Remote Control of an Autonomous Robotic Platform Based on Eye Tracking

Alexandru PĂSĂRICĂ[1], Gabriela Gladiola ANDRUSEAC[2*], Ioana ADOCHIEI[3], Cristian ROTARIU[2], Hariton COSTIN[2,4], Felix ADOCHIEI[5]
[1]*Gheorghe Asachi Technical University, Iaşi, Romania*
[2]*Grigore T. Popa University of Medicine and Pharmacy, Iasi, Romania*
[3]*Military Technical Academy, Bucharest, Romania*
[4]*Institute of Computer Science of Romanian Academy, Iasi Branch, Romania*
[5]*Politehnica University of Bucharest, Romania*
**gladiola.andruseac@bioinginerie.ro*

Abstract—**Eye-tracking devices are currently used for improving communication and psychosocial status among patients with neuro-motor disabilities. This paper presents the experimental implementation of a control system for a robotic platform using eye tracking technology. The main system is based on an eye tracking subsystem that uses the circular Hough transform algorithm. A central processing unit performs the data transmission between the user and the robotic platform. Experimental tests were conducted to determine the device's performances and usability for patients with neuro-motor disabilities. Moreover, the test results were used to determine the control system learning curve. We created a data base containing information on the robotic platform processing time and precision of movement for improving the platform's performances.**

Index Terms—**biomedical engineering, computer aided analysis, image processing, image segmentation, robot control.**

I. Introduction

Assistive technology is the area of research that focuses on developing new methods and devices meant to reintegrate people with disabilities into society, by helping them to interact with their environment. Assistive technology is designed to provide assistance to people who have problems in carrying out daily activities, whether these problems are present from birth or had occurred during life because of medical conditions. The use of such technology is determined by the ratio of improvement of the quality of life of the user [1]. These technologies can either have rehabilitation role, used to help restore the natural function of the organism such as reading tools, learning disabilities programs and text synthesizers, or used to replace irrecoverable functions of human organism, such as Braille embossers, sip and puff systems, trackballs or eye tracking systems [2]. Assistive technologies can transform these people lives by allowing them to perform form simple to complex everyday tasks.

The main goal of this research is to improve the life and health of people with neuro-motor disabilities that present cognitive function and their total or partial reintegration in society. According to the statistics published on June the 3rd 2016 by the Romanian Ministry of Labour, Family, Social Protection and Elder, 3.49% of the Romanian citizens residing in Romania presented a disability, and 23.80% of these suffered from a physical disability: 36.31% were diagnosed with severe disabilities, 52.06% with accentuated disabilities and 11.63% with medium or small handicap. Of this total, 97.7% were in the care of families and/or living independent (not institutionalized) while the remaining 2.3% were in public support for adults with disabilities [3].

By combining different types of technologies, advanced integrated systems can be achieved. We developed a robotic platform with an eye tracking controlling system to offer patients with neuro-motor disabilities the possibility to remotely control a moving platform [4].

The proposed system is based on an eye tracking subsystem, that uses the circular Hough transform algorithm [5], and a central processing unit. For this application we developed a robotic platform based on Mindstorms EV3 development kit. We selected this platform because it is highly customizable and provides advanced programming features [6].

A high performance camera is mounted on the robotic platform for transmitting a live video to the user screen. The eye tracking subsystem functions are: to identify the user's eye movement and to translate these gaze direction changes into the robotic platform's movements. To determine the system's performance, we conducted a series of tests in laboratory conditions on healthy subjects [7], [8]. The goal of these tests was to determine the learning curve necessary to use such a system and the behaviour of the system on the processing time and precision of movement of the robotic platform. Similar control systems are using sip and puff systems, brain computer interface (BCI) [9] or electromyography of a functioning muscular area [10].

II. System Architecture

The system's architecture is divided into seven levels: the first three related to the eye tracking subsystem and the eye movement translation into robotic platform commands; the next three on the data transmission to the platform and command execution; the last stage is responsible with the feedback to the user (Figure 1).

