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MM denotes that a paper includes multimedia material and can be viewed at *www.ijrr.org*.

R. Barea
L. Boquete
L.M. Bergasa
E. López
M. Mazo
Electronics Department
University of Alcala
Campus Universitario s/n
28871 Alcalá de Henares
Madrid, Spain
barea@depeca.uah.es

Electro-Oculographic Guidance of a Wheelchair Using Eye Movements Codification

Abstract

In this paper we present a new method to guide mobile robots. An eye-control device based on electro-oculography (EOG) is designed to develop a system for assisted mobility. Control is made by means eye movements detected using electro-oculographic potential. Using an inverse eye model, the saccadic eye movements can be detected and know where the user is looking. This control technique can be useful in multiple applications, but in this work it is used to guide a wheelchair for helping people with severe disabilities. The system consists of a standard electric wheelchair, an on-board computer, sensors and a graphical user interface. Finally, we comment on some experimental results and conclusions about electro-oculographic guidance using ocular commands.

KEY WORDS—electro-oculographic potential, eye model, control system, handicapped people, wheelchair

1. Introduction

Assistive robotics can improve the quality of life for disabled people. Nowadays, there are many help systems to control and guide autonomous mobile robots. All these systems allow their users to travel more efficiently and with greater ease (Mazo et al. 2001). In the last few years, the applications for developing help systems for people with several disabilities have increased, improving the traditional systems. These include videooculography (VOG) systems or infrared oculography (IROG) based on detection of the eye position using a camera (Lahoud and Cleveland 1994). There are several techniques based on voice recognition for detecting basic commands to control some instruments or robots. The joystick (sometimes a tactile screen) is the most popular technique used to control different applications by people with limited upper body mobility, but it requires fine control, which the person may have difficulty in accomplishing. All these techniques can be applied to different people according to their degree of disability, always using the technique or techniques more efficiently for each person.

This work is included in a general purpose navigational assistant in environments with accesible features to allow a wheelchair to pass. This project is known as the SIAMO project (SIAMO 1999). A complete sensory system has been designed, made up of ultrasonic, infrared sensors and cameras in order to allow the detection of obstacles, dangerous situations and to generate a map of the environment. Then, the control and navigation module has to guarantee a comfortable path tracking. Experimental results with users have shown that these demand interaction with the system, making the robotic system semi-autonomous rather than completely autonomous.

Our goal is the development of a robotic wheelchair system based on electro-oculography (Gips et al. 1996; Barea et al. 1999). Our system must allow users to tell the robot where to move in gross terms, and it will then carry out that navigational task using common sensical constraints, such as avoiding collision.

This paper is divided as follows. In Section 2 we describe the electro-oculography technique used to register the eye movement and the gaze. In Section 3 an eye model based on electro-oculography is proposed. In Section 4, we comment on the visual control system. In Section 5, we show some guidance results, and in Section 6 we put forward our main conclusions. Section 7 lays down the main lines of work to be followed in the future.

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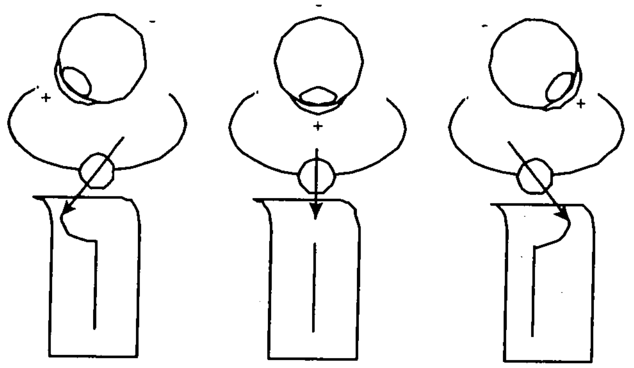


Fig. 1. Ocular dipole.

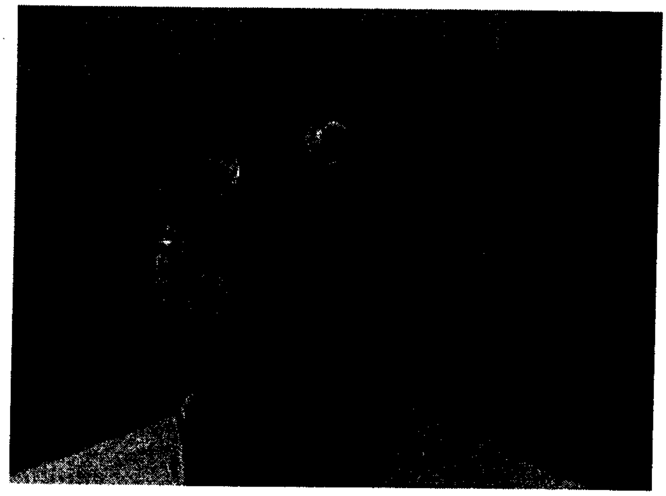


Fig. 2. Placement of the electrodes.

2. Electro-Oculographic Potential

A survey of eye movements recording methods can be seen in Glenstup and Engell (1995) where the main advantages and drawbacks of each one are described. In this work, the goal is to sense the electro-oculographic potential (EOG) because it presents a good face access, it has good accuracy, resolution and a great range of eye displacements, it works in real time and it is cheap. Our discrete electro-oculographic control system (DECS) is based on recording the polarization potential or corneal-retinal potential (CRP) (Nicoulau, Burcet, and Rial 1995). This potential is commonly known as an electro-oculogram. The EOG ranges from 0.05 to 3.5 mV in humans and is linearly proportional to eye displacement. The human eye is an electrical dipole with a negative pole at the fundus and a positive pole at the cornea. Figure 1 shows the ocular dipole.

This system may be used for increasing communication and/or control. The analog signal from the oculographic measurements has been turned into a signal suitable for control purposes. The derivation of the EOG is achieved by placing two electrodes on the outer side of the eyes to detect horizontal movement and another pair above and below the eye to detect vertical movement. A reference electrode is placed on the forehead. Figure 2 shows the placement of the electrodes.

