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# A HUMAN-MACHINE INTERFACE BASED ON EYE TRACKING FOR CONTROLLING AND MONITORING A SMART HOME USING THE INTERNET OF THINGS

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PhD Thesis presented to the Postgraduate Program in Electrical Engineering of the Federal University of Espirito Santo, as a partial requirement to obtain the degree of Doctor in Electrical Engineering, in the area of concentration: Robotics and Intelligent Automation.

Advisor: Dr. Teodiano Freire Bastos Filho

Co-advisor: Dr. Lucas Frizera Encarnação

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To my grandparents Augusto Bissoli (*in memoriam*) and Dulce Mauro; João Cardoso (*in memoriam*) and Irene Coelho.

To my parents José Luiz and Elizete.

To my dear friends of UFES and INPI.

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To all of you, thank you very much!

I want to say now the opposite of what I said before. I prefer to be that ambulant metamorphosis than to have that old opinion formed about everything.

(Raul Seixas)

# ABSTRACT

People with severe disabilities may have difficulties when interacting with their home devices, due to the limitations inherent to their disability. Simple home activities may be even impossible for this group of people. Although many works have been devoted to proposing new assistive technologies to improve the lives of people with disabilities, some studies have found that the abandonment of such technologies is quite high. In this sense, this work presents a new and useful assistive system based on eye tracking for controlling and monitoring a smart home based on internet of things, which was developed following concepts of user-centered design and usability. With this system, a person with severe disabilities was able to control everyday equipment of her residence, such as lamps, television, fan and radio. In addition, her caregiver was able to monitor remotely, by internet, her use of the system in real time. Additionally, the user interface developed here has some functionalities that allowed improving the usability of the system as a whole. The experiments were divided into two steps. In the first step, the assistive system was assembled in an actual home, where tests were conducted with 29 participants without disabilities (group of able-bodied participants). In the second step, the system was tested with online monitoring, for seven days, by a person with severe disability (end-user), in her own home, not only to increase convenience and comfort, but also so that the system could be tested where it would in fact be used. At the end of both steps, all the participants answered the SUS questionnaire, which showed that both the group of able-bodied participants and the person with severe disabilities evaluated the assistive system with a mean of 89.9 and 92.5, respectively.

**Keywords:** Human-Machine Interface (HMI); Human-Computer Interaction (HCI); Smart Home; Eye Tracking; Assistive Technology; Usability Evaluation; User-Centered Design (UCD); Home Automation; Internet of Things (IoT).

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# ABBREVIATIONS

AJAX – Asynchronous JavaScript and XML

API – Application Programming Interface

AHRI – Aware Home Research Initiative

BCI – Brain-Computer Interface

BT – Bluetooth

CASAS – Center for Advanced Studies in Adaptive Systems

CEP/UFES – Human Research Ethics Committee of the Federal University of Espirito Santo

CUP – Convention of the Union of Paris

DLL – Dynamic-Link Library

DWPI – Derwent Innovation

EEG – Electroencephalography

EEPROM – Electrically-Erasable Programmable Read-Only Memory

EMG – Electromyography

EOG – Electrooculography

EPO – European Patent Office

GAS – Goal Attainment Scaling

GTSH – Gator Tech Smart House

gBox – GlobalBox

GUI – Graphical User Interface

GSH – Gloucester Smart House

HCD – Human-Centered Design

HCI – Human-Computer Interaction

HMI – Human-Machine Interface

HTTP – Hypertext Transfer Protocol

INPI/Brazil – National Institute of Industrial Property / Brazil

IoT – Internet of Things

IP – Internet Protocol

IPC – International Patent Classification

IR – Infrared

IROG – Infrared Oculography

ITR – Information Transfer Rate

JPO – Japan Patent Office

JSON – JavaScript Object Notation

LAI – Laboratory of Intelligent Automation

MATCH – Mobilising Advanced Technologies for Care at Home

SDK – Software Development Kit

sEMG – Surface electromyography

SPIFFS – Serial Peripheral Interface Flash File System

SSC – Scleral Search Coil

SSID – Service Set IDentifier

SUS - System Usability Scale

TCLE – Informed Consent Form

TCP – Transmission Control Protocol

U – Utility

UART – Universal Asynchronous Receiver / Transmitter

UCD – User-Centered Design

UDP – User Datagram Protocol

UI – User Interface

USB – Universal Serial Bus

USPTO – United States Patent and Trademark Office

UX – User Experience

VOG – Videooculography

WIPO – World Intellectual Property Organization

WS – WebSockt

## SUMMARY

# 1 INTRODUCTION

People with severe disabilities may have difficulties interacting with their home devices, due to the limitations inherent to their own disability. Simple activities like to turn on or off the lamp, fan, television or any other equipment, independently, may be even impossible for this group of people. With technological advances in the field of sensors and actuators, in recent years some researchers have begun to transfer these technologies to improve the quality of life of people with disabilities, increasing the autonomy of these people regarding the control of existing equipment in the environment (BOUMPA et al., 2018; KONSTANTINIDIS et al., 2015; SCHWIEGELSHOHN et al., 2015; TANG et al., 2015).

Technologies dedicated to improving the lives of people with disabilities are known as assistive technologies. Assistive technology is an area of knowledge, with an interdisciplinary characteristic, which encompasses products, resources, methodologies, strategies, practices and services that aim to promote the functionality related to the activity and participation of people with disabilities, inability or reduced mobility, aiming at their autonomy, independence, quality of life and social inclusion (BRAZIL, 2009).

In order to increase the usability of an assistive system, it is also critical to consider the role of the human-computer interaction (HCI). The concept of HCI refers to a discipline, which studies information exchange between people and computers by using software. HCI mainly focuses on designing, assessing and implementing interactive technologically devices that cover the largest possible number of uses (MARCOS; FOLEY, 2001).

The ultimate goal of HCI is to make this interaction as efficient as possible, looking to minimize errors, increase satisfaction, lessen frustration, include users in development processes, work in multidisciplinary teams, and perform usability tests. In short, the goal is to make interaction between people and computers more productive (LAMBERTI et al., 2015).

New technologies have arisen with health-related developments which, by using HCI, meet the needs of different groups such as people with disabilities, the elderly, etc. (BISIO et al., 2015; WANG et al., 2015). Although these advances were unthinkable just a few years ago, they are gradually becoming a part of people’s daily lives

(BUTALA et al., 2012; LOPEZ-BASTERRETXEA; MENDEZ-ZORRILLA; GARCIA-ZAPIRAIN, 2015).

Human–computer interaction and the need for a suitable user interface has been an important issue in modern life. Nowadays, products and technologies used by society have created concerns about computer technology. For this reason, researchers and designers are interested in the assessment of human and machine behavior, where the machines varying according to the system functionality and the system or product requirements (AHAMED; BAKAR, 2017).

## 1.1 PROBLEM STATEMENT

### 1.1.1 Problem Definition

Although many works have been devoted to proposing new assistive technologies to improve the lives of people with disabilities (DAHER et al., 2012; ELAKKIYA; GAYATHRI, 2017; FALCÓ; VAQUERIZO; ARTIGAS, 2014; GHAYVAT et al., 2018; KIM, E. Y., 2016; KRISTÁLY et al., 2018; MIZUMOTO et al., 2018; RAFFERTY et al., 2017; VALADÃO et al., 2016; WAN et al., 2018), some studies have found that the abandonment of such technologies is quite high, reaching a rate of up to 30% (COSTA et al., 2015; CRUZ; EMMEL, 2015, 2018; HOLLOWAY; DAWES, 2016).

The reasons for abandoning the assistive technology are diverse, the most recurrent being that:

- The user does not like the technology;
- The user is afraid to use the equipment;
- The user does not believe in the benefit of the device;
- The technology is not physically fit for the user;
- The price of the technology is very expensive;
- The user does not know how to use the equipment correctly;
- The user disapproves of the equipment aesthetic factors.

### 1.1.2 Hypothesis

Based on these facts, our hypothesis is that to improve usability, in order to avoid, or at least to reduce, the abandonment of new technologies, in developing a new system, engineers should be concerned with:

- Developing a system that is useful to the user, i.e., that it brings benefits;
- Developing a system to suit the needs of the user;
- Designing tests to validate the technology;
- Evaluating the usability of the system;
- Performing end-user testing;
- Testing the system outside the laboratory, i.e., testing the system where it will be actually used.

## 1.2 THESIS OBJECTIVES

### 1.2.1 General Objectives

This work aims to assist people with physical disability to pursue daily living autonomously, taking into account concepts of user-centered design and usability, in order to avoid the abandonment of the proposed system. To this end, we present a new useful assistive system based on eye tracking for controlling and monitoring a smart home, based on the Internet of Things. With this assistive system, a person with severe disabilities was able to control everyday equipment in her residence, such as lamps, television, fan, and radio, and the caregiver was able to remotely monitor the use of the system by the user in real time. In addition, the user interface developed here has some functionalities that allowed improving the usability of the system as a whole.

### 1.2.2 Specific Objectives

Beyond the general goal, several specific objectives were accomplished:

- Study assistive smart homes;
- Prospect eye tracking technologies using patent databases;

- Design a device controller module, which consists of the hardware and software that receives the action identifier, transmits the information to the home devices by internet, monitors the use of devices and transmits it to the Cloud (GlobalBox);
- Design web applications with Internet of Things and Cloud Computing Platform (including user interface and caregiver interface);
- Design a customized system (equipment chosen by the volunteers, IR Protocol of TV, setting of control times in user interface)
- Design a user-centered system (installation and adaptation of the system in the house);
- Evaluate the system performance, based on usability and user experience, with volunteers in an actual home (29 participants);
- Evaluate the system performance in long-term tests in the end-user home (person with disability) without any technical intervention.

## 1.3 CONTRIBUTIONS OF THIS THESIS

Such as aforementioned, the focus of this work was the development of a human-machine interface based on eye tracking for controlling and monitoring a smart home using the internet of things. Briefly, the contributions of this PhD Thesis are:

- Development of a web application, based on free software, that can be accessed from any computer connected to the Internet;
- Adapting a residence, transforming conventional equipment of people's daily life into equipment connected and controlled by the internet;
- Increase the autonomy of people with disabilities in performing day-to-day tasks, and allowing the control of the equipment of the house through an interface appropriate to their physical condition;
- Conduct long-term usability pilot tests with the end-user, in her own home, reducing the possibility of abandonment of the assistive technology.

## 1.4 THESIS OUTLINE

The subsequent chapters of this work are organized as follows.

In Chapter 2, a brief review about the user-centered design approach and usability is presented. In addition, the state-of-the-art related works about eye tracking and smart homes, mainly the ones related to internet of things and assistive technologies, is introduced.

In Chapter 3, a study of technological prospection of eye tracking from the perspective of Industrial Property, more specifically of Patents, is presented. In this sense, a methodology of Technological Prospection using the Derwent Innovation patent database is addressed.

In Chapter 4, the new assistive smart home, proposed in this work is introduced. All of the most relevant characteristics and information about the system architecture, connectivity, device controller module, wireless communication, user and caregiver interfaces are addressed.

In Chapter 5, tests protocols, experimental results and evaluations are reported. The experiments were divided into two steps. In the first step, the assistive system was assembled in an actual home, where tests were conducted with 29 participants (group of able-bodied participants). In the second step, a person with severe disability (end-user), in her own home, tested the system with online monitoring, for seven days.

In Chapter 6, conclusions and some recommendations for future works are presented.

# 2 FUNDAMENTALS AND LITERATURE REVIEW

In this chapter, the state-of-the-art of related works is introduced, by dividing the literature into three parts: i) user-centered design and usability; ii) eye tracking; and iii) smart homes.

## 2.1 USER-CENTERED DESIGN (UCD)

A User-Centered Design (UCD) approach can be used in any type of product from the perspective of HCI design. UCD, also called Human-Centered Design (HCD), is a method that defines the needs, desires, limitations, services, or processes that serve the end-user of a product/system at all stages of a project. In other words, UCD is a multistage troubleshooting process that follows all product development requirements. UCD tries to optimize how the user can use the product/system, what they want or what they need, instead of changing the user's behavior with the product/system (IIVARI; IIVARI, 2011).

The approach of UCD is to put human needs, resources, and behavior first, and then design technology to accommodate those needs, resources, and behaviors. It is necessary to understand the psychology and technology to start the design, which requires good communication, mainly between human and machine, indicating available options, the actual status, and the next step (NORMAN, 2002).

The term “interaction” from human–computer interaction (HCI) is a basis for designing or developing a user interface and an interaction between humans and machines. There are four basic activities of an interaction design: i) identify needs and establish requirements; ii) development of alternative projects; iii) construction of interactive versions of projects; and iv) evaluating projects. They also describe three characteristics for interaction design: i) focus on users; ii) specific usability criteria; and iii) iteration (PREECE; ROGERS; SHARP, 2002).

Regarding the user experience, the process is not only to learn about the user experience with the technology, but also for designers to experience interacting in their own work (GOODMAN; STOLTERMAN; WAKKARY, 2011). They report that user experience tests must be applied during the design, the approaches of which could be: (i) reported approaches; ii) anecdotal descriptions; and iii) first-person research. In addition, (BEGUM, 2014) presents the user interface (UI), proposing an extended UCD process that adds the “Understand” phase to the methods. The conventional steps of a UCD approach are (i) study, (ii) design, (iii) build, and (iv) evaluate; however, (BEGUM, 2014) has extended it to: i) understand; ii) study; iii) design; iv) construct; and v) evaluate.

### 2.1.1 Usability

The definition of usability is when a product is used by specific users to achieve specific goals with effectiveness, efficiency, and satisfaction in a specific context of use (“ISO 9241-210 - Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems”, 2010). Usability is more than just about whether users can perform tasks easily; it is also concerned with user satisfaction, where users will consider whether the product is engaging and aesthetically pleasing.

Usability testing is a technique in UCD which is used to evaluate a product by testing it with actual users. It allows developers to obtain direct feedback on how users interact with a product. Thus, through usability testing, it is possible to measure how well users perform against a reference and note if they meet predefined goals, also taking into account that users can do unexpected things during a test. Therefore, to create a design that works, it is helpful for developers to evaluate its Usability, i.e., to see what people do when they interact with a product (AHAMED; BAKAR, 2017; GOODMAN; STOLTERMAN; WAKKARY, 2011).

Usability is then the outcome of a UCD process, which is a process that examines how and why a user will adopt a product and seeks to evaluate that use. That process is an iterative one and seeks to improve the design following each evaluation cycle continuously.

### 2.1.2 System Usability Scale (SUS)

The System Usability Scale (SUS) provides a reliable tool for measuring the usability. It consists of a 10-item questionnaire with five response options, which are scored by a 5-point Likert scale, ranging from "1 - strongly disagree" to "5 - strongly agree". Originally created by Brooke (BROOKE, 1986), it allows researchers, engineers and designers to evaluate a wide variety of products and services, including hardware, software, mobile devices, websites and applications.

The 10 sentences of SUS are:

1) I think that I would like to use this system frequently.

2) I found the system unnecessarily complex.

3) I thought the system was easy to use.

4) I think that I would need the support of a technical person to be able to use this system.

5) I found the various functions in this system were well integrated.

6) I thought there was too much inconsistency in this system.

7) I would imagine that most people would learn to use this system very quickly.

8) I found the system very cumbersome to use.

9) I felt very confident using the system.

10) I needed to learn a lot of things before I could get going with this system.

After completion of the questionnaires by the interviewees, the SUS score is calculated as follows:

- For odd-numbered items: subtract 1 from the user response;
- For even-numbered items: subtract the user responses from 5;
- This scales all values from 0 to 4 (with 4 being the most positive response);
- Add the converted responses for each user and multiply that total by 2.5. This converts the range of possible values from 0 to 100 instead of from 0 to 40.

Although the scores are from 0 to 100, these are not percentages and should be considered only in terms of their percentile ranking. Based on the research of

(BROOKE, 1986), a SUS score above 68 would be considered “above average”, and anything below 68 is “below average”. However, the best way to interpret the results involves normalizing the scores to produce a percentile ranking. This process is similar to grading on a curve based on the distribution of all scores. To get an A (the top 10% of scores), a product needs to score above an 80.3. This is also the score in which users are more likely to be recommending the product to a friend. Scoring at the mean score of 68 gives the product a C, and anything below 51 is an F (putting the product in the bottom 15%).

### 2.1.3 User Experience (UX)

User Experience (UX) is critical to the success or failure of a product/system. While it is true that UX as a discipline began with usability, UX has grown to accommodate much more than usability and paying attention to all facets of UX in order to deliver successful products/systems is vital.

There are seven factors that describe user experience: i) useful, ii) usable, iii) findable, iv) credible, v) desirable; vi) accessible; and vii) valuable.

The product/system needs to be useful. If it has no purpose, it is unlikely to be able to compete for attention alongside a market full of purposeful and useful products. It is worth noting that ‘useful’ is in the eye of the beholder, and things can be deemed “useful” if they deliver non-practical benefits such as fun or aesthetic appeal.

Usability is concerned with enabling users to achieve their end objective with a product effectively and efficiently. Products can succeed if they are not usable, but they are less likely to do so. Poor usability is often associated with the very first generation of a product/system.

Findable refers to the idea that the product/system must be easy to find, and in the instance of digital and information products/systems, the content within them must be easy to find, too. Findability is thus vital to the user experience of many products/systems.

Credibility relates to the ability of the user to trust in the product/system that have been provided, not only that it will do the task it is supposed to do, but also that it will last for a reasonable amount of time and that the information provided with it is accurate and fit-for-purpose.

Desirability is conveyed in design through branding, image, identity, aesthetics, and emotional design. The more desirable a product is, the more likely it is that the user who has it will create desire in other users.

Accessibility is about providing an experience, which can be accessed even by users without a full range of abilities—this includes those who are disabled in some respect, such as the hearing, vision, motion, or learning impaired. It is also worth remembering that when the product/system is designed for accessibility, often it is find that the products/systems are easier for everyone to use, not just those with disabilities.

Finally, the product/system must deliver value. A low cost product that solves a very expensive problem is one that is likely to succeed. On the other hand, a very expensive product that solves a low cost problem is far less likely to do so.