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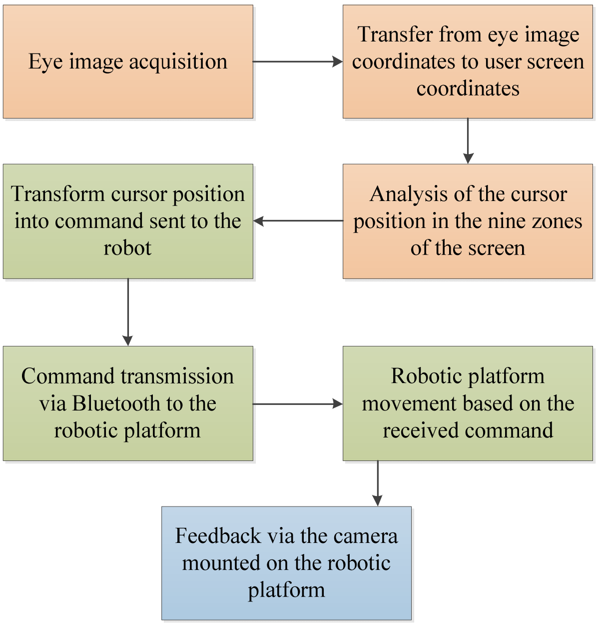


Figure 1. Structure and functionality of the system

Eye image acquisition is made using a modified USB camera with infrared (IR) lighting and an IR lens filter [11] (Figure 2). The transfer from eye image coordinates to user screen coordinates is done through the calibration and mapping stages of the eye tracking subsystem.

Figure 2. Device used for image acquisition

The cursor position in a specific zone of the user's screen determines the command that will be transmitted to the robotic platform. The zones and the commands are as follows (Figure 3):

- Zone 1 – turn the robot forward by 45 degrees to the left;
- Zone 2 – move the robot forward;
- Zone 3 – turn the robot forward by 45 degrees to the right;
- Zone 4 – turn the robot 90 degrees to the left;
- Zone 5 – the robot maintains the previous command;
- Zone 6 – turn the robot 90 degrees right;
- Zone 7 – turn the robot backwards by 45 degrees left;
- Zone 8 – stop the robot;
- Zone 9 – turn the robot backwards by 45 degrees right.

The cursor position is translated into a command and this is sent to the robotic platform. This stage is done through Bluetooth transmission between the PC that has a USB Bluetooth dongle connected and the robotic platform that has an incorporated Bluetooth module. Once the command is received, the platform movement stage begins.

To offer a user feedback, a camera is mounted on the robotic platform. This sends a live video feed to the user's PC that can be used to adjust the robotic platform movements. For this application we used a phone camera that sends a live video feed within the same network as the user PC via Wi-Fi [12]. To implement this feature we used a free mobile application called IP Webcam that sets up a live stream on an IP address in the current network [13].

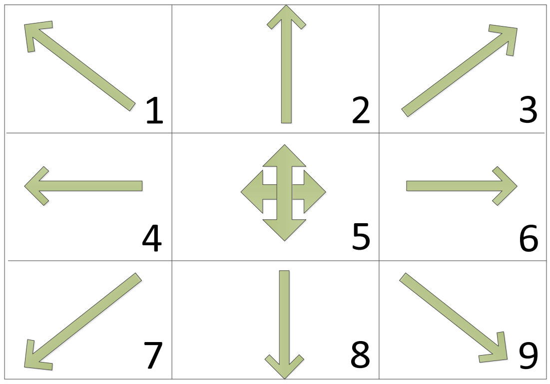


Figure 3. The nine zones of the user's screen and the platform movement commands

III. Eye Tracking Subsystem

The eye tracking subsystem for gaze detection is based on the circular Hough Transform (CHT) algorithm. The performance of the algorithm is influenced by the noise generated by the camera and infrared lighting (corneal reflection of the IR LEDs), by the natural physiological tremor caused by the changes in the pupil's shape, size, blinking and head movement.