The EOG signal changes by approximately 20 μV for each degree of eye movement. In our system, the signals are sampled ten times per second.

The recording of the EOG signal has several problems (Jacob 1996). Firstly, this signal is seldom deterministic, even for same person in different experiments.The EOG signal is a result of a number of factors, such as eyeball rotation, eye movement, eyelid movement, different sources of artifact, e.g., EEG, electrode placement, head movements, influence of the luminance, etc.

For these reasons, it is neccesary to eliminate the shifting resting potential (mean value) because this value changes. To avoid this problem, it is necessary to use an ac differential amplifier where a high pass filter with a cutoff at 0.05 Hz and a relatively long time constant is used. The amplifier used has programmable gain of 500, 1000, 2000 and 5000.

3. Eye Model Based on EOG (BIDIM-EOG)

Our aim is to design a system capable of obtaining the gaze direction by detecting the eye movements. In view of the physiology of the oculomotor system, the modeling thereof could be tackled from two main points of view: (a) anatomical modeling of the gaze-fixing system, describing the spatial configuration thereof and the ways the visual information is transmitted and processed; (b) modeling of the eye movements, studying the different types of movements and the ways of making them.

On the basis of the physiological and morphological data of the EOG, we propose a model, the bi-dimensional dipolar model EOG (BiDiM-EOG), of the ocular motor system based on electro-oculography (Figure 3).

The "filter" block has as its mission to eliminate the problems associated to the electro-oculographic signal. These problems are due mainly to its variability, as well as possible interferences on the same one, such as the effect of blinking, facial movements (movements of the brows, of the mouth, the action of chewing, of speaking, of smiling, etc.) and devices or interferences taken place by other biopotentials (EMG, EEG) or electrode displacements on the skin. It should also eliminate the possible power supply interference (at a frequency of 50 Hz). At the same time, it is suitable to develop algorithms for improving the signal/noise relationship. Keeping this in mind, the "filter" block should be compound for a high pass filter with a cutoff frequency of 0.05 Hz that eliminates

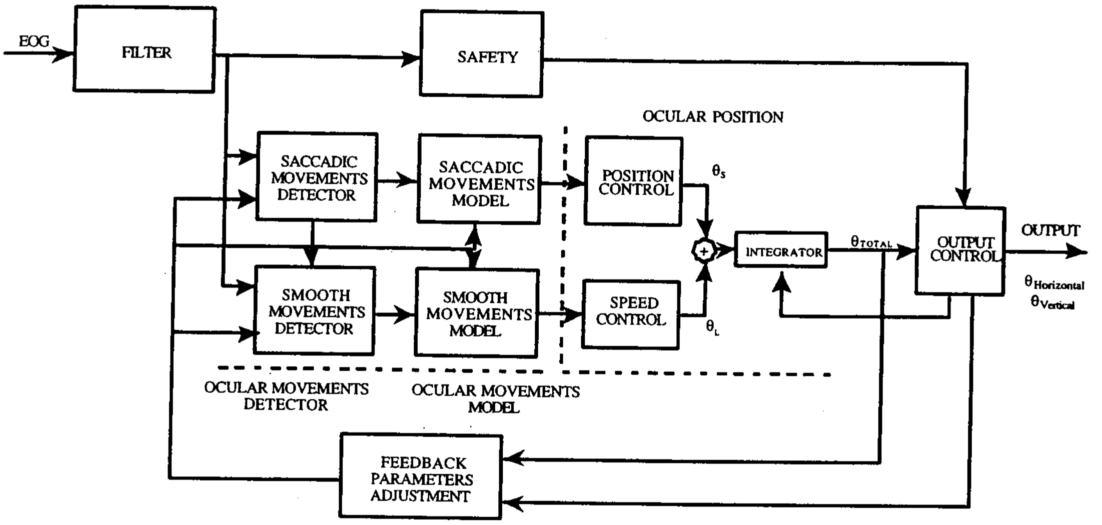


Fig. 3. BiDiM-EOG.

the continuous component, and therefore its variability. To eliminate high-frequency interferences on the EOG, a low pass filter with a cutoff frequency of 35 Hz is used. Finally, to enhance the signal and to improve the characteristics, an ALE_LMS (adaptive line method using least-mean squares) algorithm based on a Wiener filter is used (Akay 1994). The internal structure of the "filter" block is shown in Figure 4.

The "ocular movement detector" block allows us to separate saccadic and smooth eye movements using the EOG derivative, as can be seen in Figure 5.

The "ocular movement model" block models the eye movement. For simplicity, a lineal saccadic model is chosen. This model obtains a good accuracy in the detection of saccadic movement (with an error of less than 2°) (Barea 2001). The smooth movement model block corresponds to a foveal persecution model (Barea 2001).

The final calculation of the ocular position inside its orbit is carried out in the "ocular position" block. If a saccadic movement is detected, a position control is used; i.e., the displacement angle corresponding to this movement is determined and added to the angle corresponding to the previous position of the eye. Whereas if a smooth movement takes place, a speed control is used, i.e., the speed, duration and direction of the movement is calculated, allowing us in this way to calculate the displacement angle corresponding to the smooth movement. The final position (angle) is calculated as the sum of the saccadic and smooth movements. Figure 6 shows this process.

The security block detects when the eyes are closed and, in this case, the ouput is disabled. Moreover, the model has to adapt itself to the possible variations of acquisition conditions (electrode placement, electrode-skin contact, etc.). To do this, the model parameters are adjusted in accordance with the angle detected.

A person, in a voluntary way, can only make saccadic movements if he tries to follow a moving object. Therefore, to control some interface by means of eye movement codification, it is convenient to focus the study on the detection of saccadic movements (rapid movements). This way, the MD-BEOG can be simplified and the detection of smooth eye movements can be eliminated. Figure 7 shows the new eye model for this case.