## 2.2 EYE TRACKING

Eye tracking is a technique of measuring either the point of gaze (where someone is gazing) or the motion of an eye relative to the head. An eye tracker is a sensor/device for measuring either eye positions or eye movements. Eye tracking technology, used in eye trackers sensors/devices, has applications in industry and researches about:

- Visual system (KHAN et al., 2012; RICHSTONE et al., 2010; WILSON et al., 2010; WILSON et al., 2011);
- Psychology (MOORE et al., 2012; SUN et al., 2016);
- Assistive technologies (EID; GIAKOUMIDIS; SADDIK, 2016; LUPU; UNGUREANU, 2012; LUPU; UNGUREANU; SIRITEANU, 2013);
- Marketing (SCOTT; GREEN; FAIRLEY, 2015);

- As an input device for human-computer interaction (CECOTTI, 2016; FRUTOS-PASCUAL; GARCIA-ZAPIRAIN, 2015; LEWIS; PEREIRA; ALMEIDA, 2013; NEHETE; LOKHANDE; AHIRE, 2013); and
- In product and web-site design (LEE, S.; YOO; HAN, 2015).

Generally, eye tracking measures the eyeball position and determines gaze direction of a person. The eye movements can be tracked using different methods, which can be categorized into the categories:

- Scleral Search Coil (SSC) – measurement of the movement of an object attached to the eye (LOPEZ-BASTERRETXEA; MENDEZ-ZORRILLA; GARCIA-ZAPIRAIN, 2015; TAKEMURA; TAKAHASHI; TAKAMATSU, 2014);
- Video-oculography (VOG) / Infrared-oculography (IROG) – optical tracking without direct contact to the eye (FRUTOS-PASCUAL; GARCIA-ZAPIRAIN, 2015; LUPU; UNGUREANU; SIRITEANU, 2013); and
- Electrooculography (EOG) – measurement of electric potentials using electrodes placed around the eyes (MANABE; FUKUMOTO; YAGI, 2015).

Currently, most of the eye tracking researches for HCI are based on VOG/IROG, because these techniques have minimized the invasiveness to user in some degree (EID; GIAKOUMIDIS; SADDIK, 2016).

The eye is one of main human input media, and about 80 to 90 percent of the outside world information is obtained from the human eye (HOLZMAN; PROCTOR; HUGHES, 1973). For communication from user to computer, the eye movements can be regarded as a pivotal real-time input medium, which is especially important for people with severe motor disability, who have limited anatomical sites to use to control input devices (DONAGHY et al., 2011).

The research into eye tracking techniques in HCI is mainly focused on incorporating eye movements into the communication with the computer in a convenient and natural way. The most intuitive solution for incorporating eye movements into HCI is the use of an eye tracker directly connected to a manual input source, such as a mouse. By installing an eye tracker and using its x, y coordinate output stream as a virtual mouse, the movement of the user's gaze directly causes the mouse cursor to move (eye mouse). In order to provide such appropriate interaction, several eye-tracking-based control systems have been developed, detailed as follows.

Chin et al. (2008) proposed a cursor control system for computer users which integrated electromyogram signals from muscles on the face and point-of-gaze coordinates produced by an eye-gaze tracking system as inputs. Although it enabled a reliable click operation, it was slower than the control system that only used eye tracking, and its accuracy was low.

Missimer and Betke (2010) constructed a system that used the head position to control a mouse cursor and simulate left-click and right-click of the mouse by blinking the left or right eye. This system relied on the position of the user's head to control the mouse cursor position. However, irregular movement of the user's head affected the accuracy of the click function.

Lupu and Ungureanu (2012) proposed a communication system for people with disabilities, which was based on a special device composed of a webcam mounted on the frame of a pair of glasses for image acquisition and processing. The device detected the eye movement, and the voluntary eye blinking was correlated with a pictogram or keyword selection, reflecting the patient's needs. The drawback of this system was that the image-processing algorithm could not accurately detect the acquired image (low resolution) and was not robust to light intensity. Later, to improve the reliability of the communication system, they proposed an eye tracking mouse system using video glasses and a new robust eye tracking algorithm based on the adaptive binary segmentation threshold of the acquired images (LUPU; UNGUREANU; SIRITEANU, 2013).

Lately, several similar systems were also developed (MEGHNA; KACHAN; BAVISKAR, 2016; WANKHEDE; CHHABRIA, 2013), and the main concept of these systems is to capture images from a camera, either mounted on headgear worn by the user or mounted remotely, and extract the information from different eye features to determine the point of the gaze. Since, at the time the research was performed, commercial eye trackers were prohibitively expensive to use in HCI, all the aforementioned eye tracking control systems were proposed with self-designed hardware and software. It was difficult for these systems to achieve widespread adoption, as the software and hardware designs were closed source.

## 2.3 SMART HOMES

The expression “smart home” is used for a home environment with advanced technology that allows control and monitoring to its occupants, and boosts the independent living through sensors and actuators to control the environment or through wellness forecasting based on behavioral pattern generation and detection. To identify the challenges and difficulties for the key performance of a smart home control and monitoring, it is necessary to know the researches in this field.

### 2.3.1 Smart Homes using Internet of Things (IoT)

There are many motivations to design and develop applications in smart homes, the main ones being:

- Independent living (BISWAS et al., 2011; DAHER et al., 2012; GHAYVAT et al., 2018; KONSTANTINIDIS et al., 2015; RAFFERTY et al., 2017; WAN et al., 2018);
- Enhancement the wellbeing (BOUMPA et al., 2018; ELAKKIYA; GAYATHRI, 2017; KRISTÁLY et al., 2018; MIZUMOTO et al., 2018; VISUTSAK; DAOUDI, 2017),
- Efficient use of electricity (BAŞOL; GÜNTÜRKÜN; BAŞOL, 2017; BELIGIANNI et al., 2016; BOUCHET et al., 2014; BUHL et al., 2017; HAN, J. et al., 2014; KIAT; BARSOUM, 2017; KIBRIA et al., 2017; LI, C. et al., 2017; LIM et al., 2017; LIN; CHEN, 2017; MELHEM; GRUNDER; HAMMOUDAN, 2017; OLIVEIRA et al., 2017; SOE et al., 2017; WU et al., 2017); and
- Safety and security (ALOHALI; MERABTI; KIFAYAT, 2014; ARABO, 2015; DATTA, 2016; GOLAIT, 2015; HAN; KIM, 2015; HUTH et al., 2015; HUTH; DUPLYS; TIM, 2016; JACOBSSON; DAVIDSSON, 2015; PENG et al., 2015; PERETTI; LAKKUNDIT; ZORZI, 2015; RAHMAN; SHAH, 2016; RAJIV; RAJ;

CHANDRA, 2016; SANTOSO; VUN, 2015; SCHIEFER, 2015; SIVARAMAN et al., 2015; WURM et al., 2016).

A variety of smart home systems for assisted living environments were proposed and developed, but there are, in fact, few homes that apply smart technologies. One of the main reasons for this is the complexity and varied design requirements associated with different domains of the home, which are:

- Communication (AMADEO et al., 2015, 2016; ELKHODR; SHAHRESTANI; CHEUNG, 2015; LI, H. et al., 2016; RIZOPOULOS, 2011; SEO et al., 2016; WALTARI; KANGASHARJU, 2016);
- Control (BHIDE; WAGH, 2015; BIAN; FAN; ZHANG, 2011; CHEUQUE et al., 2016; HASIBUAN et al., 2015; HERNANDEZ; REIFF-MARGANIEC, 2015; JACOBSSON; BOLDT; CARLSSON, 2016; LAZAREVIC et al., 2015; LEE; TENG; HOU, 2016; MICLAUS; RIEDEL; BEIGL, 1990; MITTAL et al., 2016; MORAVCEVIC et al., 2016; PAPP et al., 2016; RYAN, 1988; YEAZELL, 1998);
- Monitoring (BHOLE et al., 2015; KANARIS et al., 2016; LEE et al., 2016; MANO et al., 2016; THOMAS; BOUROBOU; YOO, 2015; ZANJAL; TALMALE, 2016);
- Entertainment (HOSSAIN; ALAMRI; PARRA, 2013; JIANG et al., 2014; SCHOLZ et al., 2011; TECHNOLOGIES, 2017); and
- Residential and living spaces (DOOLEY et al., 2011; MORAIS; WICKSTRÖM, 2013).

As an important component of the Internet of Things (IoT), smart homes serve users effectively by connecting them with devices based on IoT. Smart home technology based on IoT has changed human life by providing connectivity to everyone regardless of time and place (GAIKWAD; GABHANE; GOLAIT, 2015; SAMUEL, 2016). Home automation systems have become increasingly sophisticated in recent years, as these systems provide infrastructure and methods to exchange all types of appliance information and services (KIM et al., 2013). A smart home is a domain of IoT, which is the network of physical devices that provide electronic, sensor, software, and network connectivity inside a home.

### 2.3.2 Assistive Smart Homes

In this section, some of the major smart home projects across the world are reviewed. The regions covered include Asia, Europe and North America.

In Asia, it is important to highlight Welfare Techno Houses (MOHKTAR et al., 2015; TAMURA et al., 2007), Smart House Ikeda (MATSUOKA, 2004), Robotics Room and Sensing Room (MORI et al., 2006), ActiveHome (LEE et al., 2008), ubiHome (OH; LEE; WOO, 2005; OH; WOO, 2004; “ubiHome”, 2018; “Ubihome | Mind the gap”, 2018), Intelligent Sweet Home (BIEN et al., 2003), UKARI Project and Ubiquitous Home (MINOH, 2007; TETSUYA; HIROTADA; MICHIHIKO, 2007), and Toyota Dream Home PAPI (“Toyota Dream House PAPI”, 2018).

The Welfare Techno Houses (WTH) are experimental homes to monitoring the independence for the disable and elderly and improve their quality of life. In particular, the researchers observed and monitored the sleep and toilet activities of the volunteers by using sensors to detect the status of doors and windows. The Smart House Ikeda (SHI) is a smart home where a family spent a month living, and their behaviors was automatically classified into 12 types of life actions by recording data of 167 sensors of 15 different types. The Sensing Room is an extension of the Robotics Room, whose researchers claim that details of human behavior over the long term in a small room can be measured. The ActiveHome is a residential apartment consisting of bedroom, bathroom, kitchen and living room, used to several experiments to evaluate context-aware services according to the type of human behavior. The ubiHome is a smart home, which is applied to ubiquitous computing technologies. It provides a personalized service that autonomously takes appropriate action by adapting to an individual’s situation; for example, the system automatically monitors the light controls in accordance with the user’s preferences. The Intelligent Sweet Home (ISH) is a service-robot-integrated smart home platform with a sensor-based home network system, which provides various kinds of daily living assistance to the users, especially for elderly and people with disabilities. The UKARI Project and Ubiquitous Home is a smart home for context-aware service experiments and real-life experiments to collect several data of real-life situations, which is composes of 6 companies and 10 universities. The Toyota Dream Home PAPI is a commercial smart home designed to plan and realize an environment-friendly, energy efficient and intelligent house design, with modern permeating network and computing technologies. It includes ubiquitous network, ubiquitous network/home and car, home theater, intelligent storage system, smart security system, smart auto door, a bedroom for high quality sleep, comfortable air conditioning system, blind shutter, residential elevator, eco interior furnishing, unobtrusive window screens, a power outage proof house, solar hot water supply and heating system, dye-sensitized solar cells and residential fuel cells.

In Europe, it is important to highlight comHOME (JUNESTRAND; KEIJER; TOLLMAR, 2001), Gloucester Smart Home (ORPWOOD et al., 2004), CUSTODIAN Project (DAVIS et al., 2003), Siemens (MEHROTRA; DHANDE, 2015), myGEKKO (“myGEKKO”, 2018), and MATCH (“MATCH - Mobilising Advanced Technologies for Care at Home”, 2018).

ComHOME is a smart home, which consists of three rooms, each room being connected by video-mediated communication. The Gloucester Smart House (GSH) is a smart home to carry out user-involved evaluations and to support people with dementia, which includes safety-related tasks, such as the use of the cooker and reminder devices (e.g. for taking medication). By using sensors to monitor the behavior of its occupants and their interactions with appliances, the GSH responds by controlling the supporting devices and by proving reminders. The CUSTODIAN is a project to create a software tool to facilitate the design of smart homes for people with disabilities. The software is aimed at facilitating interactions and exchanges among engineers, designers, care and housing providers, and users involved in the process of creating the solutions for these homes. The Siemens smart home consists of a complete apartment, fully equipped with Siemens household electrical, building, communications, multi-media technologies, and a test living environment. A software allows the integration of various wireless protocols and interfaces while building technologies system. The myGEKKO is a commercial smart home solution, user-friendly, manufacturer-independent and multiprotocol automation and control system. It utilizes power more efficiently, adaptable and cost-effective manner to monitor and control the plants and devices centrally: whether at home, in enterprises or a big network. It offers home automation with fully integrated with the internet of things. For instance, fire control automation system is installed to detect and handle any kind of fire hazards. The Mobilizing Advanced Technologies for Care at Home (MATCH) is a smart home care through monitoring and pattern generation of activities of occupants and voice recognition. It is based on an effective reminder system, in which the tracking system assists the people by forecasting for future routine and restricts them to avoid certain activities.

In North America, it is important to highlight Adaptive Smart House (LINDSEY et al., 2018; “The Adaptive House Boulder, Colorado”, 2018), Aware Home Research Initiative (AHRI) (“Aware Home Research Initiative (AHRI)”, 2018), MavHome Project (COOK et al., 2003; “MavHome: Managing an Adaptive Versatile Home”, 2018]), House_n (MIT House) (“House_n Materials and Media”, 2018; INTILLE, 2006), EasyLiving Project (SHAFER et al., 1998), Gator Tech Smart House (HELAL; MANN, 2005), DOMUS Laboratory (PIGOT; LEFEBVRE, 2003), Intelligent Home Project (LESSER; ATIGHETCHI, 1999), CASAS (“CASAS - Center for Advanced Studies in Adaptive Systems”, 2018; GHODS et al., 2018), Smart Home Lab (HEINZ et al., 2012; YANG et al., 2012), AgingMO (WANG et al., 2014), and Home Monitoring at Rochester University (“Rochester”, 2018).

The Adaptive Smart House is a smart home constructed in an actual residence. It is equipped with more than 75 sensors that provide information on environmental conditions such as temperature, ambient light levels, sound, motion, door and window openings, and actuators to control the furnace, space heaters, water heater, lighting units, and ceiling fans. The Aware Home Project is a smart home that functions as a living laboratory for ubiquitous computing in home life. It is used to the multidisciplinary exploration of emerging technologies and services for the home, which are health, education, entertainment, and security, and to the evaluation of the user experience with such domestic technologies. The project includes camera-based monitoring, which is efficient and easy home monitoring. The MavHome is a smart home system that perceives the state of the home through sensors, and intelligently acts upon the environment through controllers. This smart home system acts as a rational agent in a manner that maximizes the comfort of its inhabitants and minimizes operating costs. The House_n Project is a smart home with sensor-driven pervasive technologies to empower people with information that helps them make decisions, but they do not want to strip people of their sense of control over their environment. The researchers are focused on how the design of a home and its related technologies, products, and services should involve to better meet the opportunities and challenges of the future. The EasyLiving Project is a smart home designed to provide context-aware computing services through video tracking and recognition, and sensor readings in the sensing room, by using the geometric model of the room and taking readings from sensors embedded within. The Gator Tech Smart House (GTSH) is a programmable pervasive smart home, which exists as both a runtime environment and a software library. In this smart home, service discovery and gateway protocols automatically integrate system components by using generic middleware that maintains a service definition for every sensor and actuator in the space. Researchers at the GTSH are also working on cognitive prompting applications to assist an individual with mild dementia in sequencing through activities of daily living, such as washing hands or oral hygiene. The DOMUS Laboratory is a research pole on cognitive assistance in smart homes and mobile computing. It consists of an apartment with a living room, a kitchen and a bedroom, and the maintenance of the apartment is supported by the computer server room. Ongoing research focuses on cognitive assistance to people suffering from dementia. The Intelligent Home Project is a smart home designed and implemented to be a set of distributed autonomous home control agents, deploying them in a simulated home environment. Each agent is associated with a particular appliance to realize resource coordination in the intelligent home environment. The Center for Advanced Studies in Adaptive Systems (CASAS) is a smart home, which not only enhances the comfort of the user but also makes the cost economical. The enhancement of comfort is done by identifying, analyzing and generating a pattern from user’s daily lives for intelligent and reactive automation. The cost is maintained at economic level by reducing the maintenance and power usage. The Smart Home Lab is a smart home that introduced the independent living with decent daily routine through technologies of automation and security. In this project, the researchers designed intelligence at different levels of security, such as smart doors with the camera and RFID access for access authentication. The AgingMO is a smart home for elderly assisted living, which consists of elder health care and medical support by telemedicine, by deployment of heterogeneous sensors in the home. The Home Monitoring at Rochester University is a smart home-like setting packed with technology designed to progress early recognition and anticipation of health and medical problems.

# 3 TECHNOLOGICAL PROSPECTING

In this chapter, a study of technological prospection of eye tracking from the perspective of Industrial Property, more specifically of Patents, is presented. In this sense, a methodology of Technological Prospection using the Derwent Innovation patent database is addressed.

## 3.1 INTRODUCTION

Technological Prospecting studies are the basic tool for the foundation in decision-making processes at different levels in modern society. The purpose of prospecting studies is not to unravel the future, but rather to delineate and test possible and desirable views so that choices are made today that will most positively contribute to building the future. Such visions can help generate medium- and long-term policies, strategies, and plans that provide for probable and desired future circumstances in a given segment.

There are several definitions for Prospecting Studies, which seek to distinguish the different approaches and methodologies that can be used in their elaboration. Specifically, Technological Prospecting can be defined as "a systematic means of mapping future scientific and technological developments capable of significantly influencing an industry, economy or society as a whole" (MAYERHOFF, 2008).

There are three types of approaches that can be employed in the task of prospecting the future: i) through inferences, which project the future by reproducing the past, within certain limits, disregarding discontinuities or ruptures; ii) through the systematic generation of alternative trajectories, with the construction of possible scenarios; or iii) by consensus, through the subjective view of specialists.

The historical information used in prospecting methods should be obtained through continuous and reliable series. The Technological Prospecting studies that need this information find in the Intellectual Property system, specifically in the Patents system, a valuable resource, since this system feeds a database that has been growing significantly in the last decades, due to the growing importance of patents in the economy (FISHER, 2001).

The phenomenon of patent filing has both micro and macroeconomic facets, which makes it interesting to use research to predict technological development in several sectors. There are a number of advantages in using this source of information, in addition to the growing number of documents and their relevance to the technology market. Among them is the ease of access to the databases available free of charge on the Internet.

## 3.2 INDUSTRIAL PROPERTY INSTRUMENTS – PATENTS

According to the Convention of the Union of Paris (CUP), Industrial Property is the set of rights comprising patents, utility models, trade names and indications of origin or designations of origin, and the suppression of unfair competition (BARBOSA, 2009).