Circular Hough Transform algorithm for eye tracking

By using the circular Hough transform algorithm the circle parameters within a given image are identified: the circle centre coordinates "a" and "b" and the circle radius "r", as presented in the circle equation [14]:

$$r^2 = (x-a)^2 + (y-b)^2 \tag{1}$$

To improve precision and decrease the analysis time, we implemented a pre-processing step: a segmentation threshold to cut image components such as eyelashes and eyebrows and keep only the pupil contour. This can be done due to the fact that the images are acquired in IR light, effect called dark pupil technique [15] (Figure 4). The segmentation threshold is selected automatically using the minimum value of the histogram as the threshold value (Figure 5).

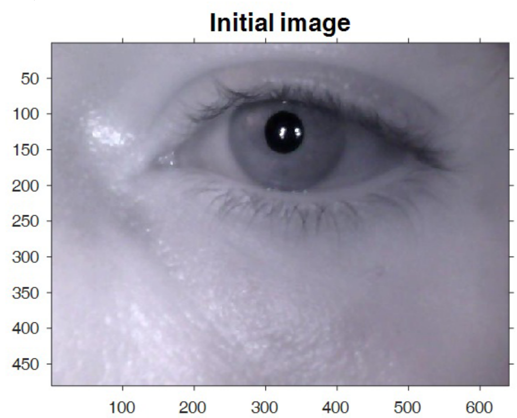


Figure 4. IR eye image acquired with the eye tracking system

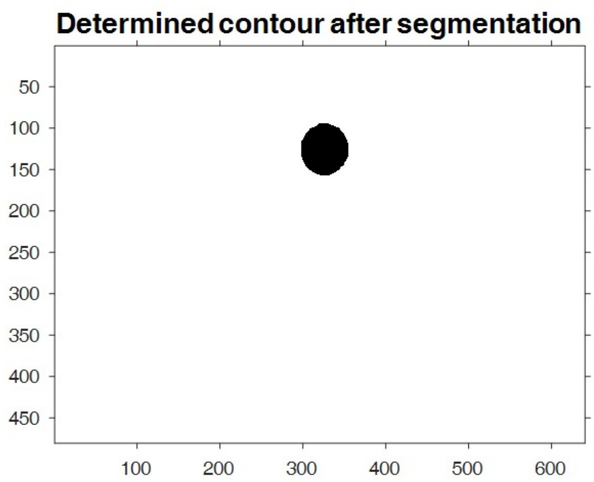
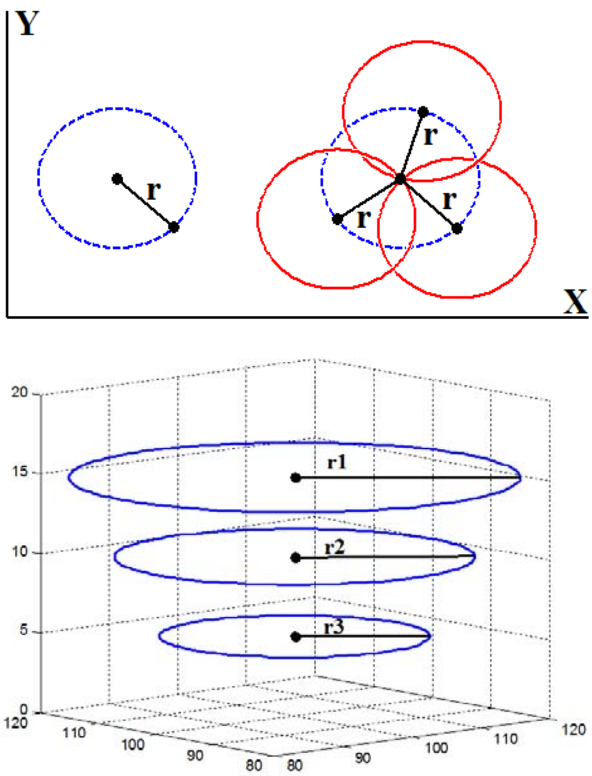


Figure 5. Segmentation of the eye image using an adaptive threshold

Based on the condition of a known or unknown radius, the CHT algorithm can be divided into two cases presented in Figure 6(a) and (b).



a)

b)

Figure 6. Principle of the CHT for known and unknown radius

CHT with known radius requires only to determine the centre coordinates "a" and "b", meaning that the running time of the algorithm will be drastically reduced and the result will be a matrix type accumulator with a greatest value of the elements that corresponds to the circle centre.