The process followed (using a linear saccadic eye model) can be observed in Figure 8. This figure shows the results of a process in which the user made a sequence of saccadic movements from $\pm 10°$ to $\pm 40°$ in horizontal derivation (shift). It can be seen that the derivative of the electro-oculographic signal allows us to determinate when a sudden movement is made in the eye gaze. This variation can be easily translated to angles (Figure 8(d)). The results obtained have demonstrated that this model obtained an error of less than 2° in saccadic movements in tests carried out for more than one working hour (Barea 2001). These results will be more accurate when the process of the initial calibration of the system, which should adapt to each user, is improved.

In the following sections, we show the current results obtained in the Electronics Department, University of Alcalá. Although in this paper we comment on the results obtained for the guidance of a wheelchair (help with mobility), other applications have been developed to increase facilities in people communication, such as an electro-oculographic mouse (Barea et al. 2000a).

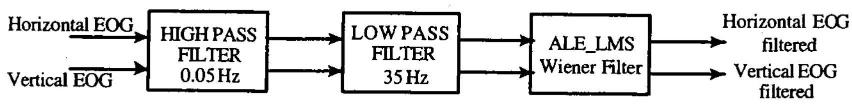


Fig. 4. Filter block structure.

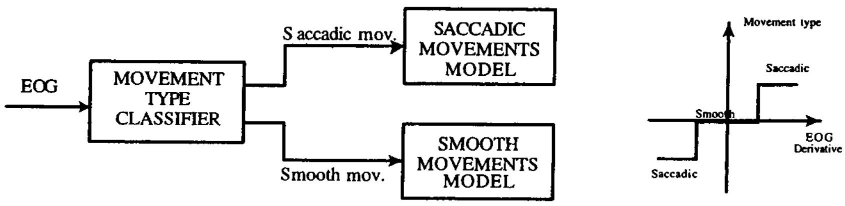


Fig. 5. Ocular movement detector block.

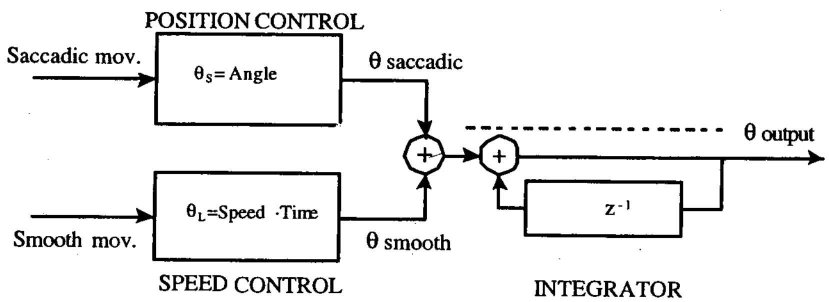


Fig. 6. Ocular position block.

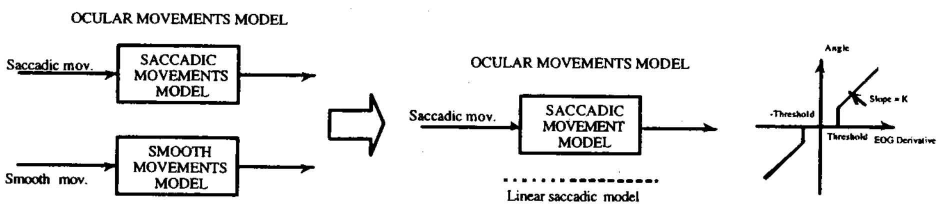


Fig. 7. Ocular movement model for eye movement codification.

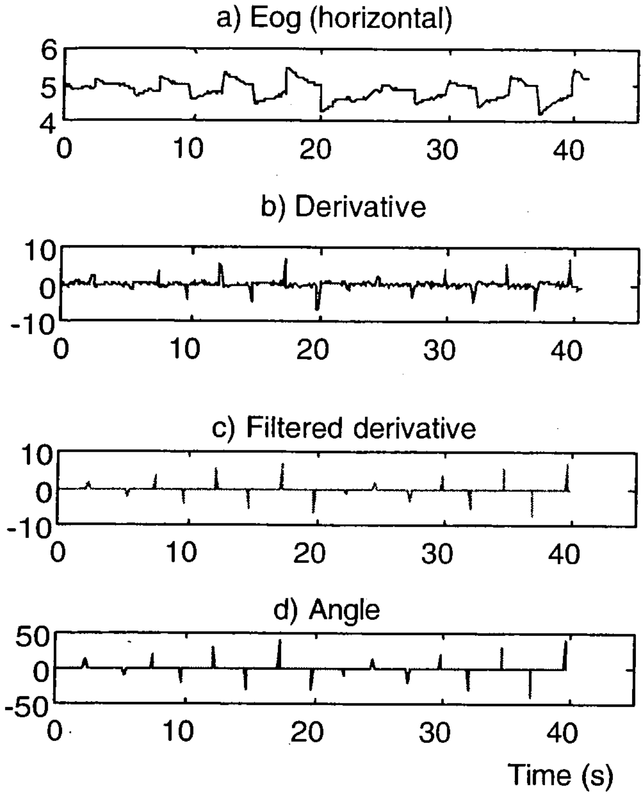


Fig. 8. Process results for gaze angle detection.

4. Guidance of a Wheelchair Using Commands Generated by Eye Movements Detected Using Electro-Oculography

The aim of this control system is to guide an autonomous mobile robot using the position of the eye in its orbit by means of the EOG signal. In this case, the autonomous vehicle is a wheelchair for disabled people. Figure 9 shows the wheelchair prototype used. Figure 10 shows a diagram of the control system. The EOG signal is recorded using Ag-AgCl electrodes and these data, by means of an acquisition system, are sent to an on-board PC (little board), in which they are processed to calculate the gaze direction or eye movements. Then, in accordance with the guidance control strategy and the ocular movement detected, the corresponding control command is activated. This generates the linear and angular speeds, which are sent to the low level control of the wheelchair. It can be seen that there is a visual feedback in the system by means of a tactile screen in front of the user.