Created in 1970, the National Institute of Industrial Property (INPI/Brazil) is a federal autarchy (formerly linked to the Ministry of Industry, Foreign Trade and Services and from 2019 linked to the Ministry of Economy), responsible for the improvement, dissemination and management of the Brazilian system of granting, guaranteeing intellectual property rights for the industry.

A patent is a right conferred by the State, which gives the holder the exclusive right to exploit a technology. In return for the public's access to knowledge of the essential points of the invention, the law confers on the patentee a time-limited right, on the assumption that it is socially more productive to exchange the *de facto* exclusivity (that of the technology secret) for exclusivity of law (BARBOSA, 2009). It is patentable the invention that meets the requirements of novelty, inventive step and industrial application. At the national level, it should be noted that Law No. 9,279 (Industrial Property Law of Brazil - LPI) of May 14, 1996 defines that:

> “Art. 8. It is patentable the invention that meets the requirements of novelty, inventive step and industrial application.
>
> Art. 9. It is patentable as a utility model the object of practical use, or part thereof, susceptible of industrial application, which presents

a new form or arrangement, involving an inventive act, that results in a functional improvement in its use or in its manufacture.

[...]

Art. 11. The invention and the utility model are considered novel when not understood in the state of the art.

Art. 12. The disclosure of invention or utility model shall not be considered as prior art when it occurs during the twelve (12) months preceding the filing date or the priority of the patent application if it is promoted:

I - by the inventor;

II - by the National Institute of Industrial Property – INPI/Brazil, through an official publication of the patent application deposited without the consent of the inventor, based on information obtained from it or as a result of acts performed by it; or

III - by third parties, based on information obtained directly or indirectly from the inventor or as a result of acts performed by the inventor.

Art. 13. The invention is endowed with inventive step whenever, for a person skilled in the art, it is not obvious from the prior art.

[...]

Article 15. The invention and the utility model are considered susceptible of industrial application when they can be used or produced in any type of industry.

[...]

> Article 30. The patent application shall be kept confidential for 18 (eighteen) months from the filing date or from the oldest priority, if any, after which it will be published.
>
> [...]
>
> Article 40. The patent invention shall be valid for a period of 20 (twenty) years and a utility model for a period of 15 (fifteen) years from the filing date."

It should be noted that the right to Priority is conferred to the signatory countries of the CUP. That is, after the first filling of a patent in a signatory country, the depositor has up to 12 months to make the deposit in another signatory country. Therefore, all search and analysis of patentability requirements must be performed based on the priority date of the application and, if there is no priority, the filling date of the application.

## 3.3 INTERNATIONAL PATENT CLASSIFICATION (IPC)

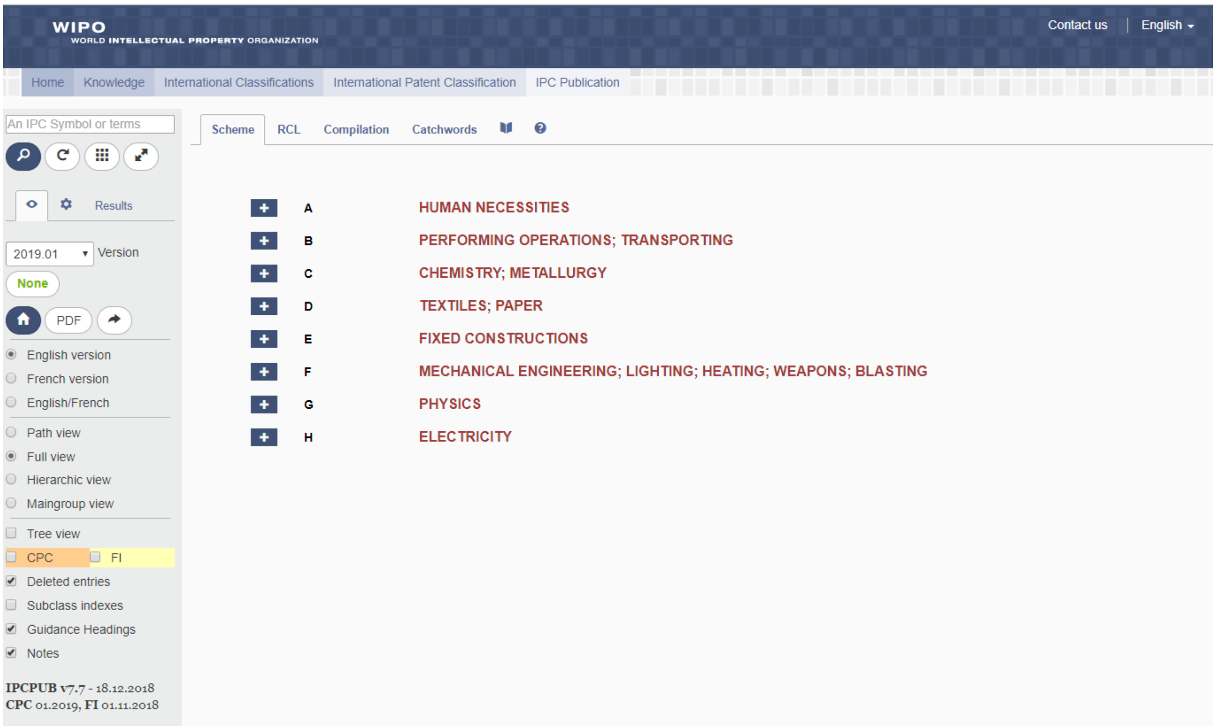
The International Patent Classification (IPC) is a very important tool in conducting patent searches. This classification is the means of standardizing the documents of several countries with different language and technical expressions.

The Classification, according to the World Intellectual Property Organization (WIPO), plays an important role in the sense of being: i) a tool for ordering patent documents in order to facilitate access to the technical and legal information presented therein; ii) a basis for the selective dissemination of information to all who use patents as a reference and / or knowledge; iii) a support to make a survey of the state of the art referring to some fields of technology; and iv) support for the development of statistics on industrial property, allowing the analysis of technological advances in several areas (DELVIZIO, 2010).

Figure 1 shows the structure of the IPC, which is composed of eight main sections, from letter A to H. These are divided into several subcategories referring to different technologies, according to the approaches: "A – Human Necessities; B – Performing

Operations, Transporting; C – Chemistry, Metallurgy; D – Textiles, Paper; E – Fixed Constructions; F – Mechanical Engineering, Lighting, Heating, Weapons, Blasting; G – Physics and H – Electricity".

Figure 1 – IPC 2019 cover sheet.




The Classification of a technology is initially constructed by a section, represented by a letter (for example G), followed by two numbers, indicating the class (for example G06). Each class may involve one or more subclasses, represented by a letter (for example G06F), each subclass having its subdivisions called groups, and may be main groups or subgroups. Each representation of the main group consists of the subclass symbol, followed by one to three numbers, the oblique bar and the number 00 (for example G06F 3/00). The subgroups form subdivisions under the main groups where the numbers after the oblique bar contain at least two digits other than 00 (for example G06F 3/01). This way, each section is subdivided by subcategories, until the final result of an IPC is presented as follows:

Example: G06F 3/01, at where:

Section – represented by a letter between A and H: G – Physics;

Class – represented by two numerical digits: 06 – Computing, Calculating or Counting;

Subclass - represented by a letter ranging from A to Z: F – Electric Digital Data Processing;

Group - represented by one or more numerical digits: 3 – Input arrangements for transferring data to be processed into a form capable of being handled by the computer and/or Output arrangements for transferring data from processing unit to output unit;

Subgroup - represented by at least two numerical digits: 01 – Input arrangements or combined input and output arrangements for interaction between user and computer.

Table 1 shows the total number of classes, subclasses, major groups and subgroups of the IPC, obtained from the WIPO website in January 2019. There are more than 74,500 different classifications.

Table 1 – Total IPC classifications in January 2019.

| Section | Number of classes | Number of subclasses | Number of main groups | Number of subgroups | Total number of groups |
|---|---|---|---|---|---|
| A | 16 | 84 | 1136 | 8048 | 9184 |
| B | 38 | 169 | 1983 | 15259 | 17242 |
| C | 21 | 87 | 1322 | 13387 | 14709 |
| D | 9 | 39 | 350 | 2726 | 3076 |
| E | 8 | 31 | 323 | 3122 | 3445 |
| F | 18 | 99 | 1099 | 8121 | 9220 |
| G | 15 | 85 | 723 | 7831 | 8554 |
| H | 6 | 51 | 547 | 8526 | 9073 |
| **Total** | **131** | **645** | **7483** | **67020** | **74503** |

## 3.4 PATENT DATABASES

Currently, the patent offices of each country provide the information they publish through its website. Documents published in Brazil can be accessed through the INPI/Brazil database.

Some free databases are considered important, depending on the temporal and territorial coverage of publications, such as the European Patent Office (EPO) database (Espacenet), or depending on the country's relevance to the Intellectual Property system, such as the United States Patent and Trademark Office (USPTO) base and the Japan Patent Office (JPO) base. However, such databases have limitations, and it is important that in using them, such limitations are considered, and the collection and processing of information are planned in order to avoid some problems they may cause.

There are other forms of access to information made available through the Intellectual Property system, which often have advantages over free bases, especially when the information will be used as a prospecting tool. These resources are made up of commercial databases and specific software for the retrieval and processing of data obtained through the patent system, such as Google Patents, Derwent Innovation (DWPI) and EPOQUE. Most of the time, these features enable the automation of many of the steps that, when using a free database, must be done manually.

Table 2 allows comparing available resources of interest in some of the main patent bases. It is noted that the USPTO, JPO and INPI/Brazil databases are quite similar. The Espacenet database is an exception, among the official databases, as it indexes, in addition to its own publications, the documents published in more than 70 countries, in addition to providing the full version, in pdf format, of much of this documentation. Google database has the advantage of being free and easy to search. However, Google Patents does not have data from many countries, it does not make it possible to compile the results of interest into graphics, and it does not have user support.

Table 2 – Comparison of patent databases.

| Resources of interest of the patent databases | Commercial Databases | | | Official Databases | | | |
|---|---|---|---|---|---|---|---|
| | Google Patents | Derwent Innovation | EPOQUE | Espacenet | USPTO | JPO | INPI / Brazil |
| Data from several countries | - | X | X | X | - | - | - |
| Updated data | X | X | X | X | X | X | X |
| Own classification | - | X | - | - | - | - | - |
| Editing and reviewing patent applications | - | X | - | - | - | - | - |
| Easy to use system | X | X | X | X | - | - | - |
| Used in patent offices | X | X | X | X | X | X | X |
| Support for users | - | X | X | - | - | - | - |
| Multiple search options | X | X | X | X | X | X | X |
| Compiling Results into Charts | - | X | - | - | - | - | - |
| Free access | X | - | - | X | X | X | X |

Commercial databases have the disadvantage of being paid. This is the main impediment to use the base EPOQUE, in which each command sent is charged. In addition, EPOQUE does not edit or revise patent applications. In contrast, this is the main advantage observed in the Derwent Innovation database. DWPI has up-to-date and cross-country data. It has more than 900 professionals who edit and revise patent applications and has its own order classification, which improves the search results. The system has multiple search options, allowing compiling the results obtained into graphics, and is very simple to use. Thus, it was decided to use the Derwent Innovation (DWPI) in this work.

## 3.5 SEARCH STRATEGIES

Initially, a preliminary search was carried out at the IPC in order to obtain the classifications related to eye tracking technologies, in order to help in the delimitation of the scope of the subsequent searches. In this sense, to obtain international trends, the first adopted search strategy considered the following categories: delimitation of the scope of the request; use of keywords; classification (IPC) and time limit. Then, to obtain the country-specific data, the second search strategy considered, in addition to the above categories, the country or region of deposit. Table 3 illustrates the adopted and variable categories used in the search strategies.

Table 3 – Search strategies.

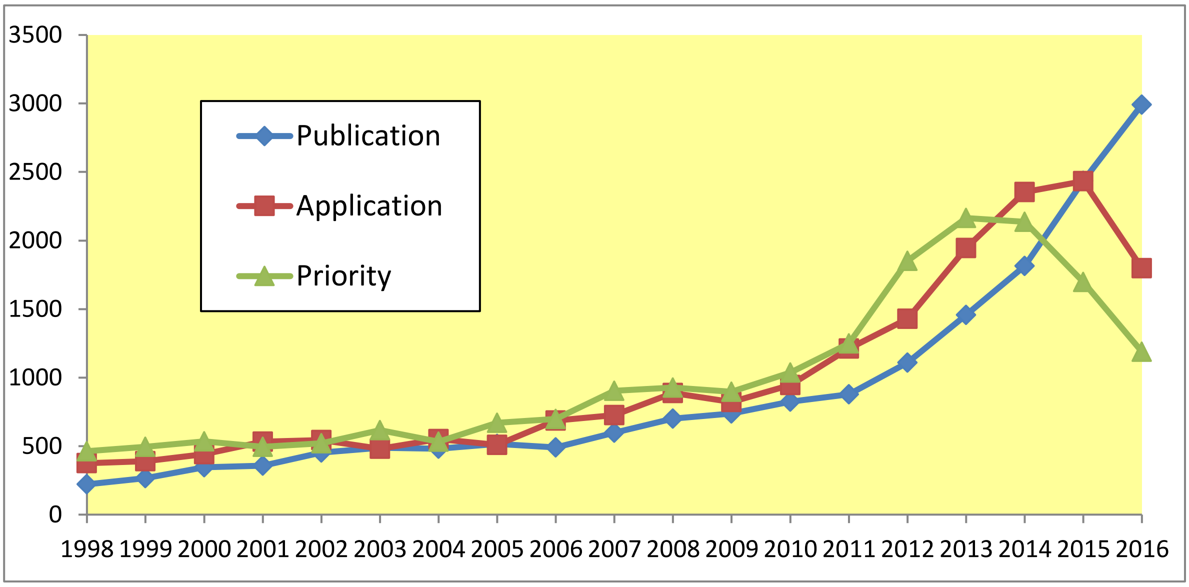
| **Categories adopted** | **Variables used** |
|---|---|
| Scope delimitation | Title and abstract |
| Keywords | (“eye” AND “tracking”) |
| Classification (IPC) | A61B and A61F |
| Time limited | 1998 to 2018 / 2000 to 2016 |
| Application Country | Brazil (BR), United States (US), China (CN)… |

With the time limit set for 1998 to 2018, the first international search was carried out. Thus, we identified the number of occurrences of deposits, priorities and publications each year, observing the behavior in this temporal cut. After this step, the search was carried out again and thus it was possible to obtain the main classifications used in this technology, the countries with more patent application fillings, and the main companies in the industry in number of patents and, finally, identify the world’s technological area using eye tracking.

## 3.6 EYE TRACKING

Figure 2 shows the international behavior of priority claims, patent applications and patents publications related to the eye tracking technology from 1998 to 2016. It can be observed that, although the growth in the period 1998 to 2010 is relatively small, from 2010 on it becomes quite high. Due to the so-called edge effect, the years 2017 and 2018 were suppressed. It was decided to keep the year 2016 on the chart, although it is still affected by the edge effect, which can be occasioned by the following reasons: i) delay of publication of the applications by the patent offices; ii) a period of secrecy of up to 18 months from the filling date until the publication of said patent application; iii) delay of the commercial base in the updating of the data coming from the official bases of the patent offices. The years before 1998 were not presented, in order to highlight the latest technologies.

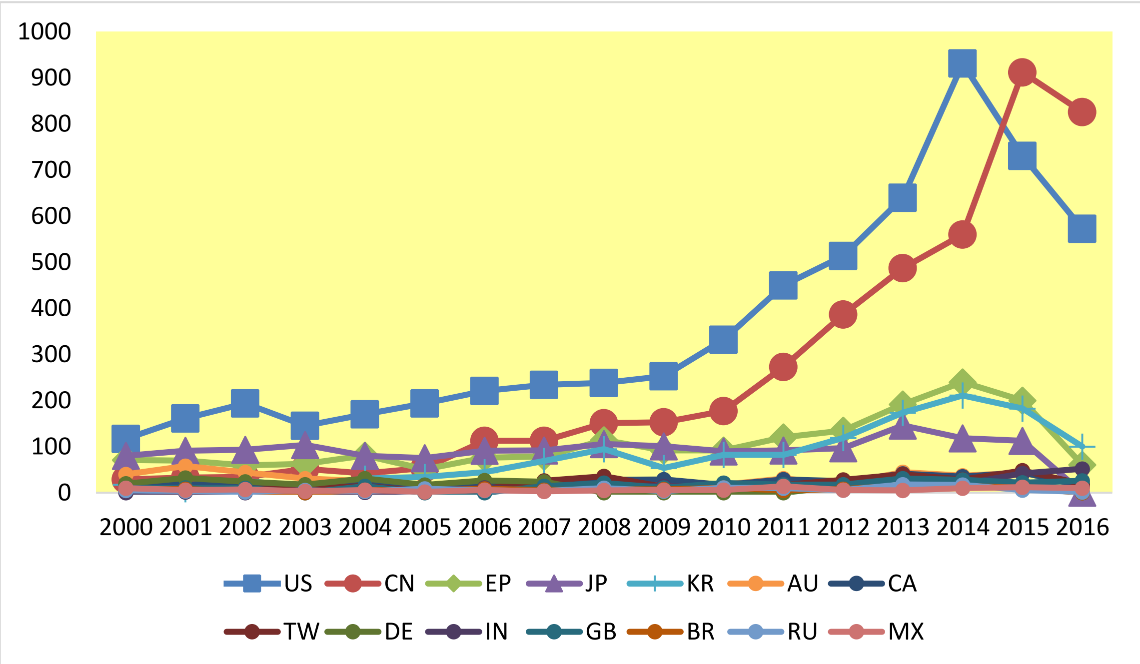
Figure 2 – Comparison of international data on priority claims, patents applications and patents publications related to eye tracking technology per year.




As expected, the profile of the three curves is similar. It can be noted that the number of priorities tends to be higher over time, since the same patent application may have more than one priority. It can be further noted that the publication curve is shifted by about one year from the application ones due to the confidentiality period of the patent application.

Figure 3 illustrates the international behavior of patents applications, related to eye tracking technology, at the world's largest patent offices in terms of number of fillings. The US leadership in the protection of these technologies over the years can be clearly observed, followed by China, Europe, Japan and South Korea, respectively, as the main markets of interest. It is worth mentioning that these five offices make up the so called IP5, which are the world's top five intellectual property offices. Again, due to the so-called edge effect, the years 2017 and 2018 were suppressed.

Figure 3 – Patent applications related to eye tracking technology per year in the international scope.

