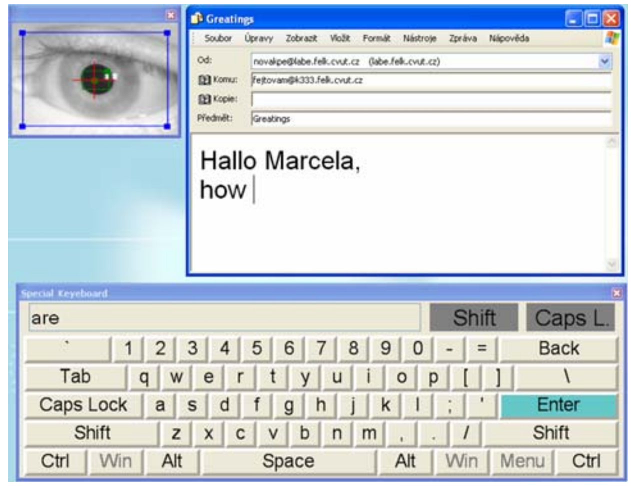

Fig. 19 Text entering with I4Control®

recent version) for text entering (Fig. 19) in the same way as it was described in Sect. 2 devoted to Magic Key. A necessary precondition for entering text in this way is the user's ability to apply eye movements for navigation of the cursor to the selected place on the computer screen. As there are more than 30 keys on the software keyboard, this requires precise positioning, and consequently, it results in a necessary increase of *take-up* time. Unfortunately, for some persons the required precision can become an insurmountable obstacle. To overcome this problem, two alternative solutions have been developed.

In the first one, the software keyboard is replaced by a simple dedicated application **IPad** [27]. Here, the full computer screen is divided into 13 boxes and the user gets access to the required letter of an alphabet by gradual division of the selected interval of ordered letters as offered by the left or right upper box—see Fig. 18. The selection is made by clicking anywhere in one of the boxes. Here, the

Fig. 18 IPad

take-up time and requirements for precise positioning are significantly reduced at the expense of speed of writing—five clicks are needed to reach the required letter.

The second solution offers a special SW keyboard (Fig. 19), where the cursor does not move smoothly and continuously, but it "jumps" in *discrete steps* from one key to the neighbouring one. The selected symbols first appear in the intermediate storage box (left to the "Shift") and the whole piece of text is moved into the text field of the selected application after "Enter" is pressed (clicked-off). The control keys (Ctrl, Caps lock, Shift, Alt) exhibit the behaviour of a switch. This means that once they are "pressed" they remain "on" until they are pressed again. This tool is also complemented by text prediction, which further decreases the number of keys necessary for writing the most frequent messages.

Another feasible option is to combine I4Control® with the Dasher system [3]. In this case, a proper language model has to be created first and the user has to get used to this specific form of writing. First experiments were very well accepted by a group of several volunteers who were able to write immediately without any training with the Dasher system using I4Control® at the same speed as if using joystick.

Discrete movement of the cursor proves useful even when working with Microsoft Internet Explorer. An implementation of a handy tool cooperating with the web browser is currently under development. Its aim is to help the user to list or skip through all the links available on the visited web page (Fig. 20). When the user enters a new web page, the program first automatically scans this web page, finds all web links used there and sets the cursor on the first link of the page. The text of the active link is highlighted by blinking (which is caused by regular changes between upper and lower case letters). The user can