The low level control of the prototype is shown in Figure 11. The mechanical structure of the wheelchair consists of a platform (measuring $100 \times 80 \times 58\,\text{cm}^3$ and weighing approximately 35 kg) on two motor wheels and two idle wheels.

Fig. 9. Wheelchair.

The motor wheels, with a radius $R_d = 16$ cm and separated by a distance $D = 54$ cm, have independent traction provided by two DC motors. There is a distributed control system based on the LonWorks technology of ECHELON (SIAMO 1999). In this way, the communication between the PC and the motor drivers of the right and left wheels is carried out by means of a PC LonTalk Adapter (PCLTA) through a dynamic exchange dates (DDE) connection (Echelon 1995). The low level control of the electronic system for controlling the DC traction motor is implemented with a PID (programmed into Neuron Chip) and its mission is to ensure that the linear speeds of the right-hand and left-hand wheels (w_r, w_l) are approximately those indicated on the electronic control cards. Given that this control loop cannot be sufficient in itself to ensure reliability in the wheelchair movements (Boquete et al. 1999), another external loop can be implemented based on a neural control (Boquete et al. 2001).

Figure 12 shows the user interface where the commands that the user can generate are forward, backwards, left, right and stop.

To control the robot movements, there are multiple options: direct access, semi-automatic and automatic sweep (scan) and eye movement codification.

Previously, we have studied the direct access guidance (Barea et al. 1999) and automatic and semiautomatic "scan" (Barea et al. 2000b). In direct access guidance, the user can see the different guidance commands on a screen (laptop) and can select them directly by gaze direction. In this way, when the user looks somewhere, the cursor is positioned where he is looking, and then the user can select the action to control the wheelchair movements. The actions are validated by time; that is, when a command is selected, it is necessary to remain looking at it for a period of time to validate the action. In "scan" guidance, it is necessary to perform an eye movement (a "tick") to select among the different commands presented

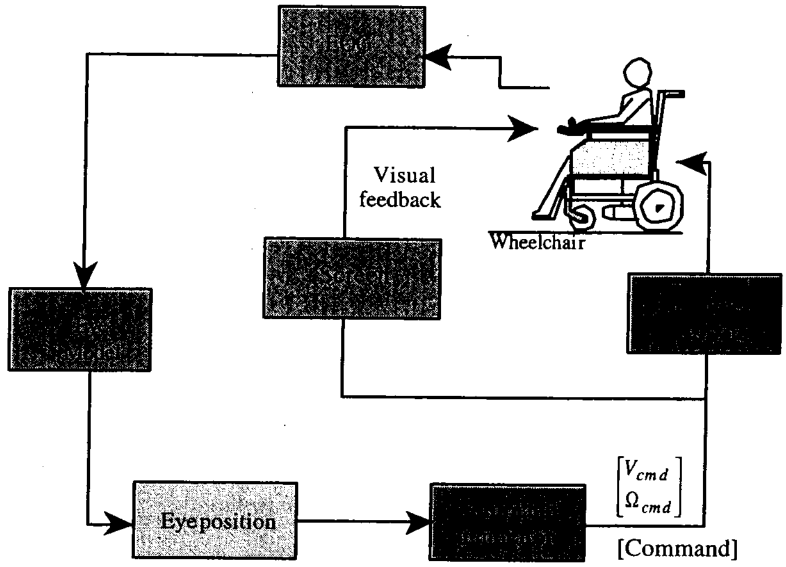


Fig. 10. Guidance system.

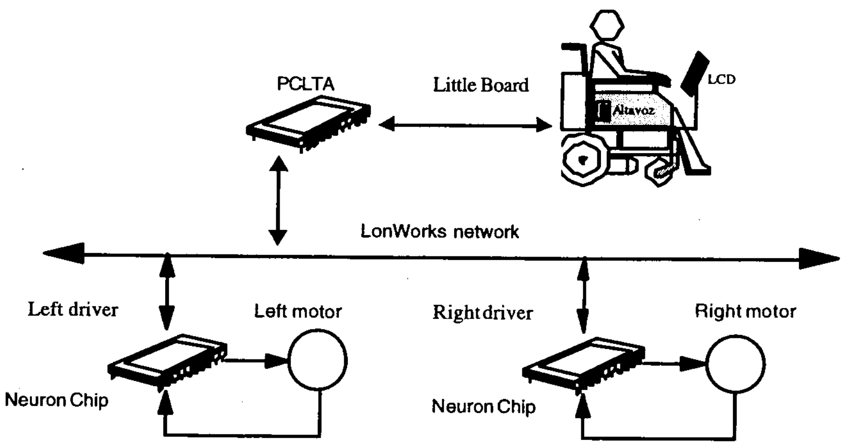


Fig. 11. Low-level control.

in the screen. The actions are validated by time; that is, when a command is selected, if another "tick" is not generated during a time interval, the command is validated and the guidance action is executed.

The guidance based on eye movement codification has different options, such as continuous guidance and on-off activation commands. The on-off activation consists of detecting some ocular action and executing an associated guidance command. The guidance commands are effected by means of the following ocular actions: UP, the wheelchair moves forward; DOWN, the wheelchair moves backwards; RIGHT, the wheelchair moves to the right; LEFT, the wheelchair moves to the left. Speeds fixed per event are used. To finish the execution of this command, it is enough to generate another ocular action (in this case, this ocular action is considered as a deactivation command) and the system reaches a rest state.

In this paper, we focus our work on the continuous control technique because it allows us to generate a simple code for controlling the wheelchair.