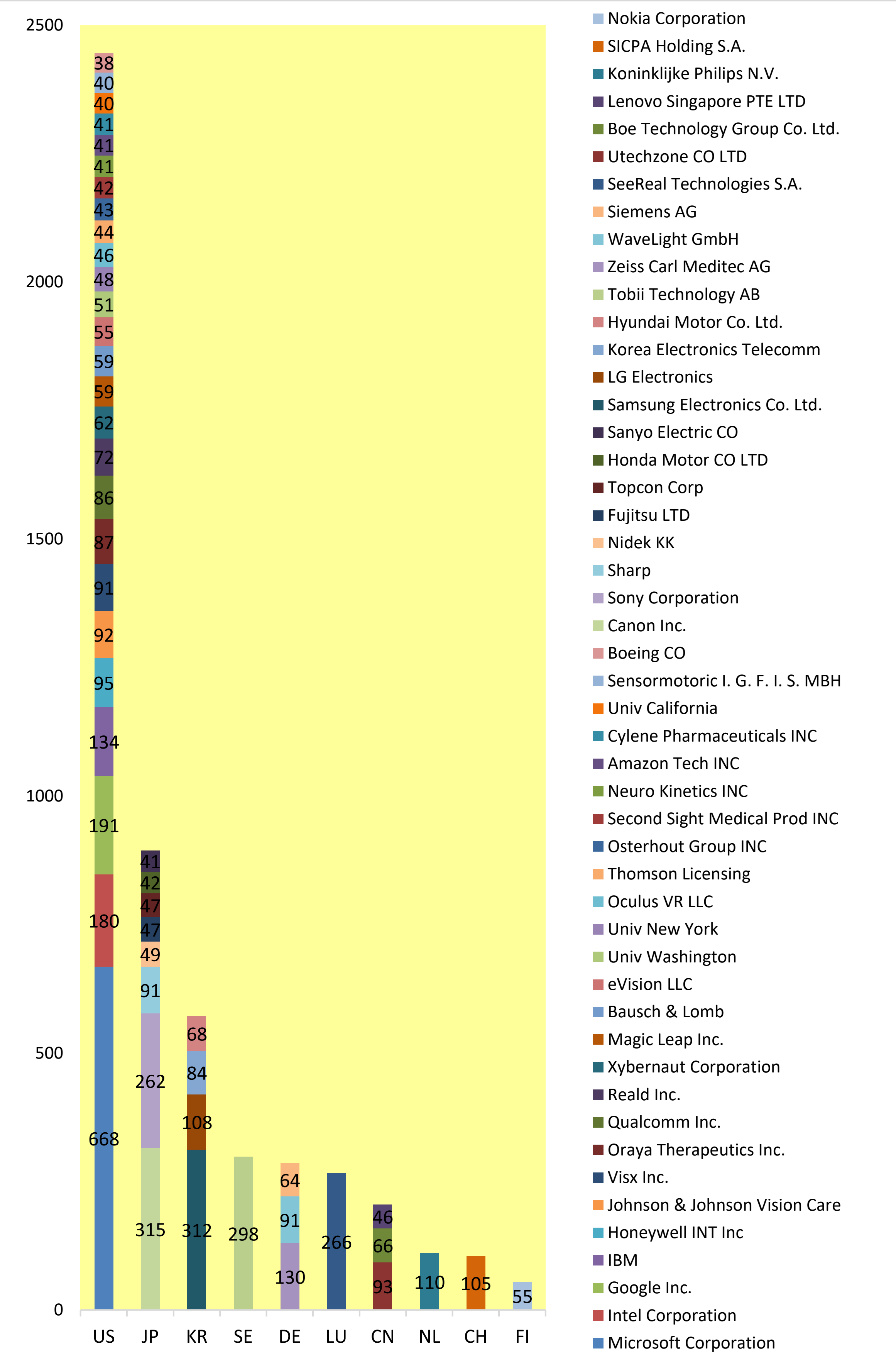



In analyzing Figure 3, it can be seen that it can be divided into three blocks with similar characteristics. In block 1 are Australia (AU), Canada (CA), Taiwan (TW), Germany (DE), India (IN), United Kingdom (GB), Brazil (BR), Russia (UK) and Mexico (MX), which are among the offices with the largest number of patent application fillings for eye tracking technology, although this number has remained approximately constant over the years. In block 2, there are Europe (EP), South Korea (KR) and Japan (JP), which stand out from the first group, mainly from 2010 on, when they achieved more relevant growth. Although they are in decline since 2014, they still have a number of patent fillings for eye tracking technology far superior to block 1. Finally, in block 3, there are United States (US) and China (CN) which receive the largest number of patent application fillings for eye tracking technology. Although the United States has the largest number of deposits over the years, it can be noted that China took the leadership from 2015. Both countries show a slight growth from 2000 to 2009 and become extremely sharp from 2010. The shift of about a year between the curves of the United States and China draws attention. One reason that may explain this fact is the right to Priority of the signatory countries of the CUP, since after the first filling of a patent in a signatory country, the depositor has up to 12 months to deposit in another signatory country. This corroborates the fact that the companies with the largest number of patent fillings are the US (Figure 4).

Figure 4 shows the ranking of the companies with the highest number of patent applications fillings grouped by country of origin. Again, there is the leadership of the United States, both in number of companies and in number of fillings. It is noteworthy that Microsoft Corporation, which develops, manufactures, licenses, supports and sells computer software, electronic products, computers and personal services, was the first in the ranking with 668 patent deposits in total. Following are Canon Inc. (JP), Samsung Electronics (KR), Tobii Technology (SE), SeeReal Technologies (LU), Sony Corporation (JP), Intel Corporation (US), Google Inc. (US) and Zeiss Carl Meditec (DE), respectively.

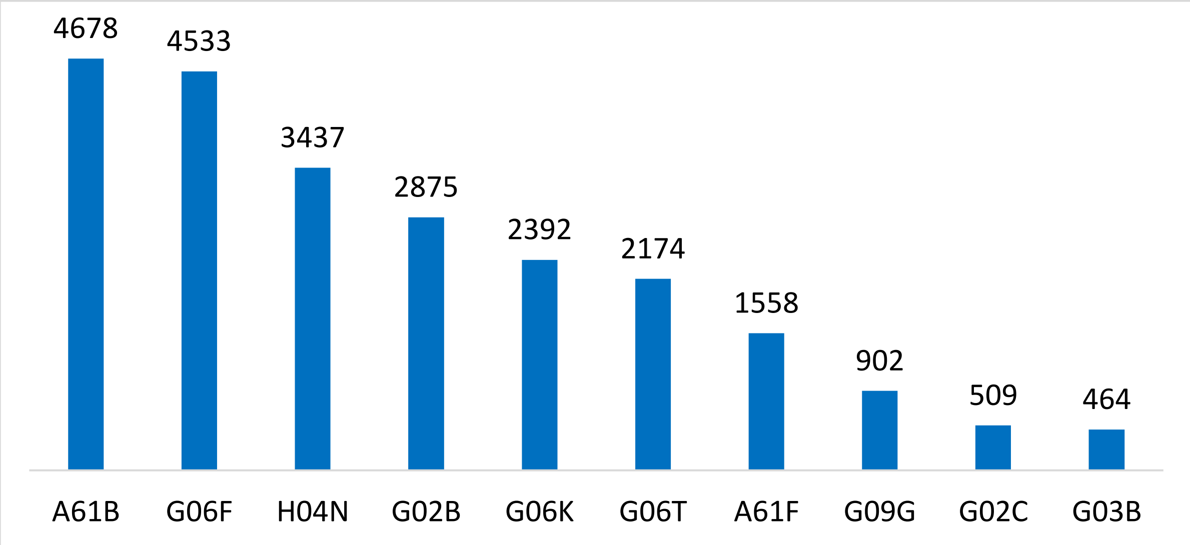
Figure 4, through the direct action of the companies, shows the leading countries in the protection of their developments and research of technology related to eye tracking. It shows clear leadership from the United States (US), followed by Japan (JP), South Korea (KR), Sweden (SE), Germany (DE), Luxembourg (LU), China (CN), Netherlands (NL), Switzerland (CH) and Finland (FI). Of note is Sweden and Luxembourg, which, even with only one company in each country, appear in the fourth and sixth positions, respectively.

Figure 4 – Ranking of the main companies in the number of patent applications grouped by country of origin.



In addition, it is interesting to identify the main technological areas involved. In this sense, Figure 5 shows the main IPC subclasses found in order of decreasing occurrence.

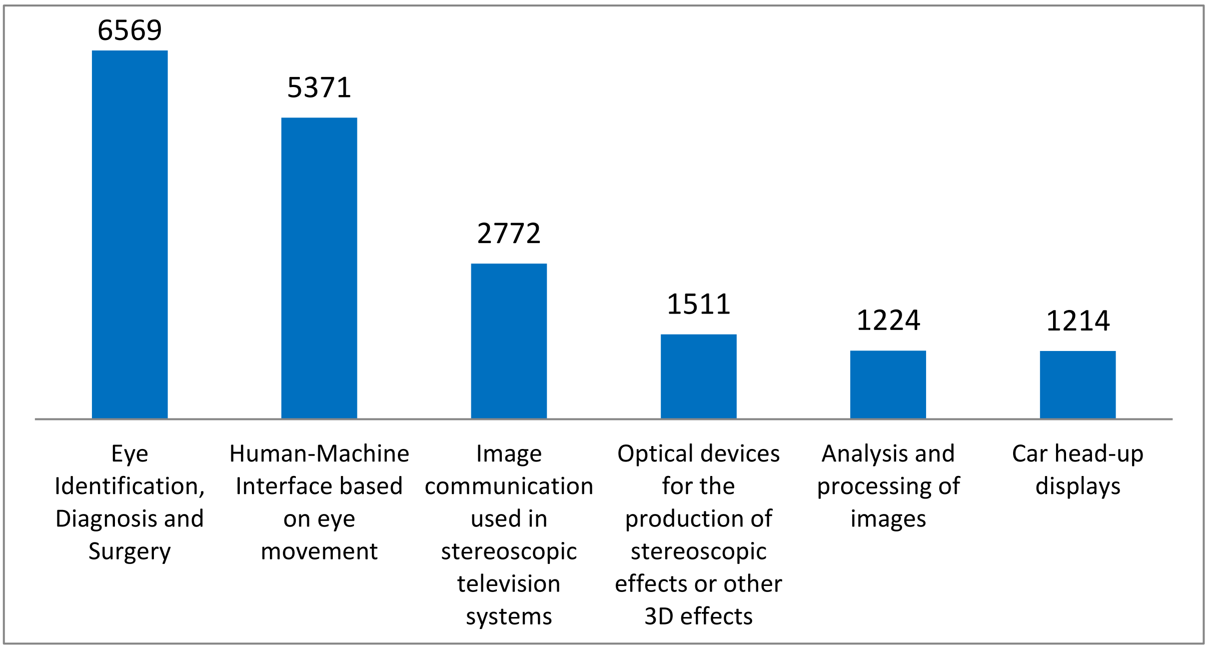
Figure 5 – Main subclasses of the IPC in descending order of occurrence.




From the analysis of Figure 5, it can be seen that the subclass A61B, referring to diagnosis and surgery appears with the highest number of occurrences, showing that the medical area is the main area related to eye tracking. Second is the subclass G06F, which is directly related to human-machine interfaces, referring to the digital processing of digital data. Then, representing the developments in the television area, we have the subclass H04N, referring to the communication of images. The next subclass found is G02B, which is also directly related to television technology, referring to optical systems or devices. G06K subclass, which is directly related to human-machine interfaces, refers to the identification, presentation, support, manipulation and transport of data.

Based on the obtained classifications, it was possible to separate the protected technologies into six distinct groups, in descending order of filling of patent applications, as shown in Figure 6.

Figure 6 – Main technological areas identified under the eye tracking technology.




From the analysis of Figure 6, it can be observed that the area related to the identification, diagnosis and surgery of the eyes appears with the greatest number of occurrences, evidencing the importance of eye tracking for the health area. Secondly, there is the human-machine interface, based on eye movements, currently used in notebooks, tablets and smartphones, to improve user interaction with such devices, especially in games. Then, in third and fourth places, respectively, appear the areas of image communication and optical devices, both related to stereoscopic television (better known as three-dimensional or 3D). Fifth, the area of image analysis and processing appears, where eye tracking can be used to identify what attracts the most attention to the images. Finally, in the sixth position, the head-up displays used in cars and airplanes, which consist of displays designed on the glass of vehicles, in order for the user does not have to look elsewhere to have access to information from the car or plane.

This chapter presented an overview of the technology of eye tracking from the point of view of Industrial Property, through the accomplishment of a technological prospection using patent bases. At the international level, the main areas of technological knowledge related to eye tracking were evidenced.

The patent base used was Derwent Innovation since it is simple to use, has updated data from several countries and still has peculiar characteristics, such as: professionals who edit and revise patent applications, develop a proper classification of the requests and rewriting of titles and abstracts, which greatly improves the search results.

The results obtained point to a growing trend regarding the number of patent fillings and patent applications for eye tracking, mainly from 2010. It should be noted that in the coming years a good increase is expected in the data obtained from 2015 onwards, due to the delay in the publication of patent applications.

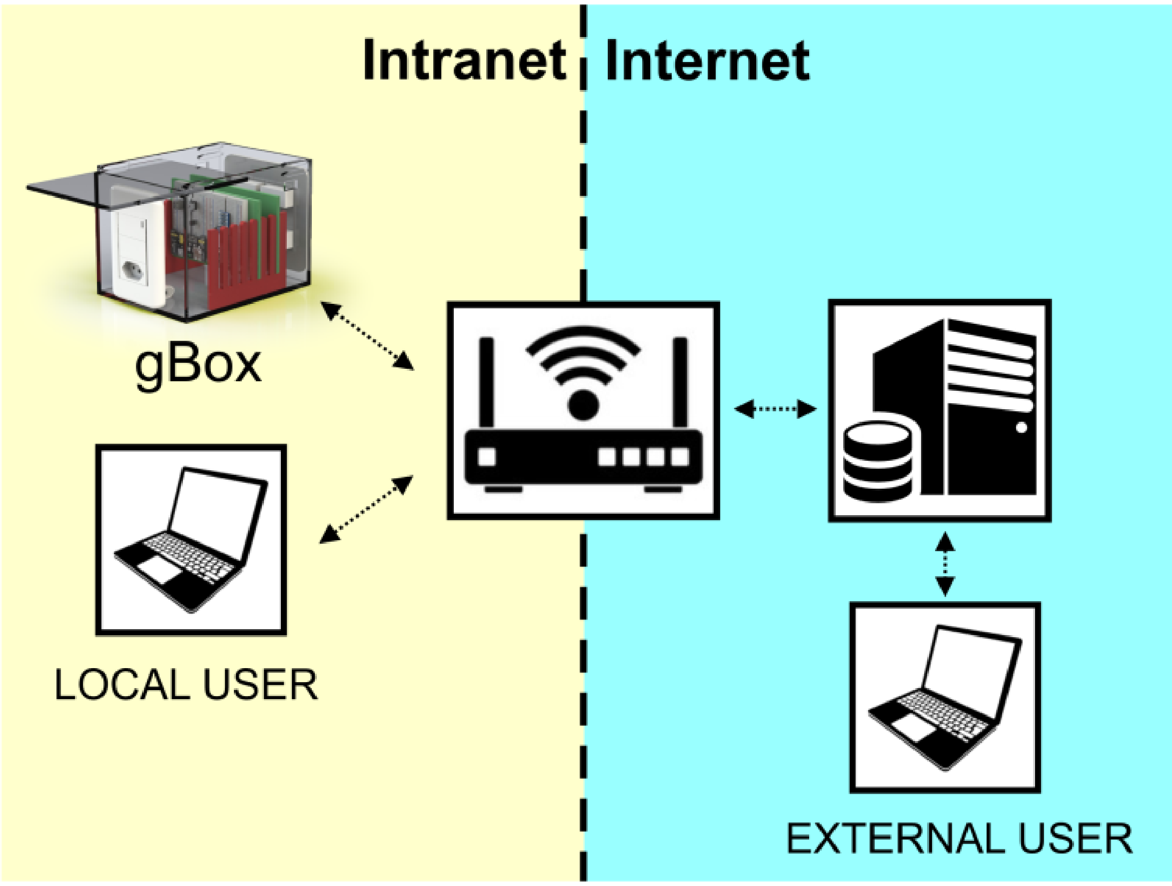
It is worth noting the leadership of the United States in the development of eye tracking technology, both in the number of patent applications filled in the country, which is an indicator of the interest in protecting this technology, as well as in the number of companies involved and in the number of applications for patents of US companies. However, the results indicate that, since 2015, the Chinese office is the international leader in the number of patent applications filled, leaving the US office in second place.

International data were stratified in different areas of technological development, with the aid of the International Patent Classification (IPC), with emphasis on the area of eye tracking for surgery and eye diagnosis, which obtained the first place, followed by human-machine interface, showing that these are important and promising areas.

## 4 PROPOSED ASSISTIVE SYSTEM

The assistive system proposed here empowers people with severe physical disability and mitigates the limitations in everyday life with which they are confronted. The system aims at assisting people with physical disability to pursue daily living autonomously. Daily living activities include communication, control and entertainment. Note that communication and entertainment components are not considered in this study. In Figure 7, the local user is the person with disability, who can control the equipment of his/her smart home through eye gaze, using the device controller (gBox). At the same time, the caregiver (external user) can monitor the use of the system.

Figure 7 – System overview.



The proposed eye-gaze-tracking-based control system is a software application running on a low-cost eye tracker (e.g., The Eye Tribe 1.0 and Tobii Pro). The application detects the user's gaze with the "mouse cursor control" function provided by the eye tracker. The mouse cursor control allows users to redirect the mouse cursor to the gaze position. Therefore, the system realizes where the user is gazing according to the position of the mouse cursor. By gazing at the point for few seconds, the tool generates the corresponding event. This way, users can select and "click" the corresponding action. The eye tracker detects and tracks the coordinates of the user's eye gaze on the screen; this made it possible to create applications that can be controlled in this way.