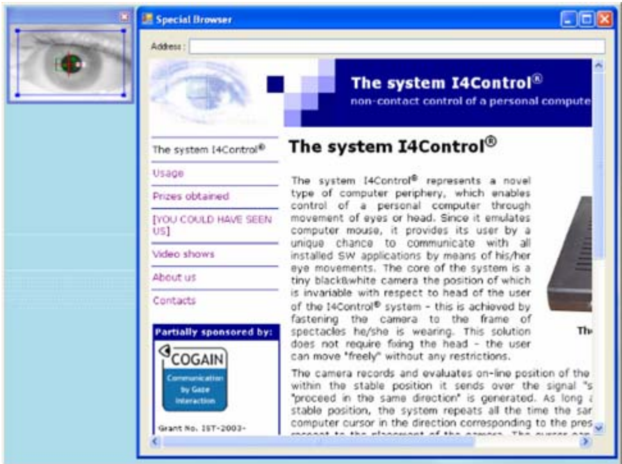

Fig. 20 Handy add-on for a web browser

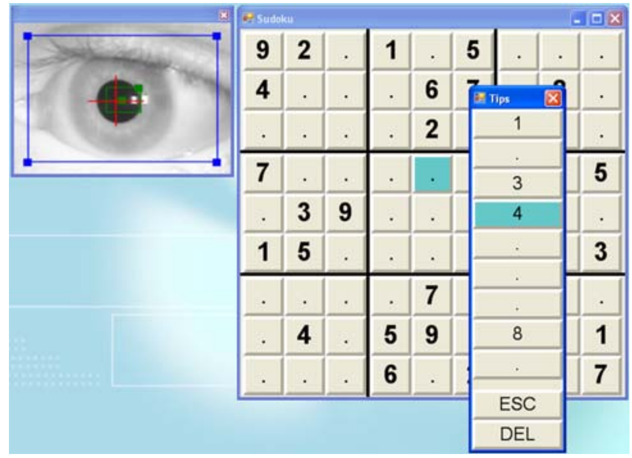

Fig. 22 Eye controlled SUDOKU puzzle

scroll down and up the page by looking in the corresponding direction (up and down). On the other hand, the horizontal movement of eyes is employed to ensure a different function: it switches among the available links which have been identified on the considered web page and which are available as a list which can be traversed. If the user looks to the left, the browser returns to the former link while if he/she looks right, the next link becomes active.

5.2 Entertainment and edutainment

Control signals produced by the I4Control® system can provide the user with direct access to many e-learning applications and provide an intellectually stimulating environment. Of course, first he/she has to master the ability to use eye movements to navigate the cursor sufficiently precisely. Well-chosen games can help in this training process and provide the user with confidence in using the gaze-based computer control. Several simple games were developed for this purpose. The introductory ones apply the discrete cursor movement described in Sect. 5.1.

An example of such a game is the Lloyd's fifteen (see Fig. 21), where the user is asked to order the numbers

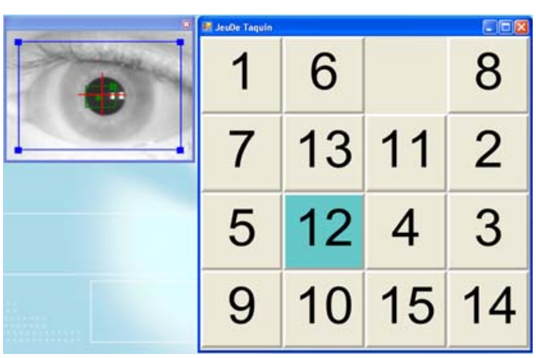

Fig. 21 Lloyd's 15

provided the only available move is "sliding the numbered box to the neighbouring empty space". The applied gaze-control is intuitive: the user moves or rather jumps from one box to the other as he/she moves he eyes. The box is selected by a longer blink corresponding to a mouse click. As a result, the selected box is moved to the neighbouring empty position.

Two types of mouse-controlled environment for solving **SUDOKU** puzzles are also used (see Fig. 22). In the first one, discrete control is applied in a way similar to Lloyd's fifteen. The second one [14] requires from the user that he/she applies the usual continuous control (described in the Sect. 3.2 Routine function) of the PC mouse movement on the screen of a computer.

The same gaze-related signals can even drive physical objects. To support this claim, a special toy-car, called **Gertie,** was designed (see Fig. 23), which is controlled directly by means of I4Control®. It is easy to specify the goal Gertie should reach—the goal can be, e.g., "to move Gertie into the soccer goal". Gertie1, the first version of the toy, was assembled from LEGO® and it used very natural coding of basic commands for the car. If the driver (=I4Control® user) looks up, the car moves straight forward, and goes backwards if he/she looks down. It turns to the side the user looks to, while eye blink sets the rotation of the locator. It reacts promptly to any change of user's eye position and one can easily estimate how far he/she is from the intended goal; thus it provides a well interpretable feedback to most types of users. Wireless communication with I4Control® is ensured through a bluetooth module in the most recent model (Gertie2).

The successful experiments with Gertie have proved that the potential application of I4Control® is not restricted to a computer. On the contrary, this system can step out from the virtual reality of a PC into the physical world. The construction of I4Control® ensures a fully stand-alone