This control attempts to emulate the intuitive control that a non-handicapped person makes when he drives a mobile. This system controls the linear speed just as a car accelerator and

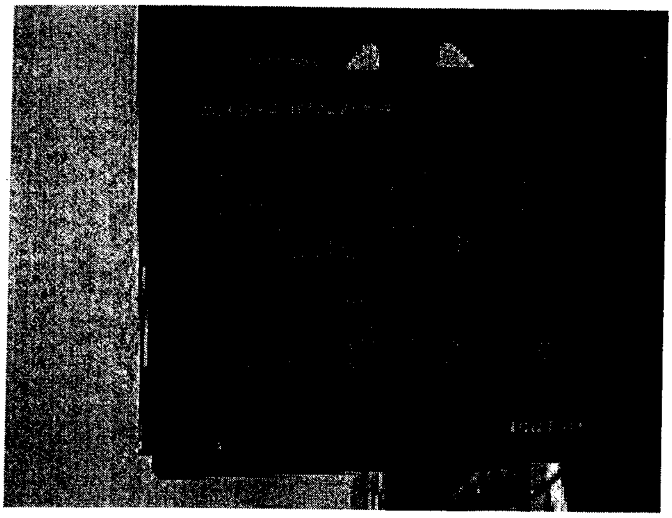


Fig. 12. User interface.

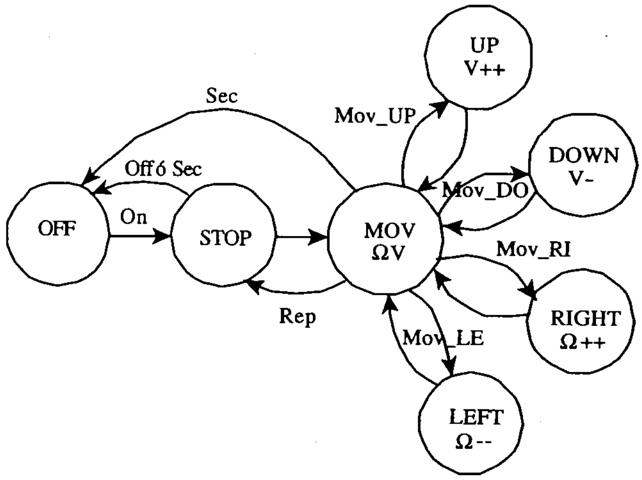


Fig. 13. State machine.

the angular speed just as the steering wheel of a car. For this, we have implemented the following movement commands:

UP, linear speed increase (V++);
DOWN, linear speed decrease (V–);
RIGHT, angular speed increase (Ω++);
LEFT, angular speed decrease (Ω–).

Command generation is coded using a state machine that establishes the state (command) where the system is working (Figure 13). As can be seen, when the user looks up (Mov_UP) the linear speed increases (V++). On the other hand, when the user looks down (Mov_DO) the linear speed decreases (V–). These increases and decreases in linear and angular speed must be adjusted to the user's possibilities. In this way, there exist three speed controls: (a) the increment or decrement are fixed; (b) a proportional number of the same commands during an interval of time, which gives a greater acceleration and deceleration of the system; (c) fuzzy control that selects the linear and angular speed as a function of V and Ω selected by the user and the trajectory that must be followed. This control allows us to reduce the linear speed if the angular speed is large and, in this way, closed curved trajectories are not allowed, which can be dangerous for the user. Besides, there are alarm and stop commands for dangerous situations that permit the user to stop (Rep) and switch off (Off) the system.

The linear and angular speeds selected by the user are converted to linear speeds of the right-hand and left-hand wheels (w_r, w_l) in accordance with

$$w_r = V - \frac{D \cdot \Omega}{2} \quad w_l = V + \frac{D \cdot \Omega}{2}, \qquad (1)$$

where V is linear speed, Ω is angular speed and D is the distance between motor wheels.

5. Experimental Results

In this section, some examples of continuous control are shown.

First, we give an example of guidance in an electronics department laboratory. Figure 14 shows the trajectory obtained using EOG continuous control, Figure 15 shows EOG horizontal and vertical derivations, Figure 16 shows the linear and angular speeds of the wheelchair, and Figure 17 shows a sequence of images of the guidance.

Secondly, in Figure 18 (extension 1, 2) we show an example of guidance between two rooms through a corridor, where we can see the trajectory followed by the wheelchair and different images of the guidance.

At present, we are starting to attempt this control with people with disabilities, but we consider that it is not difficult to learn the control commands. Learning to use this system must be an acquired skill. Some studies have shown that disabled people usually require about 15 min to learn to use this type of system (Gips et al. 1996).

In principle, we have developed an electro-oculographic guidance simulator of the wheelchair on which the disabled person trains and learns the operation of the real one and acquires enough skill to guide the prototype in a real environment. The second phase is learning to control the real prototype. Figures 19 (extension 3) and 20 show the graphical simulator interface and how a disabled user can control it.

The operation of this simulator is very simple. First, the user selects the origin (x_{ini}, y_{ini}, θ_{ini}) and later the destination (x_{end}, y_{end}, θ_{end}). Obstacles can be introduced that will be avoided during guidance. The simulator, in an automatic

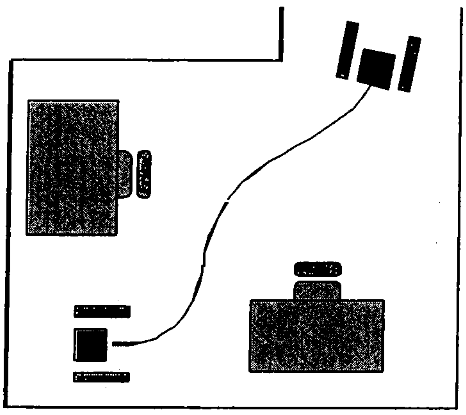


Fig. 14. Trajectory generated.