CHT with unknown radius (Figure 6.b) requires the identification of all three circle parameters, circle centre coordinates and radius, which leads to the three dimensional accumulator where each different layer corresponds to a radius value. Of course, the algorithm running time is influenced by the interval given for the radius values [16]. A larger interval will have better performances but higher running time, whereas a shorter interval will have better running time but lower precision. Again, the centre coordinates are given by the greatest value of the elements in the three dimensional accumulator [17] (Figure 7). In Figures 4, 5 and 7 the X and Y coordinates are expressed in pixels.

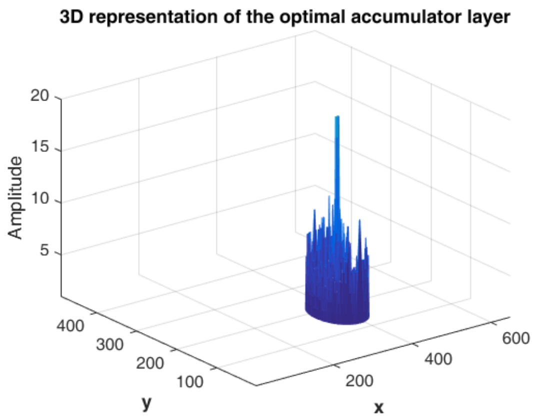


Figure 7. Representation of the optimal accumulator layer (maximum value of the accumulator elements)

The subsystem implemented for our application is based on CHT with unknown radius. The interval selected of ±3 pixels for the radius value is based around the dimension of 27 pixels, value that has been determined experimentally for the first image analysed, and the value of the previous radius for the other acquired images. The interval has been chosen because for this value we obtained the best results for static images, results presented in previous work [18].

The image acquisition is done using a modified IR LEDs USB camera having a resolution of 480x640 pixels that allows us to benefit from the dark pupil technique, as shown in Figure 8.

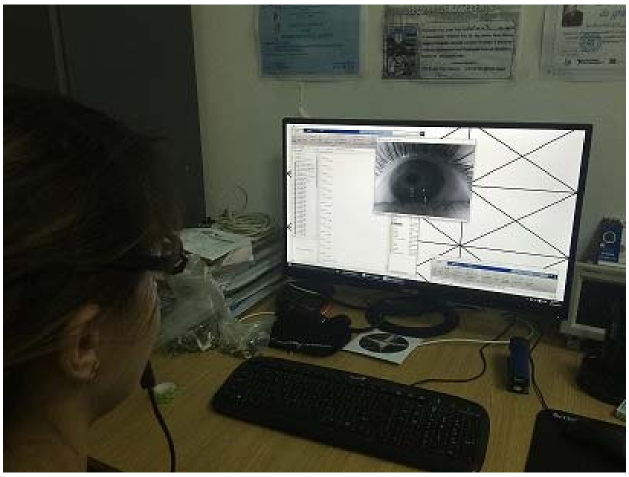


Figure 8. Experimental setup for image acquisition

The eye tracking subsystem is divided into a number of stages: image acquisition, calibration between the eye image and the user screen based on a 9 points calibration matrix and non-linear mapping between the coordinates of the eye pupil and the cursor movement on the user's screen [19]. The 9 points calibration is presented in Figure 9. This consists of a self-calibrating function that requires the user to follow the moving cursor over the 9 points in the order 1-2-3-4-5-6-7-8-9.