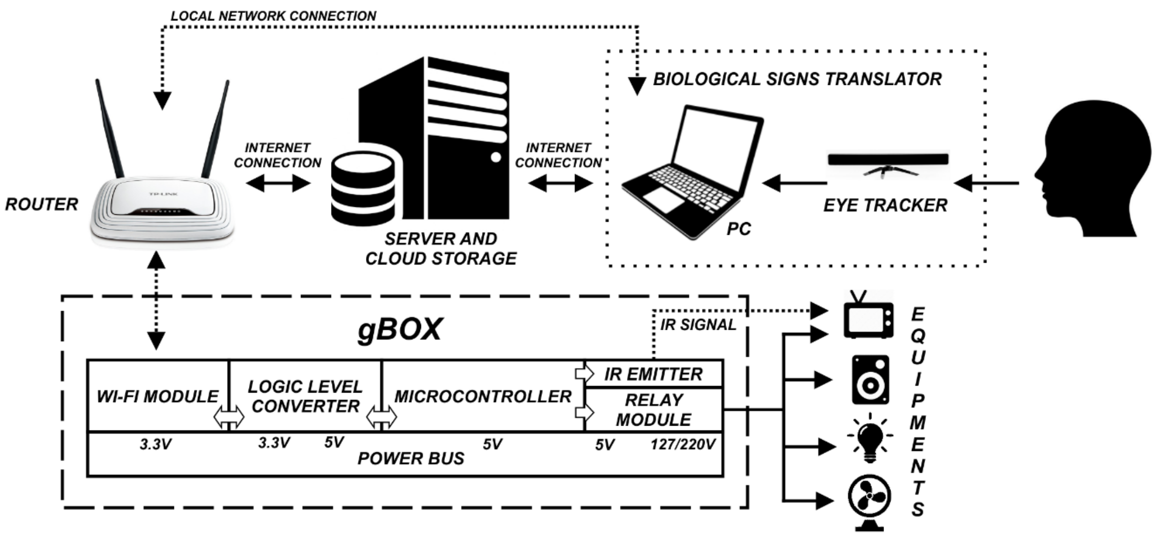
The eye tracker software is based on an open Application Programming Interface (API) that allows applications (clients) to communicate with the eye tracker server to obtain eye gaze coordinates. The communication is based on messages sent asynchronously, via Socket, using the Transmission Control Protocol (TCP).

It should be noted that to use this assistive system, it is not necessary to install any software in addition to the Internet browser, as the web application was developed to run in Internet browsers. It is only recommended to use the most up-to-date versions of well-known browsers, such as Google Chrome (preferable), Mozilla Firefox, or Internet Explorer.

## 4.1 SYSTEM ARCHITECTURE

Different systems for HCIs based on biological signals have been proposed with various techniques and applications (DU; WANG; HONG, 2013). Despite each work presenting unique properties, most of them fit into a common framework. Figure 8 shows the framework adopted in this system.

Figure 8 – Functional model of the eye/gaze-tracking based control system.




Observing the model, a loop structure can be recognized; it starts from the User, whose biological signals are the primary input, and ends with the environment that is affected by the actions of the system. Along this path, three main modules can be identified: the Biological Signal Translator module, the Server and Cloud module, and the Device Controller/Device module (gBox). Eventually, the loop is closed through user feedback of different kinds. The communication between the modules is bidirectional in order for a module to know the outcome of a command.

## 4.2 CONNECTIVITY

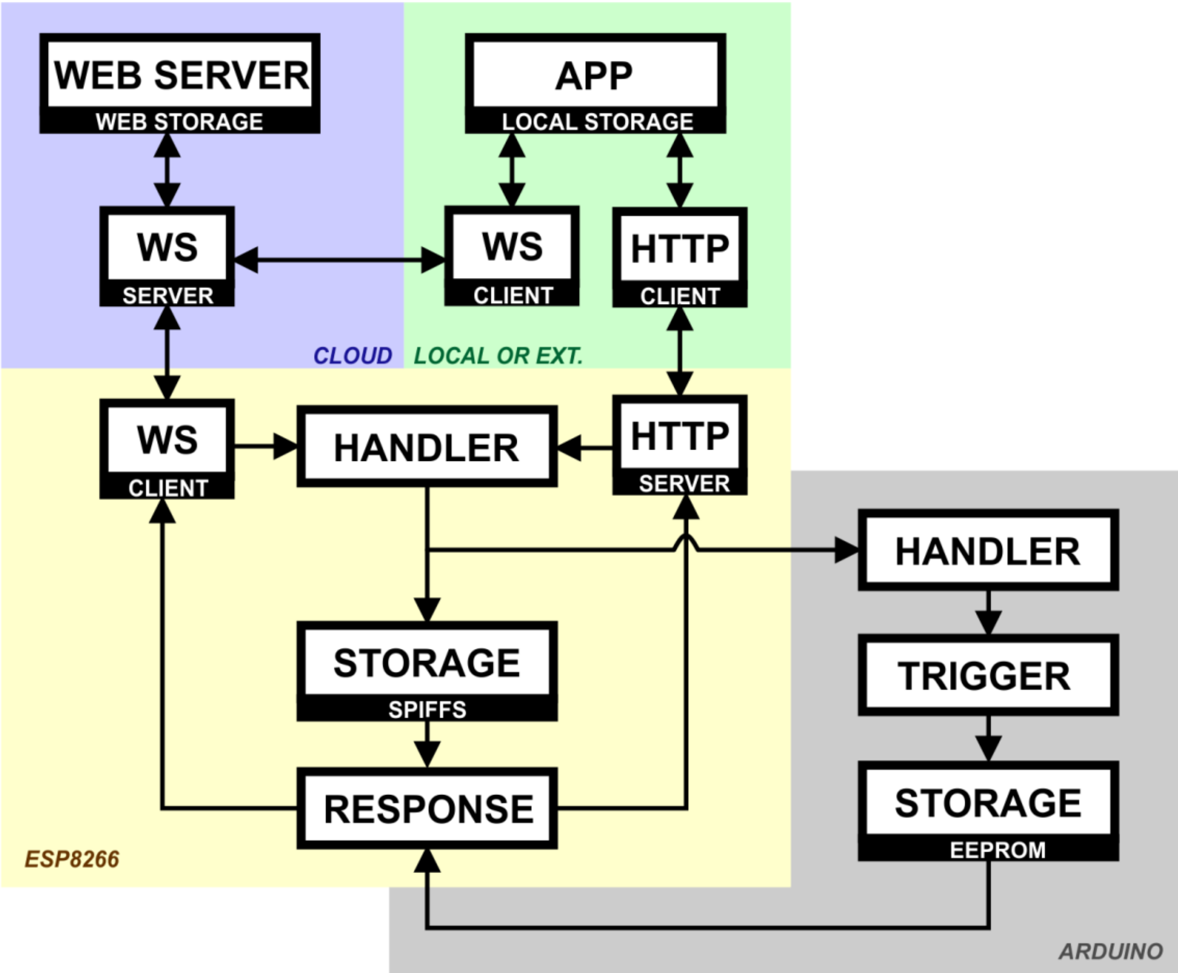
The web application was developed to work both online and offline. To open the online application and work in “online mode”, the user must simply enter the Internet browser and the domain where it is hosted (https://ntagbox.000 webhostapp.com). The online application can be hosted on any HTTP server; the domain used in this work is provided free of charge by “Hostinger”, with limited, but sufficient, configurations. Because there is an external server, an Internet connection is necessary. In this case, the connection is via WebSocket (WS), which is the best option, as the connection between the application and the physical device is done over the Internet; in this way, the user commands are stored on the server instantly.

On the other hand, to use the offline application and work in the “offline mode”, it is only necessary to have the site files in a folder on the computer, run the “intex.html” file, and the browser will run the application. In this case, the connection is via AJAX, which is used when there is no Internet access in the user’s home (or if the Internet drops out temporarily); thus, the connection between the application and the physical device is made by the Intranet, and in this way, the user commands are stored temporarily on the computer until the connection via WS is established.

In order for the local and external connection to be implemented on the physical device, two ways of WEB communication were created (Figure 9): HTTP and WS. Once a command is launched from the application (APP), an internal mechanism identifies whether there is access to the external (Internet) server or not (local connection), and also identifies whether the physical device is properly connected to that server. The application has two communication clients related to the two communication channels. If the device is connected on the Internet, WS is used as the communication channel both in the application and in the device since it is capable of establishing an endless connection with the server, allowing the data to be sent bidirectionally and asynchronously. When there is no Internet connection and the application is in the same local network as the physical device, the communication channel used is HTTP, with an HTTP server on the physical device so that it has an IP that identifies it locally.

In the physical device, the data packets can be received by the two communication channels. However, they are directed to a single channel—the HANDLER—that handles the information contained therein. The HANDLER has the function of authenticating the data received and identifying the command contained therein so that the TRIGGER can be activated. The TRIGGER is the set of triggers and sensors responsible for interacting with the user’s devices. Some commands simply require changes in the internal variables of the system. For this purpose, it also has a small non-volatile SPIFFS memory module responsible for storing such variables, such as SSID and Wi-Fi password; user password; relay states; etc. It is also essential to keep the data stable if there is any power outage. If everything succeeds, the RESPONSE block returns the confirmation message to the application, returning to the input path of the packet.

Figure 9 – Connectivity of the assistive system.

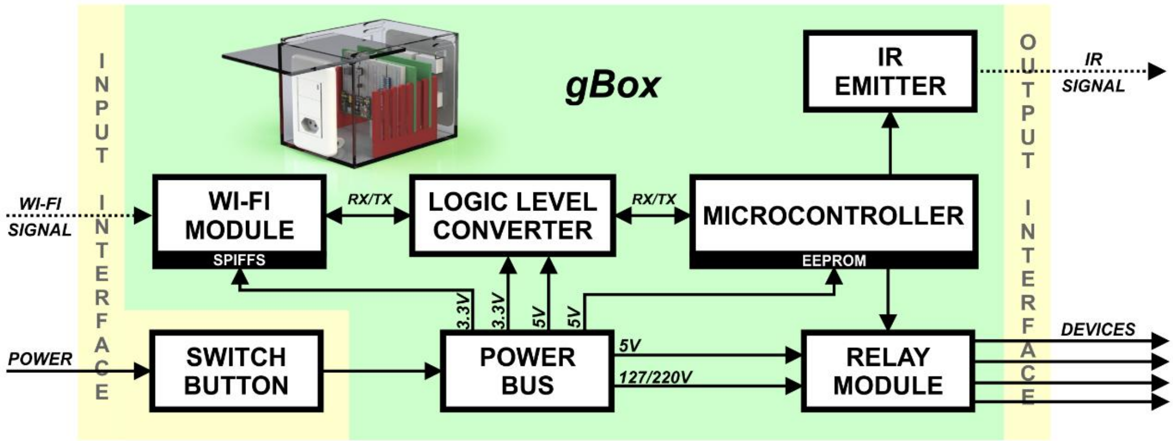



If this input path is the WS client, the packet will be returned to the WS server in the cloud, which will store the command so that it is accessible via Internet, and finally send the confirmation to the WS client of the application. If this input path is the HTTP server, the device returns the response directly to the application, which places it in a rank to be sent to the server as soon as an Internet connection is established.

## 4.3 GLOBALBOX (GBOX)

The GlobalBox (gBox) is the device controller module of the smart home. Figure 10 shows, in a simplified form, the main components of the gBox.

Figure 10 – GlobalBox (gBox) of the assistive system.



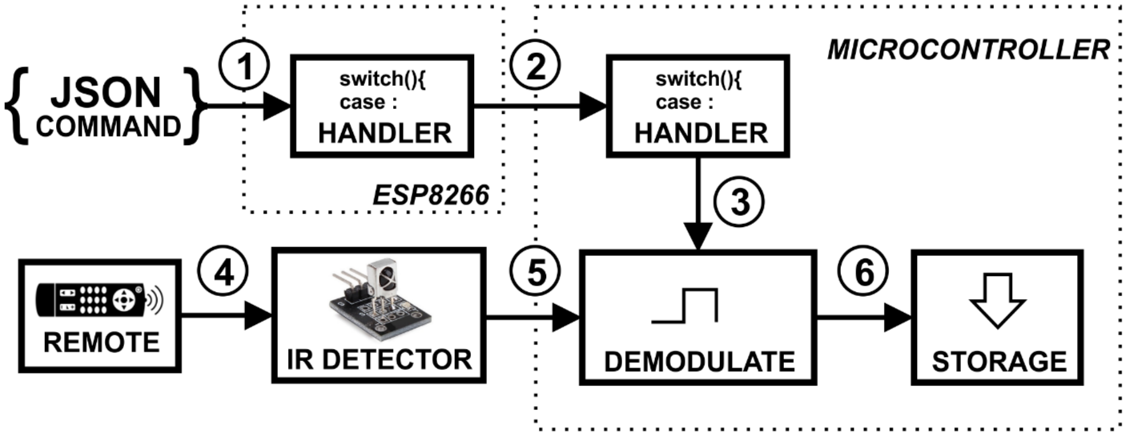

Before starting the application, the switch button must be turned on. With the box powered up, it is possible to receive information through the Wi-Fi module. This information is the command sent by the user through the user interface running on the computer. The information received by the Wi-Fi module is processed in the microcontroller, and then the actions corresponding to the received commands are performed, being able to turn the relays of the equipment on or off or send specific commands by the infrared (IR) emitter to control the functions of the TV or radio.

## 4.4 WIRELESS INFRARED COMMUNICATION

Infrared (IR) signals are essential to control some residential devices, such as TVs and radios. The gBox has an internal library with a set of IR protocols (the most used) already implemented, which assists in the task of modulation and demodulation of IR signals. The hardware consists of an IR detector that receives signals at 38 kHz, an IR emitter, and the microcontroller, which is responsible for treating and storing the signal in memory for later use.

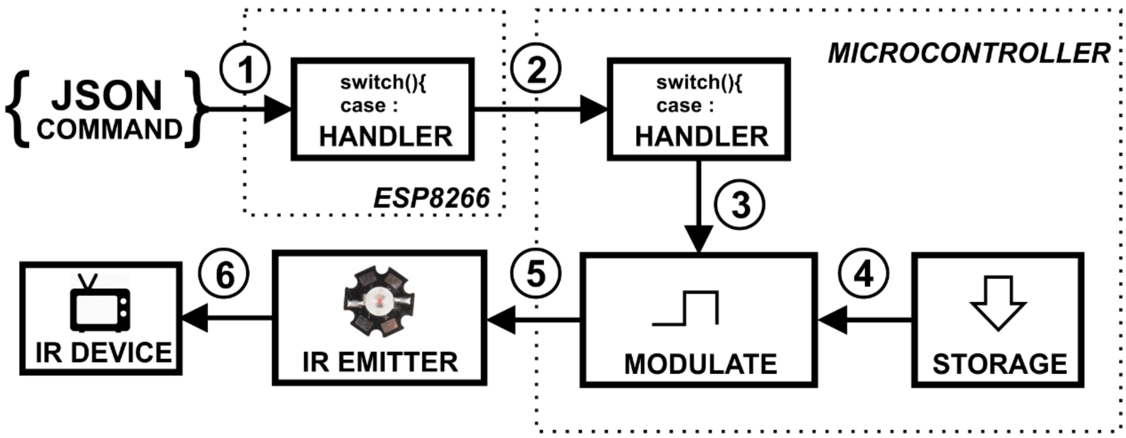
To store the code of any remote control, it is necessary to send the read command from the application so the demodulator will be activated; then, the caregiver can press the button (towards the IR detector) that he/she wants to record, which transforms the received IR signals into codes that can be stored in memory (Figure 11).

Figure 11 – Detection and storage of an IR command.




To emit an IR signal, it is necessary to start the application whose command activates the signal modulator, which takes the codes stored in the memory of the microcontroller and transforms them into the original IR signal, sending it to the IR emitter module (Figure 12). The emitter module, when pointed towards the target device, acts in the same way as the remote control in its respective function.

Figure 12 – Circuit of IR emission commands previously stored.




## 4.5 USER INTERFACE (UI)

The most well-known strategy of eye tracking applications is using the gaze to perform tasks of pointing and selecting. However, the direct mapping of the gaze (more specifically, of fixations) to a command of system selection creates a problem, called the “Midas Touch”, in which a selection can be activated in any screen position observed by the user, whether they intended to do it or not.

Thus, after filtering the eye tracker data, the Midas Touch problem must be avoided by implementing mechanisms for the user to indicate when he/she really desires to perform a selected command. The first approach to this problem is to implement a dwell time, in which the selection of one option is done only after a dwell time. Figure 13 shows screenshots of the proposed user interface.

Figure 13a shows the initial screen when the system is off. When the user turns the system on by selecting the “Start” icon, the main menu shown in Figure 13b appears. In Figure 13b, the user has three options: i) “Close”, to close the user interface of the system; ii) "Start", to open the home devices control menu; and iii) "Config", to open the configuration menu.

It is important for users to be able to turn the system on and off. That is why the interface presented in Figure 13b was included. If the user chooses “Close”, the system is closed and returns to the initial interface.

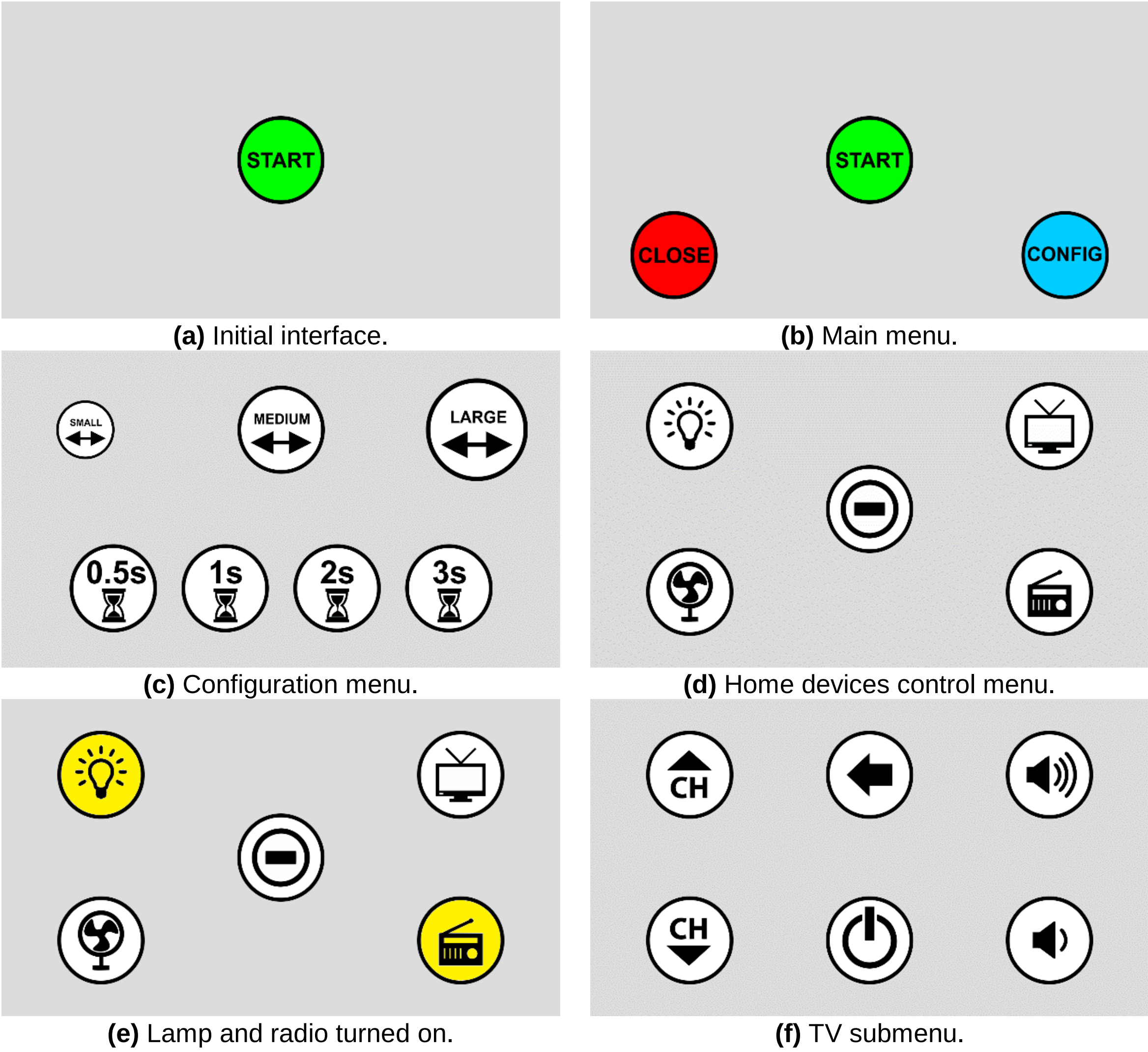
When the user selects the "Config" option in Figure 13b, the configuration menu shown in Figure 13c appears. In the configuration menu, the user can choose the icon size and the dwell time. There are three options to the icon size: i) "Small”; ii) "Medium”; and (iii) "Large”. There are four options dwell time: i) 0.5 s; ii) 1.0 s; iii) 2.0 s; and iv) 3.0 s. After choosing any of the options, the interface automatically returns to the main menu with the new configuration saved.