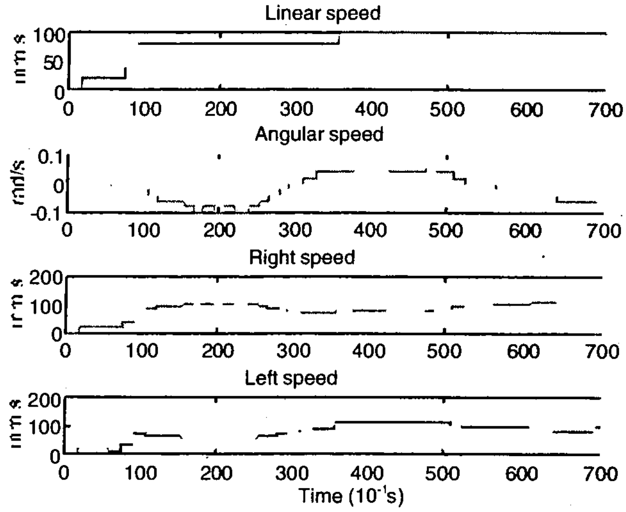


Fig. 16. Guidance speed.

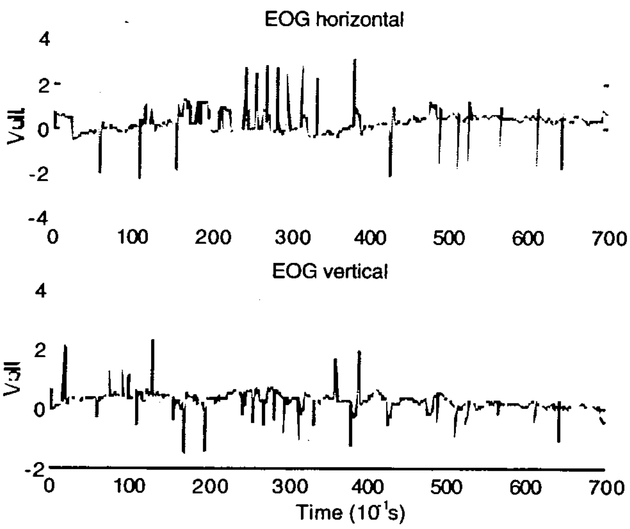


Fig. 15. EOG signal.

way, generates a possible trajectory that the user can follow (Figure 20(a)). The system allows us to configure all guidance parameters and to adapt these to the disabilities or the user's possibilities. Later, it moves to execution mode. In this way, the user guides the wheelchair following the trajectory wanted by means of the ocular commands detected using electro-oculography. When the desired objective of the system is reached, it stops. The followed trajectory can be observed on the screen (Figure 20(b)).

The results obtained in the learning and training period show that the required time is very reduced, with good control of the system possible in under half an hour. Nevertheless, these times vary with the user's possibilities, their disabilities and their skill when controlling the system. These results are successful due mainly to the simplicity of the guidance commands set and to the easy realization of the ocular actions (eye movements) associated with the same ones.

Moreover, we need several alarm and stop commands for dangerous situations. These codes can be generated by means of the blink and alpha waves in EEG or EOG signal processing to detect when the eyelids are closed. In this case, as these commands are critical (the user's security can depend on them) it is necessary to adapt them in short to each user. Nevertheless, the tests carried out show that the necessary modifications are minimum.

On the other hand, the robotic wheelchair system (real prototype) must be able to navigate indoor and outdoor environments and should switch automatically between navigation modes for these environments. Therefore, this whole system can be applied to different navigation modes as a function of disability degree, using always the techniques most efficient for each person. It is necessary to use different support systems to avoid collisions and the robotic system can switch automatically in order to control the system in an autonomous form. For example, if the user loses control and the system is unstable, the wheelchair should switch and obtain the control system.

The real prototype has been tested by five users and the main conclusions about this guidance type are as follows.

1. The guidance strategy has to be adapted to the ability of the user.

2. One of the most important factors is the self-confidence of the user and the user's ability to guide the wheelchair.

3. The interface has to be comfortable for the user.

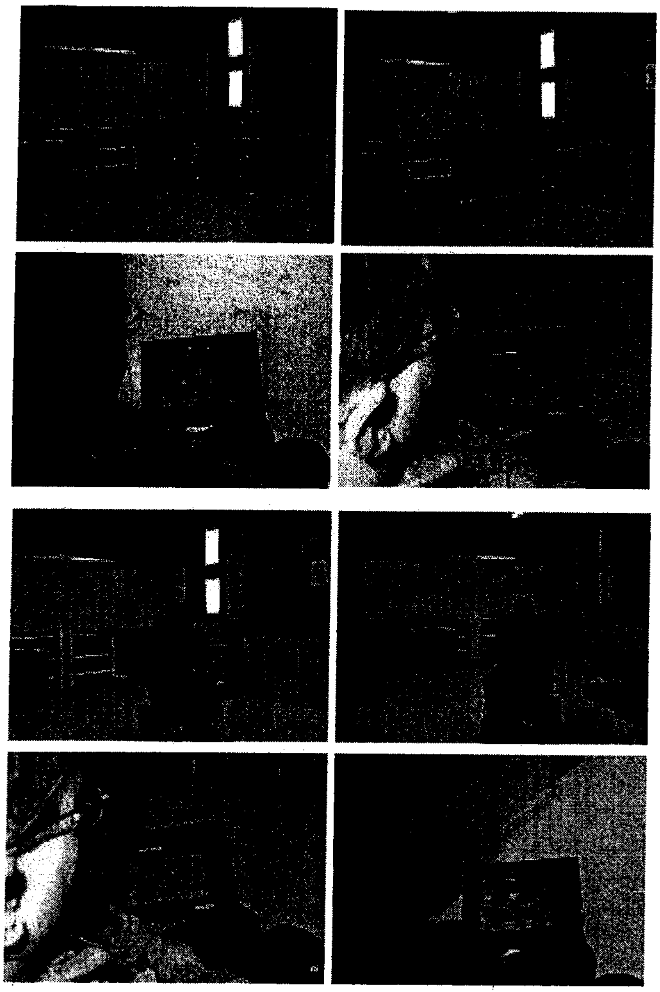


Fig. 17. Trajectory and visual interface.

4. Guidance using continuous control over linear and angular speeds of the wheelchair is more comfortable than using simple commands (forward, backwards, right and left).