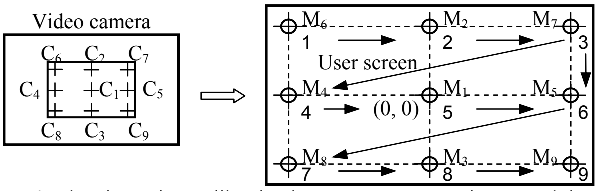


Figure 9. The nine points calibration between camera eye image and the user's screen

The results of the eye tracking algorithm are presented in Figure 10, which shows the ideal pupil contour and centre compared to the determined centre and contour using the CHT algorithm. Again, the *X* and *Y* coordinates are given in pixels.

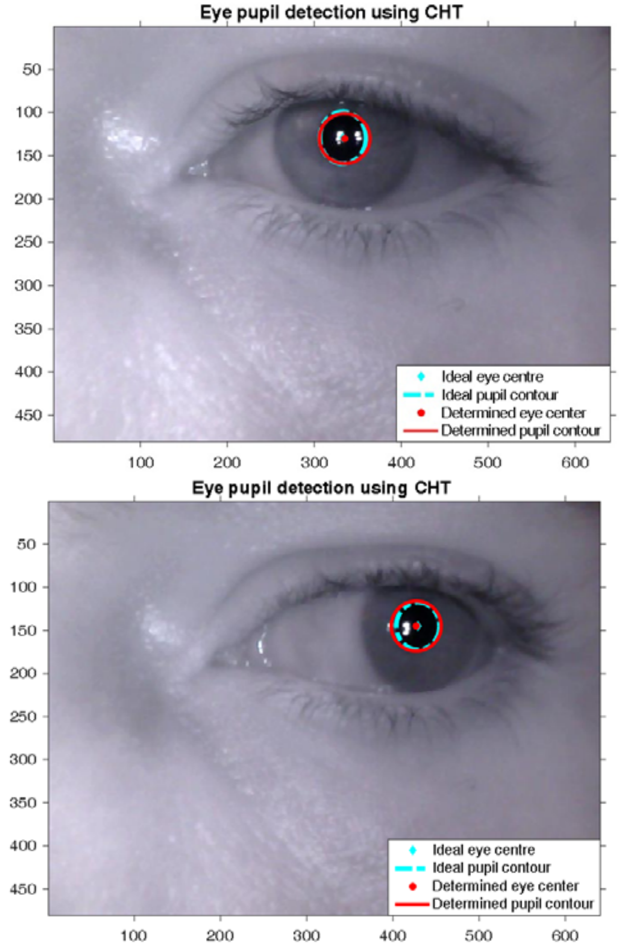


Figure 10. Results of the CHT algorithm for different pupil positions

IV. Mindstorms EV3 Robotic Platform

Recently several development frameworks have been proposed to assist researchers in the design of robotic applications [20]. From these, the Mindstorms EV3 robotic platform is an easy to use and versatile development tool-kit that has wide spread applications both in education and engineering [21].

Mindstorm EV3 platform is an ARM9-based processor (TI Sitara AM1808) at 300MHz Linux-based operating system with 64 MB RAM, 16 MB Flash memory, mini SDHC card reader 32 GB, 178x128 pixel LCD Matrix, USB and Bluetooth connections, 4 inputs for data acquisition (1000 samples/sec) with 4 outputs for commands execution. Software features includes: NXT-G, LabVIEW, RobotC, RoboLab, LejOS (Java), Matlab/Simulink. For data transmission the kit uses a Bluetooth 2.1 (Android and iOS-compatible) transmission (10 m distance), and a Wi-Fi module with ATHEROS AR 9331 (at 400 MHz) microprocessor functioning on 802.11b/g/n IEEE frequencies. Also for the upstream, a GSM transmission module (3G / GPRS) functioning at 850 MHz and 900 MHz GSM frequencies was introduced [22].

For this application, we used a Mindstorm EV3 robot controlled in the MATLAB environment to examine and test the displacement process using eye-tracking techniques. The movement information is transmitted to the robotic platform via Bluetooth where it is transformed into specific types of movement depending on the direction of the gaze [23].