When the user selects “Start” option in Figure 13b, the control menu of the home devices shown in Figure 13d appears. In this menu, the user is presented with four options of devices to be turned on/off: a fan, TV, lamp and radio. In addition, there is an option to close that menu to return to the main menu (Figure 13b), by selecting the center icon. The icon size of the interface and dwell time used are the ones that the user selected in the configuration menu.

When the device is turned on, the background of the icon becomes yellow, like "Lamp" and "Radio" shown in Figure 13e. Fan and TV are turned off; thus, the background of the icons is white. After turning the desired device on or off, the user can give the command "Close" and turn the system off. This command closes the interface, but the system keeps the selected devices in their current state (on or off).

After selecting the TV icon, the interface displays the TV submenu, shown in Figure 13f. In the TV submenu, the user can turn the TV on or off; change the channel "up" or "down"; increase or decrease the volume; and close the TV submenu. Is this last option, the TV submenu is closed and the interface returns to the home devices control menu, but the system keeps the TV in its current state (on or off).

Figure 13 – User Interface.

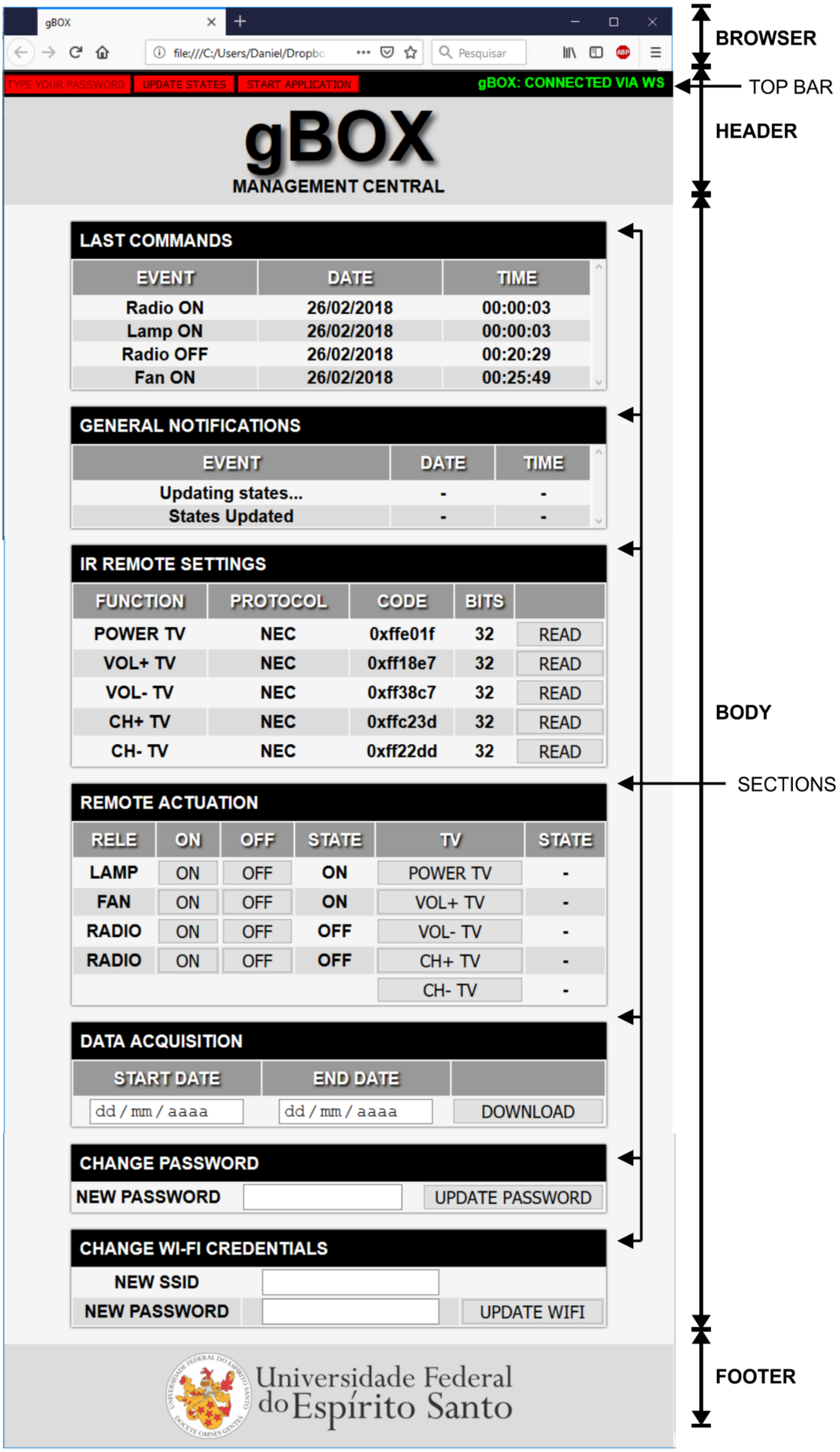



**(a)** Initial interface. **(b)** Main menu. **(c)** Configuration menu. **(d)** Home devices control menu. **(e)** Lamp and radio turned on. **(f)** TV submenu.

## 4.6 CAREGIVER INTERFACE

The gBox Central Management (Figure 14) is a web application completely developed to run in Internet browsers. It is recommended to use the most up-to-date versions of well-known browsers, such as Google Chrome. Therefore, it is not necessary to install any external programs in addition besides the browser to the application work correctly on the computer.

Figure 14 – Screenshot of gBox management graphical interface.



Such as aforementioned, the application can be opened with or without internet connection. To open the online application, it is necessary to enter the internet browser with the domain, which is hosted in (https://ntagbox.000webhostapp.com). The application can be hosted on any http server. The domain used is provided free by Hostinger, with limited, but sufficient, settings for the application. Due the application is on an external server, it is necessary an Internet connection. Additionally, it is also possible to open the application with or without Internet connection, by having the site files in some folder on the computer and running the intex.html file; this way the browser will open the application.

In the header of the caregiver interface are the top bar and titles. Before giving any command in the application, it is required to enter the password in the password field of the bar. After that, it is recommended to click “Update Status” so that the application synchronizes with the current states of the equipment. The “Start Application” button opens the user interface so the user can control the smart home with the eye tracker. On the right side of the bar, the connection status between the application and the physical devices is reported. The connection flag is independent of the access password to be updated. There are three possible connection status:

- Connected via WS. This is the best connection. It occurs when the connection between the application and the physical device is done by Internet; that way, user commands are stored on the server instantly.
- Connected via AJAX. This occurs when the connection between the application and the physical device is made by the Intranet, so the commands are stored temporarily on the user’s computer until a connection via WS is established.
- Not Connected. This occurs when there is no connection between the application and the physical device. In this case, it is suggested to refresh the site and check the connections with the physical device.

The body of the application is composed of seven sections: i) Last Commands; ii) General Notifications; iii) Infrared Remote Control Settings; iv) Remote Actuation; v) Data Acquisition; vi) Change Password; and vii) Change Wi-Fi Password, the details of which are as follows:

1) “Last Commands”: In this section, the commands successfully performed are presented, as well as the date and time they occurred. To appear in this list, it is necessary to update the states after establishing a WS connection.

2) “General Notifications”: In this section, all the notifications from the application features are presented; for example, “updating status” or “the status are updated”.

3) “Infrared Remote Control Settings”: In this section, it is possible to update the IR commands by pressing the “READ” button and follow the instructions displayed in the general notifications section. In addition, hexadecimal codes and protocols of the buttons/commands of the IR control are presented.

4) “Remote Actuation”: Remote actuation can be used to control the smart home application by using the caregiver application.

5) “Data Acquisition”: This section allows the download of the list of commands based on a specified time interval. The downloaded text file can be accessed in any text editor or spreadsheet analysis program.

6) “Change Password”: This section allows the change of the user password. It is necessary that the password field of the upper bar be correctly filled with the old password.

7) “Change Wi-Fi Password”: This functionality allows the change of the passwords of the SSID and of the Wi-Fi. It is necessary that the password field of the upper bar be correctly filled with the user password.

# 5 TESTS, RESULTS AND DISCUSSIONS

In this chapter we present the tests performed and the results obtained. Table 4 shows how the tests were divided.

Table 4 – Tests.

| **Tests** | **Participants** | | **Local** | **Evaluation tool** |
|---|---|---|---|---|
| | **Able-bodied** | **People with disabilities** | | |
| 1 | 10 | 0 | Laboratory | IRT and Utility |
| 2 | 15 | 2 | Laboratory | SUS |
| 3 | 29 | 0 | Adapted house | SUS |
| 4 | 0 | 1 | End-user house | SUS |

As can be seen in Table 4, the tests were divided into four steps. The first two steps of project testing were done previously in the laboratory (BISSOLI, 2016). The objective of the first step was to test the eye tracker and evaluate the Information Transfer Rate (ITR) and Utility. In contrast, the second stage was conducted by 15 participants (able-bodied) and two people with disabilities. After the end of the test, participants answered the SUS questionnaire. In the two test steps the same protocol was followed.

The third and fourth steps were performed outside the laboratory. In the third step, the system was completely installed in a residence and the tests were conducted with 29 participants. Finally, in the fourth stage, the system has been completely adapted to be used for a long period in the home of an end-user (person with disabilities) and monitored remotely by the caregiver.

According to Resolution No. 466/12 of the National Health Council of Brazil, the research was approved by the Committee of Ethics in Human Beings Research of the Federal University of Espirito Santo (CEP / UFES) through opinion nº 2.020.868, of April 18, 2017.

## 5.1 SYSTEM EVALUATION

Ten people without disabilities (able-bodied) performed five pre-determined tasks, listed below, using the eye tracker. The volunteers sat on a comfortable chair, in front of a notebook, in which the systems were run.

1) Turn the interface on, turn the light on, turn the fan on and turn the interface off.
2) Turn the interface on, turn the TV on, change the channel "up", return and turn the interface off.
3) Turn the interface on, turn the TV on, turn the TV off, turn the radio on and turn the interface off.
4) Turn the interface on, turn the radio off, turn the fan off and turn the interface off.
5) Turn the interface on, turn the light off and turn the interface off.

Table 4 shows the system performance using the eye tracker. This HCI has an average accuracy of 100% and mean duration of task of 1.85s (0.16s of standard deviation). The average ITR was 75.69 bits/min (standard deviation of 6.61) and average Utility of 37.86 bits/min (standard deviation of 3.31). Most ITR and Utility was achieved in Task 5 (84.37 and 37.86) and the lowest was in Task 3 (67.91 and 33.97).

Table 5 – System performance with eye tracker.

| Task | Accuracy (%) | Time (s) | ITR (bits/min) | Utility (bits/min) |
|---|---|---|---|---|
| 1 | 1.00 | 1.83 | 76.28 | 38.16 |
| 2 | 1.00 | 2.03 | 68.58 | 34.31 |
| 3 | 1.00 | 2.05 | 67.91 | 33.97 |
| 4 | 1.00 | 1.71 | 81.29 | 40.67 |
| 5 | 1.00 | 1.65 | 84.37 | 42.21 |
| Average | 1.00 | 1.85 | 75.69 | 37.86 |
| Deviation | 0.00 | 0.16 | 6.61 | 3.31 |

## 5.2 TESTS IN THE LABORATORY

Such as aforementioned, 15 participants (able-bodied) performed the protocol, being 12 male (76.5%) and 3 female (23.5%), aged 20-38 years. In addition, two people with motor disabilities also performed the tests in the laboratory (BISSOLI, 2016).

Characterization of people with disabilities who performed the tests:

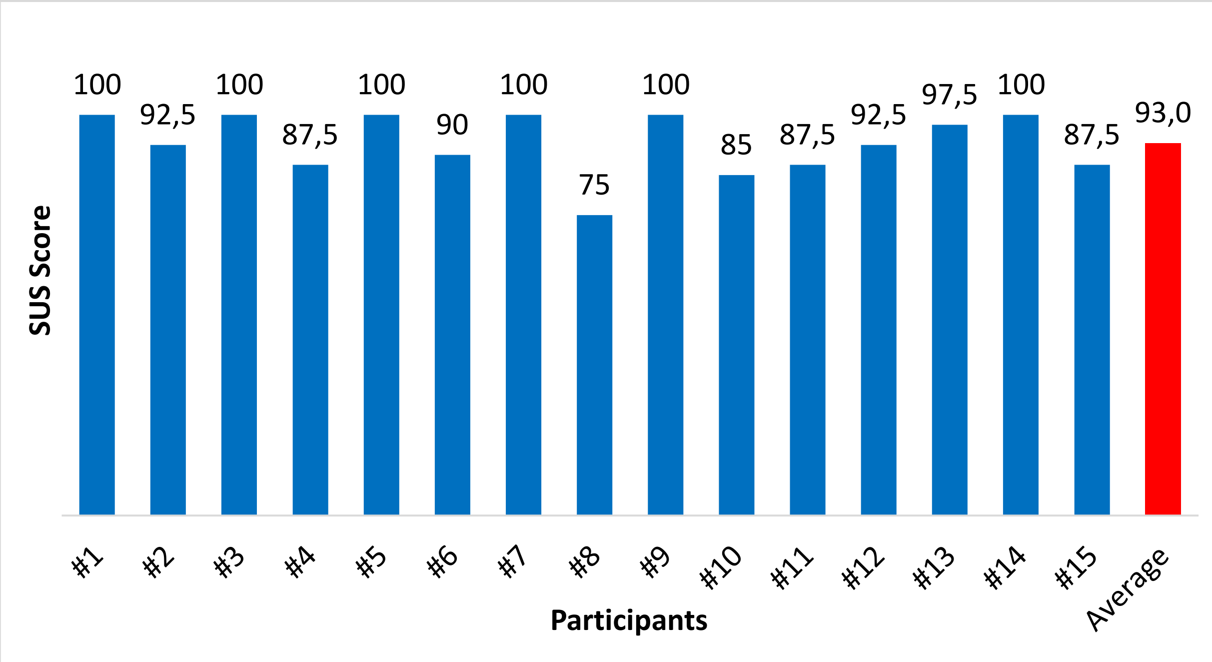
1. Volunteer #16, female gender, 36 years old. Diagnosis: Wernicke syndrome since June 2012, leading to incoordination of movements (ataxia) and deficit of balance. The most committed activities are those that require fine manual dexterity (typing on the computer, writing, using the mobile device) and wandering (walking).

2. Volunteer #17, male gender, 28 years old. Diagnosis: Stroke (stroke) since September 2011, leading to left hemiparesis and aphasia (difficulty for verbal expression).

In the case of this study, only one punctual intervention was performed using the system, with no changes after its use, and the tasks and parameters were established by the group of researchers before contact with the volunteers. The aim was to verify if the user's performance, after using the system, without any training, approached the performance expected by the team.

After performing all the tasks dictated without pause, each participant answered the SUS instrument. Regarding SUS results, the overall mean was 93.00 ± 7.31. The individual results are presented in Figure 15. With regard to volunteers with disabilities, volunteers #16 and #17 evaluated the system with a SUS score of 97.5 and 67.5, respectively.

Figure 15 – Results of the SUS, per participant.




## 5.3 TESTS IN AN ACTUAL HOME

In this section, we report the experiments, which were divided into two steps, and analyze and discuss the results. In the first step, the proposed assistive system was assembled in an actual home where tests were conducted with 29 participants (group of able-bodied participants). In the second step, the system was tested for seven days, with online monitoring, by a person with severe disability (end-user) in her own home, not only to increase her convenience and comfort, but also so that the system would be tested where it would in fact be used. The objective of this test was to explore the effectiveness of the assistive system, the ability of the participant to learn how to use the system, and the efficiency and the usability of the proposed user interface.

### 5.3.1 Pre-Test Preparation

Initially, we fully installed the system and tested all possible commands to verify that the system was working properly. Some errors were found and quickly corrected so that the system was considered to work perfectly before we started the tests with the participants.

Afterwards, a pilot test was conducted with one of the involved researchers to rehearse the procedure before conducting the study with the participants. The researcher completed all the data collection instruments. The problems encountered during the pilot test helped to identify changes before conducting the experiment with the participants.

### 5.3.2 Participants

Table 6 presents the characteristics of the participants. To test the system, 29 healthy subjects (group of able-bodied participants) participated in the research with the assistive system in the smart home. The participants were 18 men and 11 women, all aged from 17 to 40 (average: 28) and height from 1.50 to 1.94 (average: 1.71). Some of the participants had had at least one experience with HCI through biological signals, but almost none of them had used eye tracking.