6. Conclusions

This research project is aimed towards developing a usable, low-cost assistive robotic wheelchair system for disabled people. In this paper, we present a system that can be used as a means of control allowing the handicapped, especially those with only eye-motor coordination, to live more independent lives. Eye movements require minimum effort and allow direct selection techniques, which increases the response time and the rate of information flow. Some previous wheelchair robotics researches are restricted to a particular location and, in many areas of robotics, environmental assumptions can be

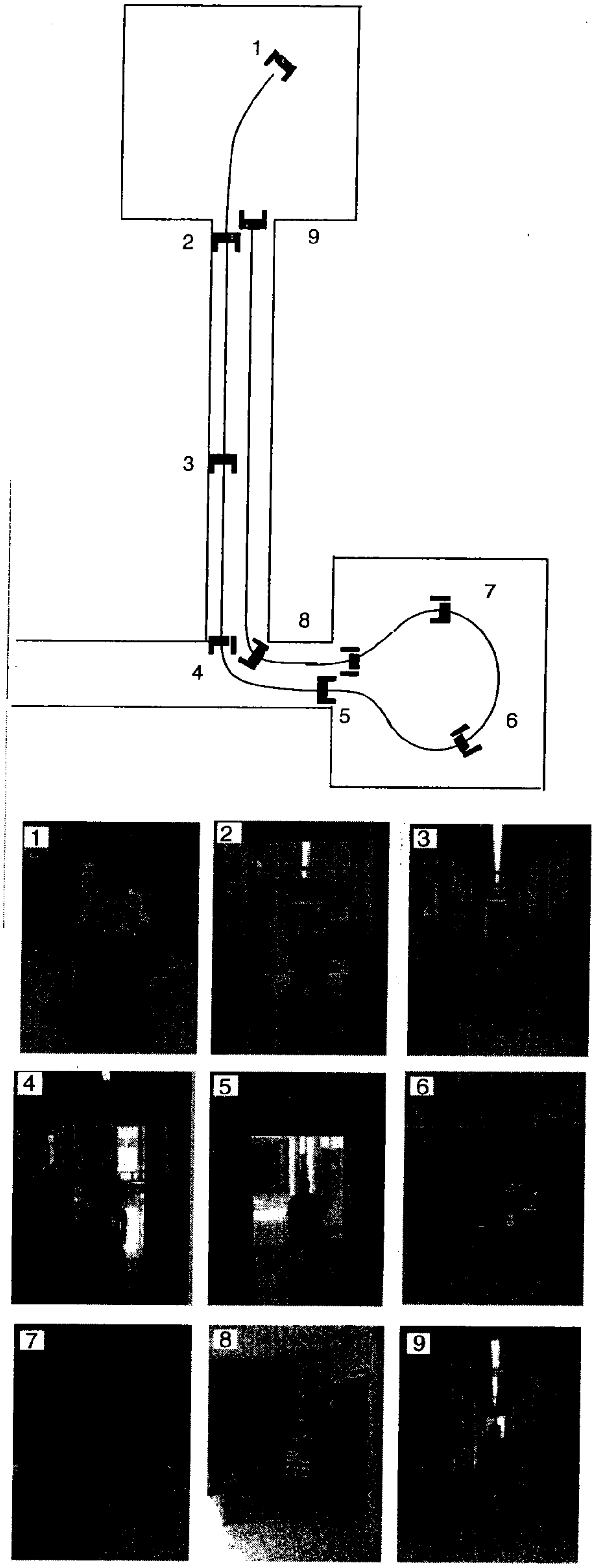


Fig. 18. Trajectory and sundry images.

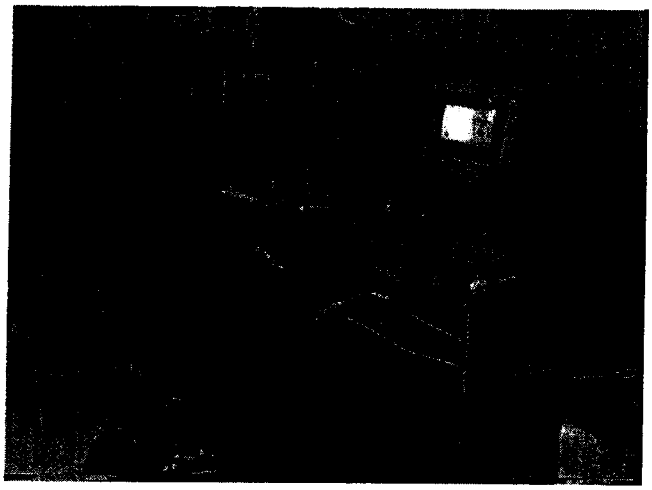
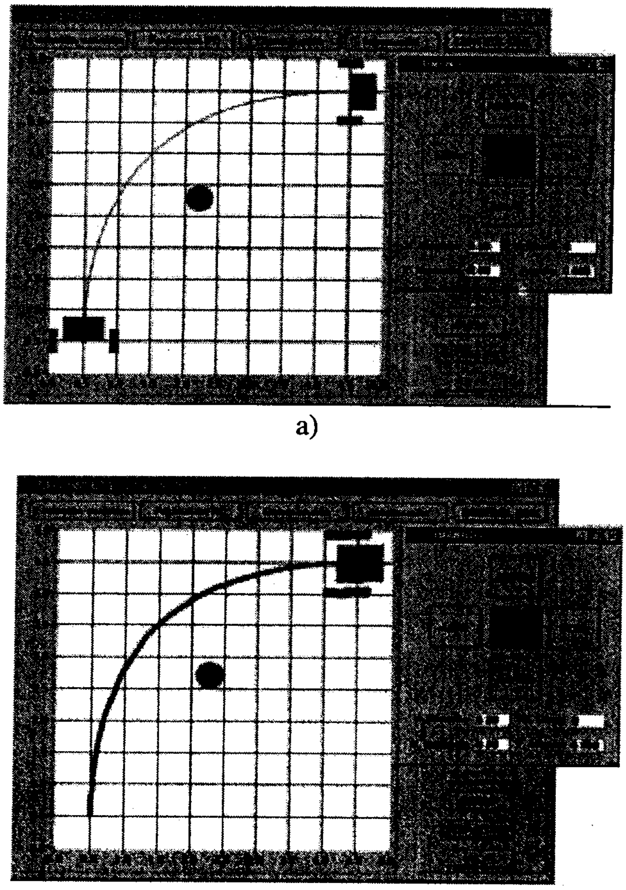