The main components of the Mindstorms EV3 platform are presented in the block diagram from Figure 11; the platform used for this specific application is presented in Figure 12.

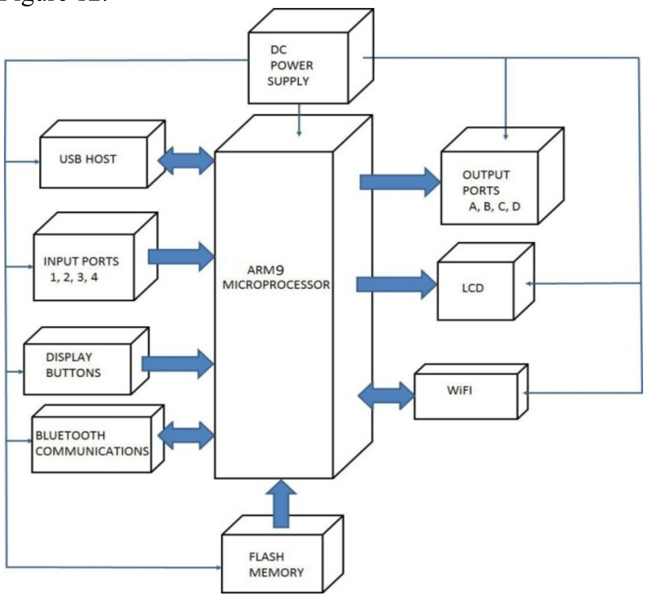


Figure 11. Block diagram of the Mindstorms platform

Figure 12. Mindstorms EV3 platform used in this application

V. Experimental Results

To determine the accuracy of the implemented control system we performed, in laboratory conditions, a series of tests on 30 healthy subjects.

During the testing phase, each subject required a learning curve to use the system. Each subject became accustomed with the system and used it effectively after, in average, 3, 4 or 5 sessions of 10 minute length testing phases.

The current application has defined nine types of states that are accessible by placing the cursor in 9 different zones of the screen, as presented in Figure 13. This allows us to identify the correct selection of a specific zone.

Figure 13. The zones presented on the user's screen

The first test consists of a two stage cursor movement using eye tracking: the first stage is represented by the first attempt to move the cursor, when the user doesn't have experience with the system, and the second stage, which consists in a later attempt, after the user has become accustomed to the system. Both these test stages are made using a predefined pattern of cursor movement from zone 1 to zone 9, as presented in Figure 14.

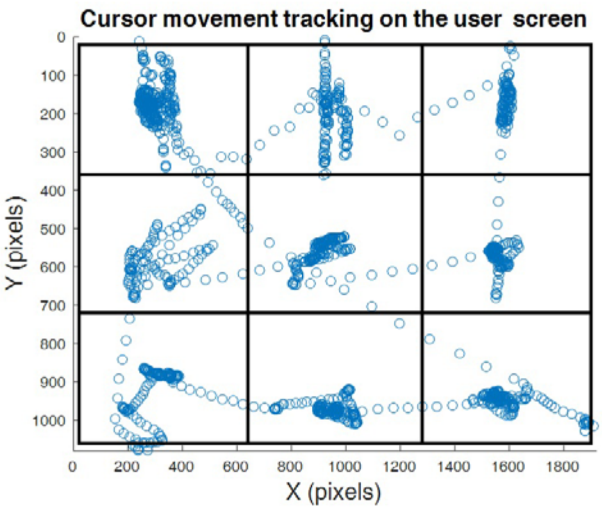


Figure 14. Cursor movement from zone 1 to zone 9 in a later attempt when the user is accustomed to the system

The second test consists of the cursor movement based on the indications given by the examiner, which calls out a specific zone. The user has to move the cursor in that specific zone and keep it there. This test is used to determine the reaction time of the user and the response of the system to received commands.