The first column differentiates each of the 29 participants. We refer to them with ordinary numbers, i.e., #1, #2, ..., #29. The second column shows the age of each participant. The third column presents the gender of each participant, being male (M) or female (F), and the fourth column shows the height of the participants (this information is important to show that the system can be used by people of different heights). Due to the customized solution, it was possible to change the inclination of the eye tracker towards the direction of the participant's eyes. The fifth column informs if the participant makes use of glasses to correct the vision. Finally, the sixth column discloses if the participant performed the tests using his/her glasses. It is important to note that 12 participants (#2, #8, #9, #11, #12, #14, #15, #16, #17, #22, #25 and #26 wear glasses); however, all of them performed the test without their glasses. In some cases, it was by preference of the participant himself/herself, but in most of cases, their glasses had anti-reflective film, which prevented, or at least disturbed, the infrared eye tracker passing through the lens of the glasses to obtain the correct position of the eyes of the participant. This is an important limitation of this study.

Table 6 – Participant characteristics.

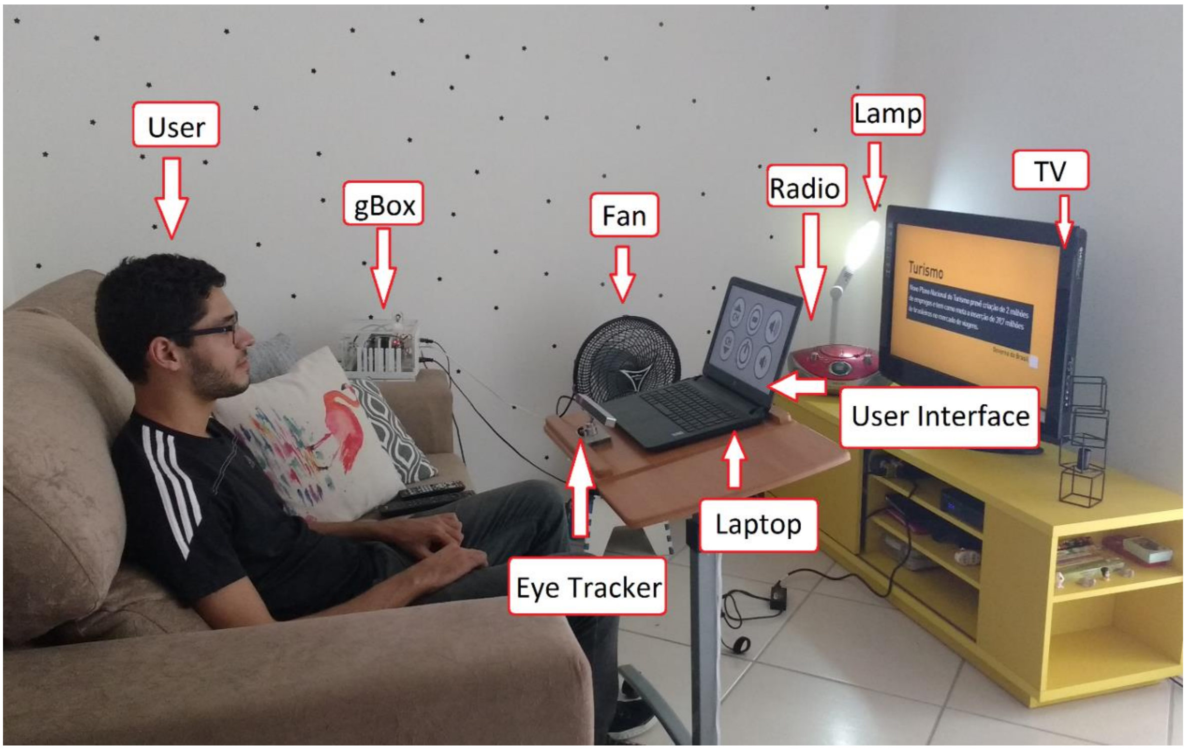
| Participant Code | Age (years) | Gender | Height (m) | Wear glasses | Performed the tests wearing glasses |
|---|---|---|---|---|---|
| #1 | 40 | F | 1.68 | No | 0 |
| #2 | 26 | M | 1.79 | Yes | No |
| #3 | 31 | F | 1.58 | Yes | Yes |
| #4 | 21 | F | 1.60 | No | 0 |
| #5 | 26 | F | 1.67 | No | 0 |
| #6 | 31 | M | 1.94 | No | 0 |
| #7 | 26 | F | 1.63 | No | 0 |
| #8 | 17 | F | 1.60 | Yes | No |
| #9 | 35 | F | 1.74 | Yes | No |
| #10 | 20 | M | 1.78 | Yes | Yes |
| #11 | 29 | M | 1.78 | Yes | No |
| #12 | 26 | M | 1.82 | Yes | No |
| #13 | 23 | M | 1.72 | No | 0 |
| #14 | 21 | M | 1.74 | Yes | No |
| #15 | 25 | M | 1.75 | Yes | No |
| #16 | 23 | F | 1.58 | Yes | No |
| #17 | 23 | F | 1.65 | Yes | No |
| #18 | 27 | M | 1.70 | No | 0 |
| #19 | 28 | M | 1.81 | No | 0 |
| #20 | 33 | M | 1.78 | No | 0 |
| #21 | 30 | F | 1.60 | No | 0 |
| #22 | 36 | M | 1.85 | Yes | No |
| #23 | 36 | M | 1.67 | No | 0 |
| #24 | 28 | M | 1.80 | No | 0 |
| #25 | 26 | M | 1.80 | Yes | No |
| #26 | 24 | M | 1.68 | Yes | No |
| #27 | 31 | M | 1.78 | No | 0 |
| #28 | 27 | M | 1.71 | Yes | Yes |
| #29 | 34 | F | 1.50 | Yes | Yes |

### 5.3.3 Experimental Sessions

The tests started by welcoming the participants and making them feel at ease. The participants were given an overview of the system and the test and were told that all their information will be kept private.

Each participant was seated on a couch in front of the laptop that contained the user interface, and the eye tracker was positioned properly pointing to his/her eyes (Figure 16).

Figure 16 – Able-bodied participant testing the system in the smart home.




After that, the participant performed the calibration stage of the eye tracker, following the manufacturer's guidelines. Each participant performed the test over about five to ten minutes. It was required of the participants to use the system long enough so they could test all the functionality options available.

It is important to mention that the user was positioned facing a glass door that provided access to a balcony, with high incidence of sunlight. Despite this, the sunlight did not cause a problem in performing the experiments, showing the robustness of the eye tracker.

It can be seen in Figure 16 that the eye tracker was positioned towards the user's eyes. In the course of the experiments, it is normal for a person to move his/her head a little, moving away from the location where the eye tracker was calibrated. We note that small vertical and horizontal position variations (around 5 to 10 cm) did not significantly interfere with the system performance. However, if the user's eyes are completely out of range of the eye tracker, then he/she will not be able to send commands to the system. In this case, it may be necessary to reposition the eye tracker and calibrate it again. Considering that this system was designed to be used by people with severe disabilities, it is not expected that they will have wide head movements.

After the end of the session, the participant answered the SUS questionnaire and was encouraged to make suggestions.

#### 5.3.4 Results and Discussions

Figure 17 shows the number of participants who opted for each of the available interface icon size options. It can be observed that, as predicted in our previous work (BISSOLI, 2016), that most users opted for the medium size option. However, it is important to note that 7 participants (24% of the total) preferred another size, thus showing the advantage of having this functionality available.

Figure 17 – Number of participants per interface icon size.

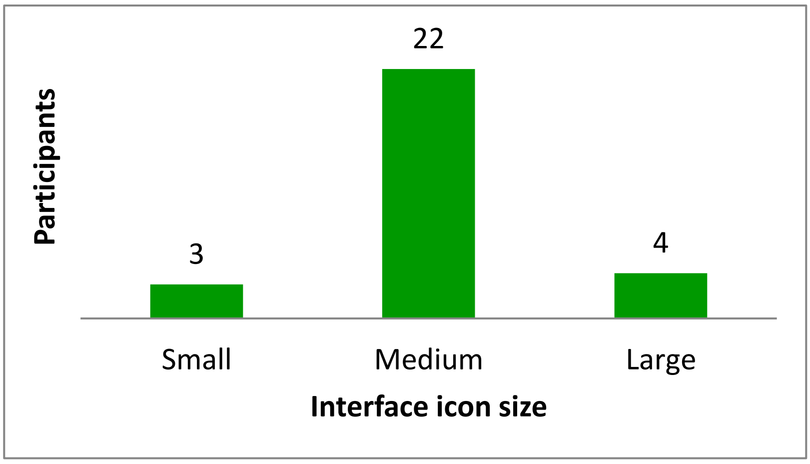
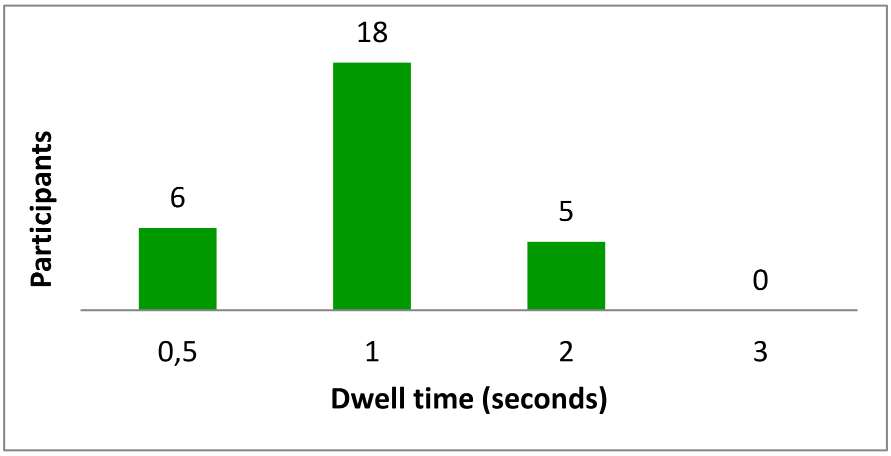



Figure 18 shows the number of participants who opted for each of the available options for dwell time. It can be observed that, as predicted in our previous work (BISSOLI, 2016), most users opted for the option of 1.0 s. However, it is important to note that 11 participants (38% of the total) preferred another dwell time, thus showing the advantage of having this functionality available.

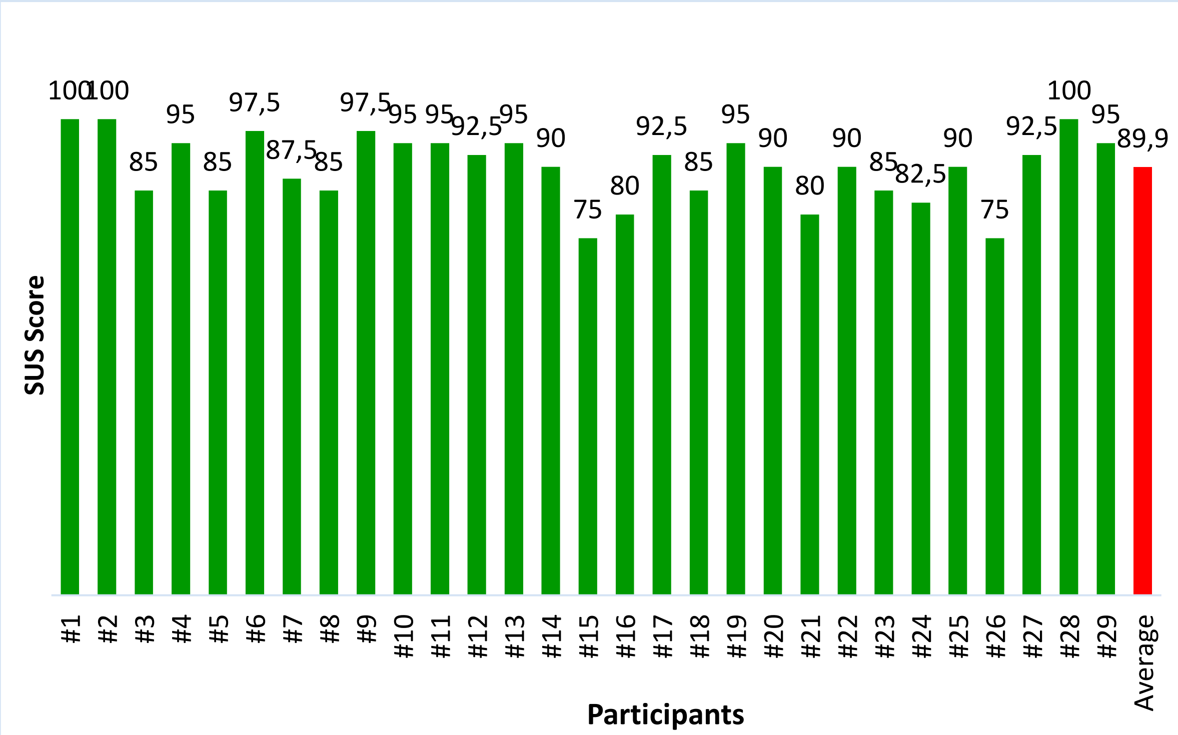
Figure 18 – Number of participants per dwell time to command the interface.




In fact, only 14 participants opted for the combination of medium size and 1.0 s. In other words, 15 participants (52% of the total) prefer another size or other dwell time, and this shows the importance of having the option to choose, in order to increase the usability of the system.

With regard to usability, Figure 19 shows the SUS score for each participant and the overall mean.

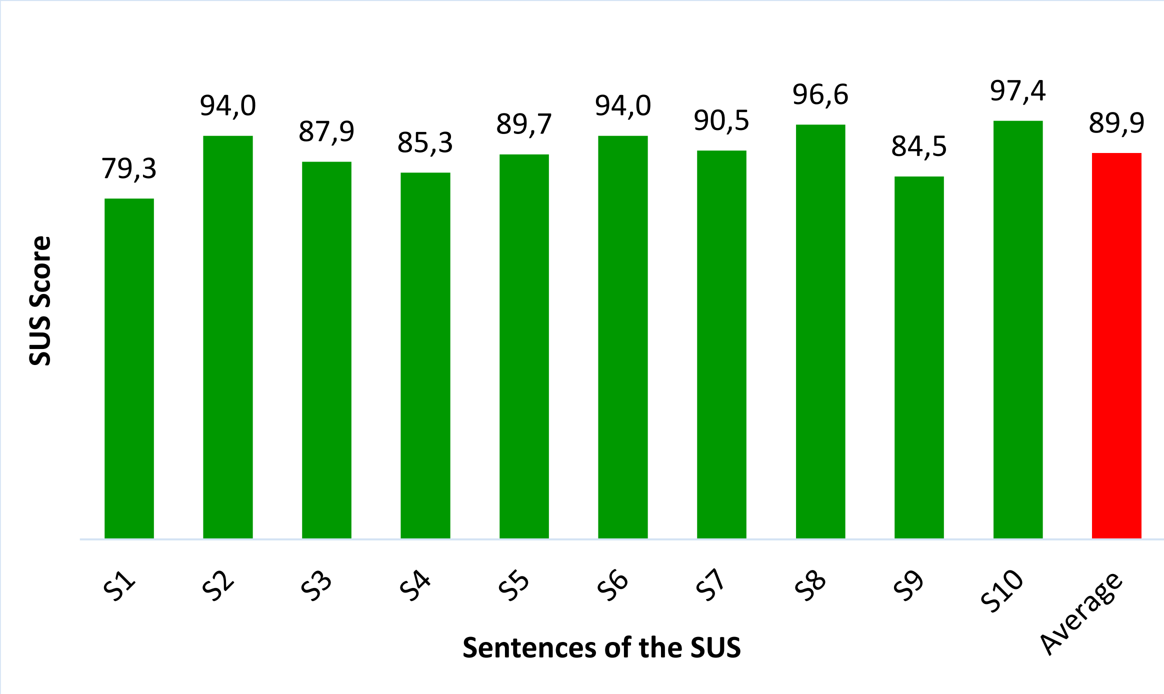
Figure 19 – SUS score of each participant.




According to Figure 19, three participants gave a maximum score, and the lowest result was 75. Thus, the overall mean was 89.9, with a standard deviation of 7.1. It is worth mentioning that products evaluated above 80.3 are in the top 10% of the scores. In fact, according to (BANGOR; PHILIP; JAMES, 2009; BROOKE, 1986), the products evaluated in the 90-point range are considered exceptional, products evaluated in the range of 80-points are considered good, and products evaluated in the range of 70-points are acceptable.

Figure 20 presents the SUS score of each item evaluated by the participants regarding the assistive system.

Figure 20 – SUS score of each of the ten sentences of the SUS.




The sentences regarding the available functionality, the complexity in using, and the confidence in the functioning all received scores above 80. The lowest score obtained (79.3) was related to the sentence S1, which is about interest in using the system frequently. Many participants said that they would not have much interest in using this system, as the system was designed for a person with disability, which is not the case for the participant (able-bodied). This reinforced the need to test the system with people with severe disabilities.

## 5.4 TESTS IN AN END-USER'S HOME

### 5.4.1 Pre-Test Preparation

Initially, an interview was conducted by the occupational therapist of our research group to better understand the potential participant. At this point, relevant information was gathered about her disability and daily life, whether there was interest in participating in the study, in what activities she was most involved, and what tasks she would like to be able to do or have the assistance of the technology to execute.

After this first contact, the information was brought to the research group and the candidate was selected to participate in the experiments. A telephone appointment was made between the occupational therapist and the participant's husband at their home, where the system would be used.

### 5.4.2 Participant Background

The participant is female and 38 years old. She was diagnosed in June 2012 with Wernicke's Encephalopathy. Thus, the participant presents a lack of coordination of movements (ataxia) and extreme difficulty in balancing and walking. Her most difficult activities are those that require manual dexterity, such as typing on the computer, writing, using a mobile device, and handling the TV remote control. In addition, the participant has difficulty walking, considered practically impossible by her, or when necessary, causing enormous discomfort.