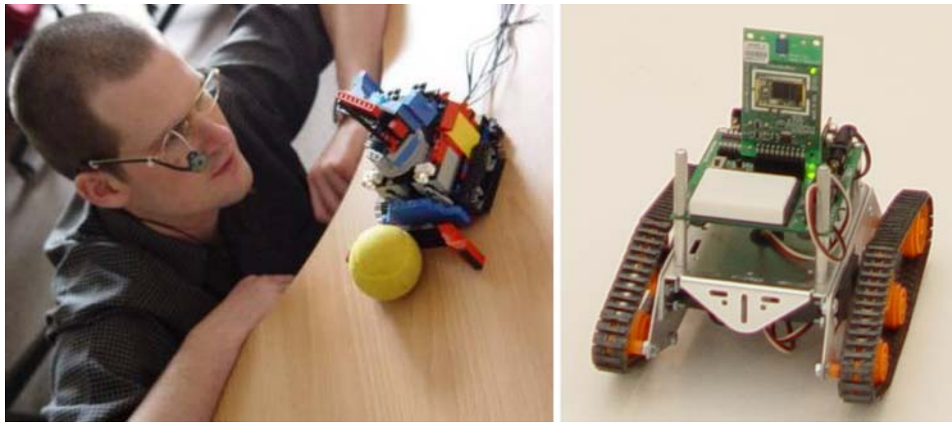

Fig. 23 An educational toy **a** Gertie 1, **b** Gertie 2

solution which is ready to function without any connection to a PC and which the user can wear in the same way as ordinary glasses all the day without any inconvenience. Currently, a new application area for our system is being tested: I4Control® is complemented by a simple bridge module which ensures communication with selected home appliances (light, radio or TV), so that the user can switch them on or off by a simple blink of an eye.

5.3 Challenges of the gaze controlled wheelchair

The functionality offered by the I4Control® seems to provide a good starting point for an ambitious goal to design a gaze-based control system for an electric wheelchair. Seemingly, this task is closely related to that of driving Gertie, the toy. This is true as far as the navigation is concerned. Numerous new problems arise, however, in connection with the question of how to guarantee the safety of the human user. Gaze control can create number of false or unintended signals caused by various reasons, for example, when the user

- suddenly looks in a different direction (towards the source of a suspicious noise)
- moves into a place with bad light conditions (and the system lacks the control signal)
- is forced to close his or her eyes due to irritation (dust, strong light, etc.)

It is clear that in real life conditions the gaze-controlled wheelchair cannot fully rely on its user only. One way of proceeding is to require confirmation of commands conveyed by gaze through an independent channel provided by an alternative approach, e.g., that used in [34]. Another approach is to consider a wheelchair equipped by a certain degree of autonomy offering to the user only a limited possibility to interfere through gaze control. One can imagine scenarios of various complexity, which have to be designed and tested—they can range from the case where mostly the user is in charge of the system equipped by some collision avoidance solution up to the situation where the chair moves autonomously to the destination described using gaze interaction. Given so many options, it seems that an appropriate combination of techniques will have to be customized according to the needs and constraints of each individual user. To build such complex systems, artificial intelligence techniques will have to be applied and enhanced. Even though it is hoped that AI can provide significant support for this purpose, the most important part of the development will still rely on close cooperation with end users and their communities.

6 Conclusions

Making use of existing technology—ordinary low-cost equipment—it was possible to develop new solutions, as described in this paper, that allow disabled people to control the PC mouse, and thereby any other associated computer application. These solutions achieve total mouse control, as they combine the high precision of the cursor movement, at the pixel level, with the high movement speed that relates to real-time movement of the user's head or eyes, and, above all, with the simple and absolute control of all types of clicks by eye control or dwell. There exist several other technical solutions for similar target group. There are three distinguishing features of the developed low cost solutions treated in this paper:

- They are able to communicate with any mouse controlled application—the experienced user can get direct access to all available SW tools and consequently he/she does not have to rely on special SW provided by the producer of assistive technology.
- Their calibration process is very quick—it does not take more than 2 min.
- They are not confined to a single default setting, but their control signals can be easily changed by taking the

choice from several options according to the needs of the individual user.

Both described applications, as a result of their efficient elaboration and implementation of their processing algorithms, do not interfere with the performance of the other computer applications. The number of tests performed, as well as its practical utilization by target users, has already shown the success of "Magic Key" which undeniably opens the doors into the world of using computers to many people. Effectively, for those whose independence is affected by disability, having an application that allows them to use the computer and access the Internet is, no doubt, a positive contribution to the quality of their lives.

As for future work, many projects are already being planned and developed, which emerged from the presented applications. The up-to-date news are published on-line on the corresponding web pages [17, 18]. Additional communication solutions are being investigated for people who suffer from strong spasms [18]. Research is also being undertaken towards improving the mobility of quadriplegic individuals [17], as well as towards meeting the needs of each individual user. More extensive testing of the developed systems is planned on the real life tasks, e.g., typing [12] or in unstable light conditions, which may cause problems to the current products. Hopefully, improved versions of the used algorithms will be inspired by the published research results [10, 13, 26, 31]. All new solutions will adhere to the principles that guided the development of the presented applications: the search for simple, low-cost but functional and efficient systems.

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