To determine the response time of the system (equation (2)), we implemented a user interface with specific buttons for each zone. When the user moves the cursor over the button, if he manages to maintain the position for 2 seconds the button is clicked and a counter is incremented. The next command is given after the user manages to click the button corresponding to that specific zone [24], [25].

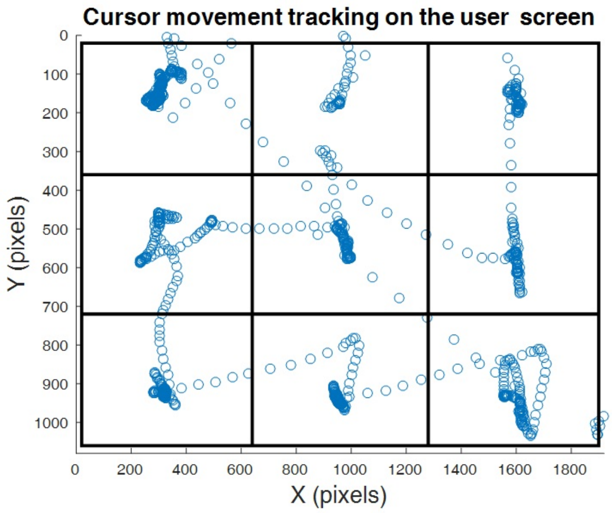


Figure 15. Second test cursor movement

$$T_{response} = T_{total} - \left(T_{click} + T_{runtime}\right) \qquad (2)$$

$T_{response}$ is the system response time, T_{total} represents the total time from when the command is given until the button is pressed and the counter is incremented, T_{click} is the time required to maintain the cursor on the same zone to click the button (2 seconds) and $T_{runtime}$ is the time required to analyse a frame and determine the pupil centre to determine the cursor position. Figure 16 presents the determined mean response time for all the subjects that used the proposed system.

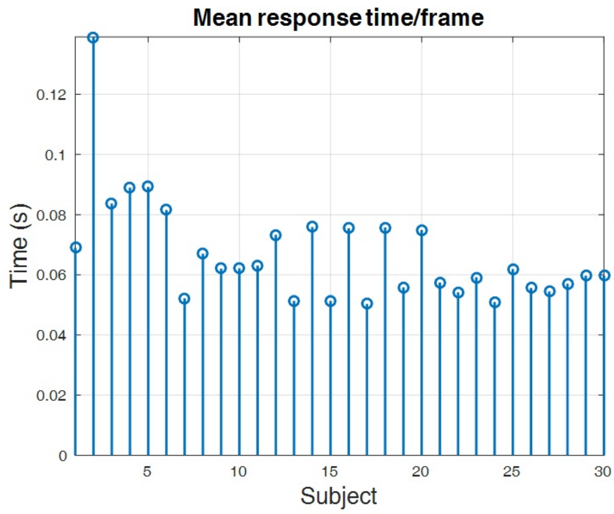


Figure 16. Second test cursor movement

Table I presents the average value for the response time and the runtime determined for all the 30 subjects that used the system.

TABLE I. RESPONSE TIME AND RUNTIME VALUES OBTAINED FOR THE 30 SUBJECTS THAT USED THE SYSTEM

Indicator	**Avg**	**Min**	**Max**
Response time (s)	0.0671	0.0504	0.1391
Runtime (s)	0.0187	0.0136	0.0234

The average response time of 0.0671 sec. is suitable for the remote control of a robotic platform and the feedback given by the implementation of the video system from the robot to the user's screen allows an efficient control.

VI. CONCLUSIONS

The proposed remote control platform, based on eye tracking, is an experimental model designed for assistive technology applications, more specific for patients with neuro-motor disabilities. This type of solution offers to patients the opportunity to better interact with their surrounding environment. The tests made on healthy subjects, in laboratory conditions, show that the learning curve for using the system is accessible, each user being able to control the system after three different sessions. The fact that the system offers a video feedback for the robotic platform movement and a low average time response, around 0.07 sec., demonstrates that the system can be used in real life situations.

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