Fig. 19. Training process.



a)

b)

Fig. 20. Results of training process.

made that simplify the navigation problem. However, a person using a wheelchair and the EOG technique should not be limited by the device intended to assist them if the environment has accessible features. The continuous control based on EOG permits wheelchair users to guide the wheelchair with a certain degree of comfort. The results obtained during the training process of this system show that the required training time is very reduced, with good control of the system possible in under half an hour.

This work is included in a general purpose navigational assistant based on a wheelchair, where a complete sensory system has been designed in order to allow the detection of obstacles, dangerous situations and the generation of a map of the environment. As a function of the conditions of the environment and of the guidance strategy selected, as well as of the guidance commands generated by the user, the control and navigation module guarantees a comfortable tracking of the trajectory or command defined by the user.

7. Future Work

Keeping in mind that there is a tendency toward the use of graphical user interfaces (GUIs) in the near future, it is necessary to develop new systems that allow disabled users of computers to continue using computers. One of our goals is to develop an eye-operated joystick based on electro-oculography (electro-oculographic mouse) that permits control of any computer program based on a graphical interface.

Other options for increasing the quality of life for disabled people consists of developing personal robotics aids that serve three primary functions, as follows.

- Guidance indoors. Mobility problems are a major problem for elderly or disabled people. For this reason, robots can be developed for guiding disabled or elderly people indoors or outdoors.
- Safeguarding. Handicapped people can pose great risks in the home. Loss of stability and problems with walking are leading problems for people living independently. This risk can be reduced through systematic monitoring.
- Social interaction. Mostly, elderly or disabled people have problems with social interaction. This can cause loss of health. Robots can augment humans, either by directly interacting with a person, or by providing a communication interface between different people.

To accommodate these needs, we have developed an experimental robot aid based on the commercial platform PeopleBot of ActivMedia Robotics (2000), equipped with an onboard PC connected to the Internet via a wireless Ethernet link, 16 ultrasonic range finders for detecting the environment, a

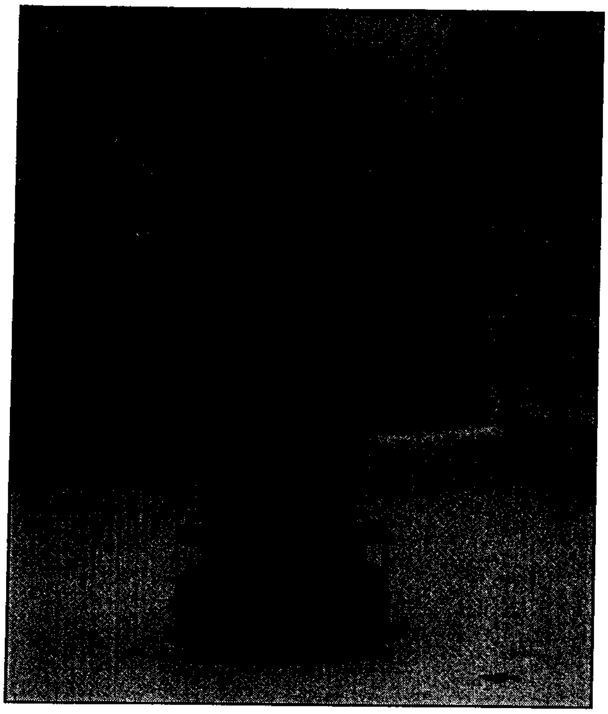


Fig. 21. Prototype based on the commercial platform PeopleBot.

CCD color camera with pan and tilt (Sony EVI-D31) connected to a frame grabber (Imagination PCX200) for image processing and high-bandwidth communication. A laptop and a speech recognition system are incorporated as communication interfaces. Figure 21 shows an image of the prototype.

This work is included in a general personal robotics aid in which we develop two projects called "PIROGAUCE" (2001) and "ANDABOT" (2002).

Appendix: Index to Multimedia Extensions

The multimedia extension page is found at http://www.ijrr.org.

Table of Multimedia Extensions

Extension	Type	Description
1	Video	Corridor: example of a wheelchair guidance in a corridor using electro-oculography
2	Video	Hall: example of a wheelchair guidance in a hall using electro-oculography
3	Video	Simulator: example of training process using a graphical simulator

Acknowledgments

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Electro-Oculographic Guidance of a Wheelchair Using Eye Movements Codification

R. Barea, L. Boquete , L. M. Bergasa, E. López and **M. Mazo** *Electronics Department, University of Alcala, Campus Universitario s/n, 28871 Alcalá de Henares, Madrid, Spain*

In this paper we present a new method to guide mobile robots. An eye-control device based on electro-oculography (EOG) is designed to develop a system for assisted mobility. Control is made by means eye movements detected using electro-oculographic potential. Using an inverse eye model, the saccadic eye movements can be detected and know where the user is looking. This control technique can be useful in multiple applications, but in this work it is used to guide a wheelchair for helping people with severe disabilities. The system consists of a standard electric wheelchair, an on-board computer, sensors and a graphical user interface. Finally, we comment on some experimental results and conclusions about electro-oculographic guidance using ocular commands.

Multimedia Key

= Video = Data = Code = Image

Extension	Type	Description
1		Example One: Corridor: example of a wheelchair guidance in a corridor using electro-oculography. (NA)
2		Example Two: Hall: example of a wheelchair guidance in a hall using electro-oculography. (NA)
3		Example Three: Simulator: example of training process using a graphical simulator. (NA)

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