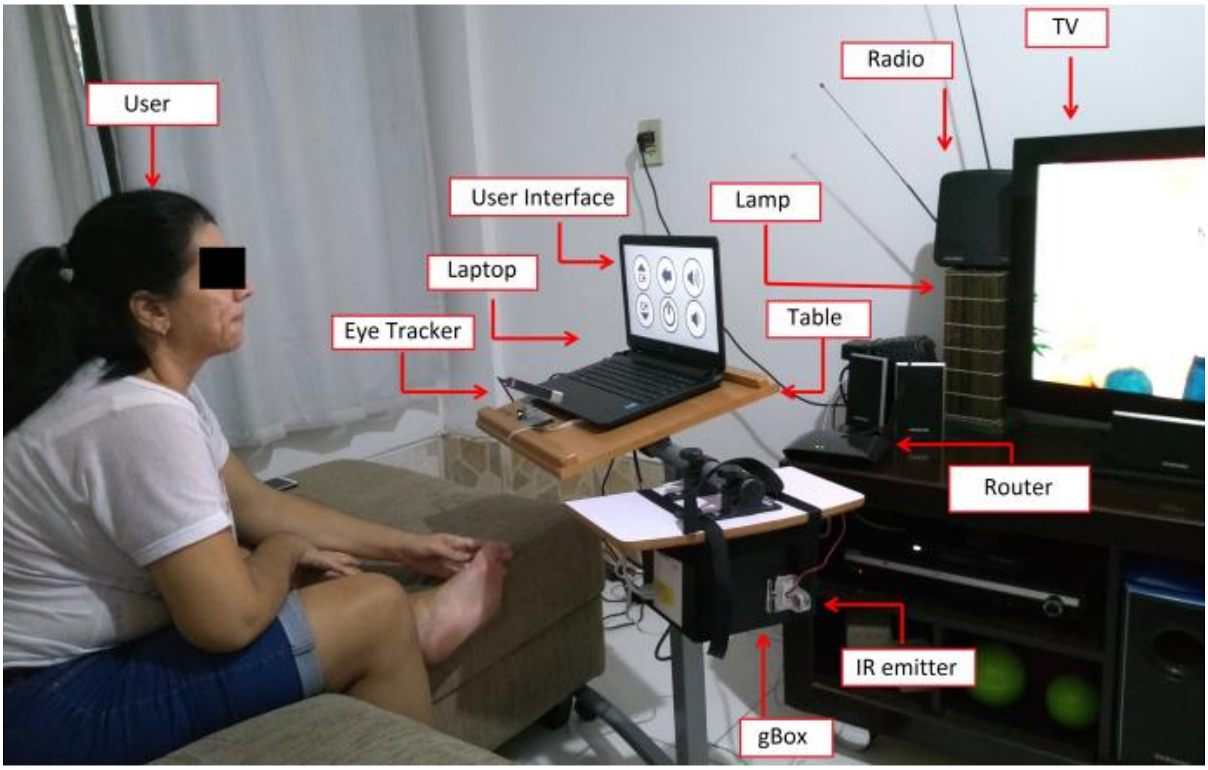
### 5.4.3 Experimental Sessions

To test the assistive system, it was firstly fully assembled and configured in the home of the end-user, who agreed to participate in the experiments (Figure 21). The participant was given an overview of the system and test. Before proceeding to the test, one of the researchers performed all possible commands to verify that the system was working properly.

Before proceeding to the test, three important quality checks were performed. First of all, a cognitive walkthrough was conducted where the system was turned on, and all the tasks supported by the system were successfully completed.

Afterwards, a pilot test was conducted with one of the involved researchers to rehearse before conducting the study with the participant. The researcher completed all the paper work. The problems encountered during the pilot test helped identify changes before conducting the experiment with the participants. No technical issues with the system were reported in this test. Finally, the complete checklist for experimental setup was double-checked.

Figure 21 – Participant with disabilities testing the system at her home.



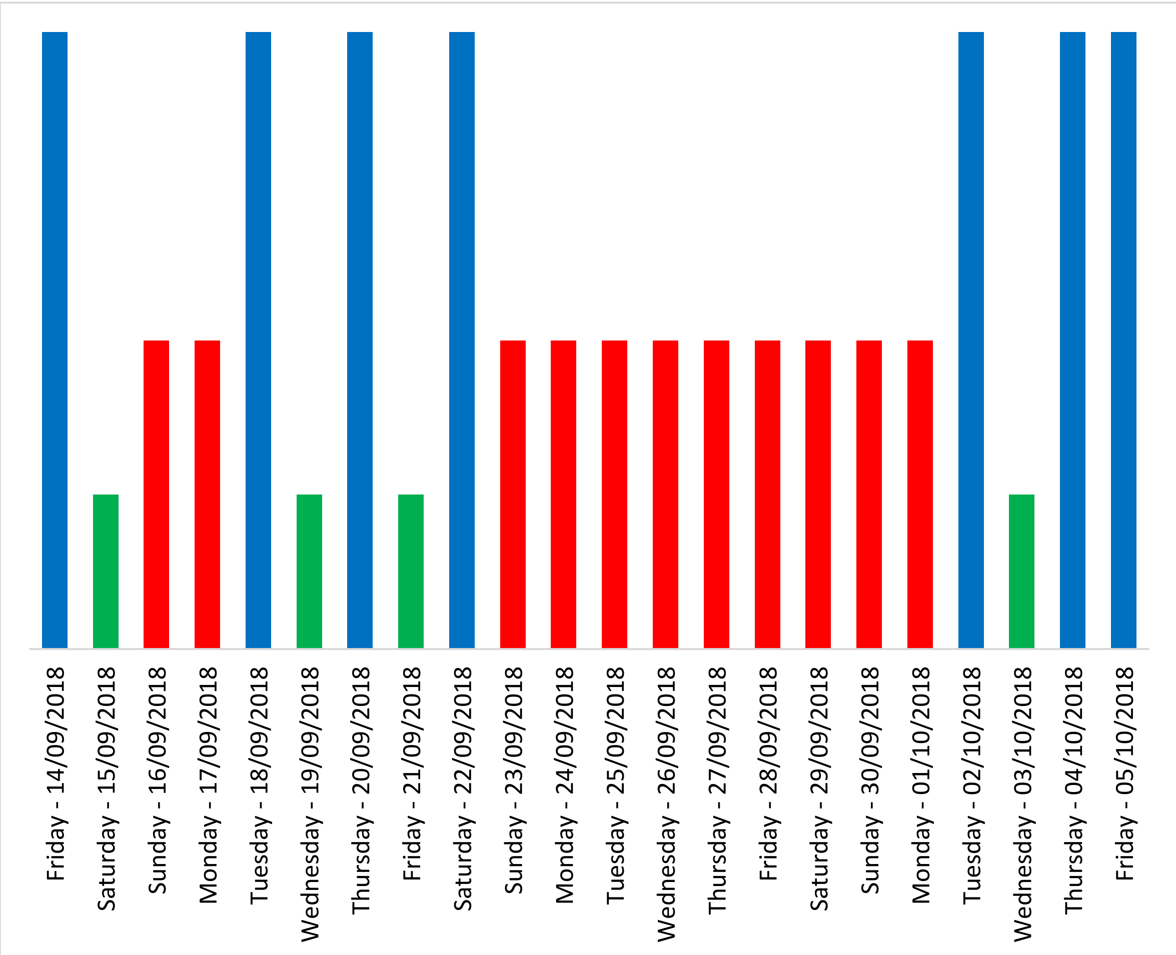

The participant was seated on a couch in front of the laptop that contained the user interface, and the eye tracker was positioned properly, pointing towards her eyes (Figure 21). After that, the participant performed the calibration stage of the eye tracker, following the manufacturer’s guidelines. The participant performed the test over seven days. It was required of the participant to use the system long enough so she could test all the functionality options available.

After the end of the session, the participant answered the SUS questionnaire and was also encouraged to make suggestions.

### 5.4.4 Results and Discussions

Figure 22 shows the days the equipment was installed and available for use at the participant's home. The large (blue) bars represent the days that the equipment was used. The medium (red) bars indicate the days that the researchers already knew beforehand that the system could not be used because of the participant's commitments. The small (green) bars indicate the days that the system could be used, but it was not.

Figure 22 – The days that the equipment was installed in the participant's home.




According to information obtained in the interview with the participant, Friday and Saturday were the best days of the week for her to receive the researchers in her home, so she opted to install the system on a Friday (September 14, 2018) and uninstall on a Saturday (October 06, 2018). Before the experiments, the participant had informed that she could not use the equipment on Sundays and Mondays, as on Sunday she usually receives many relatives in her house, and on Monday she spends the whole day away from home. In addition, the participant informed that she would need to make a trip for personal reasons during the experiment (from September 23, 2018 until October 01, 2018). All these situations put forward by the participant were considered pertinent, as they actually depict the daily life of a person with disability, revealing how technology needs to adapt to the person's life. In addition, it was considered interesting to evaluate if the participant would use the system after she was away from home for a few days without using it. In many cases, assistive technology is abandoned, which did not happen with our system.

The proposed assistive system made possible the elaboration of Figure 23, which shows the number of hours the system was used during the seven days of use.

Figure 23 – System usage time in hours per day of use.

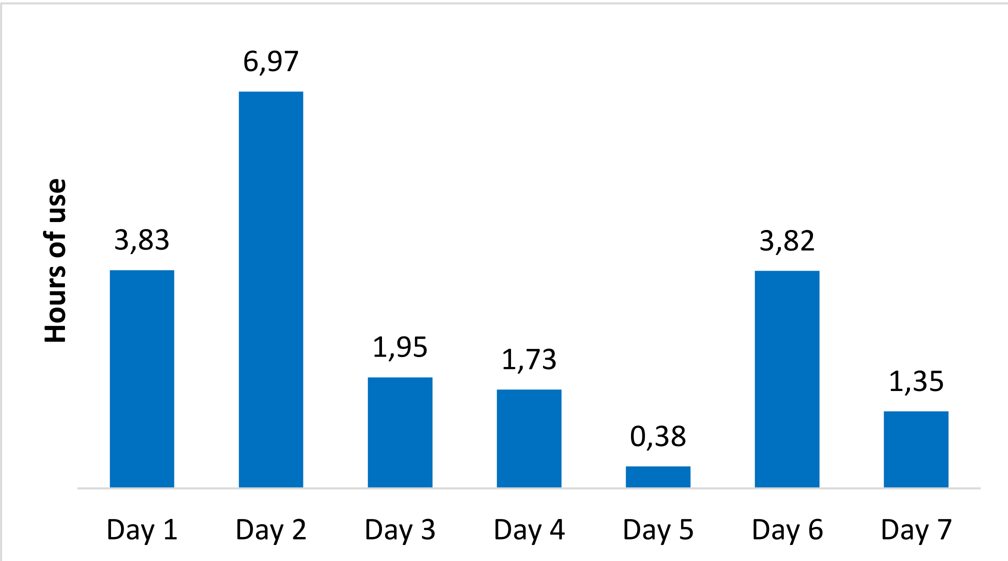



Table 7 shows the use of the assistive system by the participant, which shows the number of hours the system was used during the seven days of use. The first column indicates the days the system was used. The second indicates the time the first command was sent throughout the day. In contrast, the third column indicates the time the last command was sent on that day. The fourth column gives the duration in hours that the system was used on that day. The fifth column tells how many commands the system received and executed throughout the day.

Table 7 - Summary of system usage information

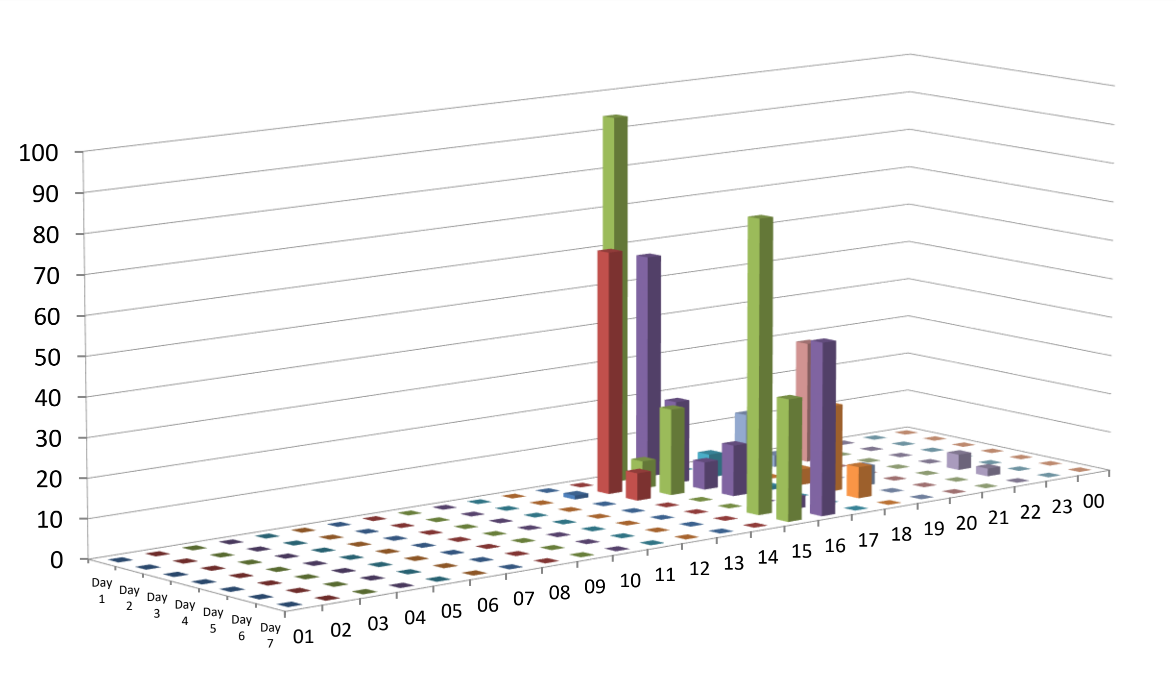
| Date | Start | End | Duration | Commands |
|---|---|---|---|---|
| 14/09/2018 | 14:20 | 18:10 | 03:50:00 | 163 |
| 18/09/2018 | 12:51 | 19:49 | 06:58:00 | 131 |
| 20/09/2018 | 13:58 | 15:55 | 01:57:00 | 36 |
| 22/09/2018 | 15:52 | 17:36 | 01:44:00 | 18 |
| 02/10/2018 | 17:38 | 18:01 | 00:23:00 | 31 |
| 04/10/2018 | 14:15 | 18:04 | 03:49:00 | 88 |
| 05/10/2018 | 14:35 | 15:56 | 01:21:00 | 75 |
| **Total** | | | **20:02:00** | **542** |

It is important to note that the system was not only used, but used for several hours over several days, which was better than expected. The tests previously performed with people without disabilities (able-bodied participants) of only 5 to 10 minutes – although they were important to evaluate the system being used by several users – were much less representative than the present test with the person with disabilities, which had a total duration of more than 20 hours.

Another fact that corroborates this is the number of commands received by the system over the days, shown in Table 7. Note that the system received a total of 542 commands and, as reported by the user, worked perfectly.

To better understand how the system was used by the participant, Figure 24 presents an hourly distribution of the commands sent to the system over the days. It can be observed that the system was always used between 2 pm and 10 pm. The vertical axis shows the number of commands executed by the system at that time of that day.

Figure 24 – Hourly distribution of the commands throughout the days of use of the system.



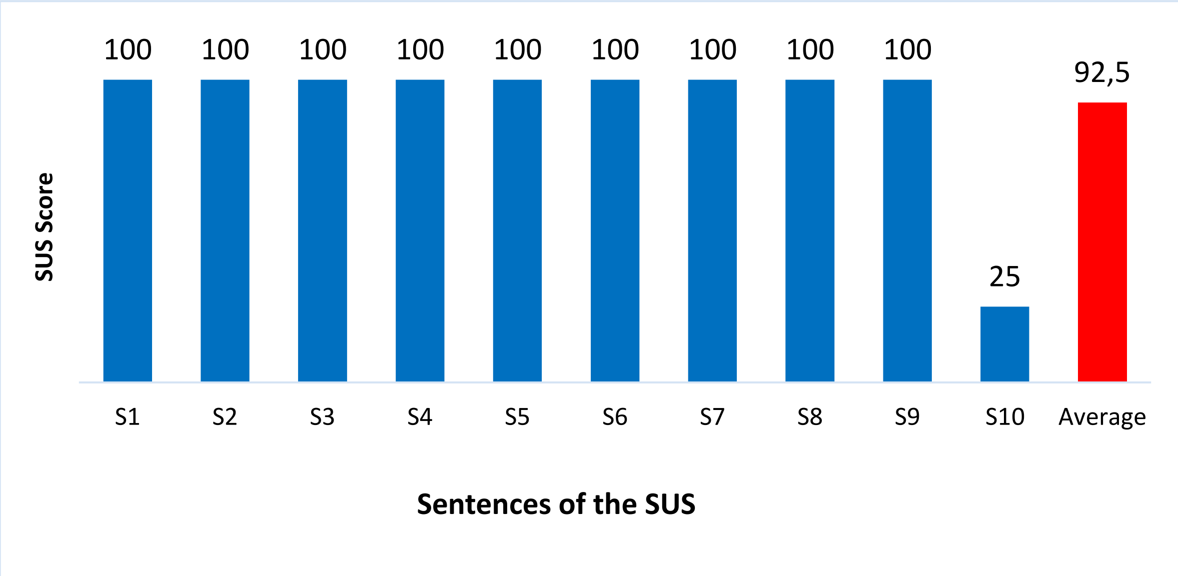

Finally, Table 8 summarizes the complete information about the commands received by the system throughout the entire test. It is possible to observe that more than 80% of the commands were sent between 1 pm and 4 pm, indicating a user routine.

Table 8 – Hourly distribution of the commands throughout the days of use of the system.

| From | To | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Day 6 | Day 7 | Percentage |
|---|---|---|---|---|---|---|---|---|---|
| 00 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 12 | 13 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0% |
| 13 | 14 | 0 | 62 | 7 | 0 | 0 | 0 | 0 | 13% |
| 14 | 15 | 94 | 7 | 22 | 0 | 0 | 75 | 31 | 42% |
| 15 | 16 | 57 | 21 | 7 | 13 | 0 | 3 | 44 | 27% |
| 16 | 17 | 0 | 6 | 0 | 1 | 0 | 0 | 0 | 1% |
| 17 | 18 | 0 | 0 | 0 | 4 | 22 | 8 | 0 | 6% |
| 18 | 19 | 12 | 3 | 0 | 0 | 5 | 0 | 0 | 4% |
| 19 | 20 | 0 | 31 | 0 | 0 | 0 | 0 | 0 | 6% |
| 20 | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 21 | 22 | 0 | 0 | 0 | 0 | 4 | 2 | 0 | 1% |
| 22 | 00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 23 | 00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| **Total** | | **163** | **131** | **36** | **18** | **31** | **88** | **75** | **542** |

Figure 25 shows the result of the SUS, answered by the user. Regarding the usability (SUS), the user gave the maximum score for all the questions regarding the willingness to use the system, available functions, ease and confidence in using it, etc. So, focusing on the only feature that the user rated low, according to her, she needed to learn many new things to be able to use the system and so she gave a low score on that item. She believes that after using the system more, she will not need to learn so much more additional information.

Figure 25 – SUS Score of each sentence according to the end-user.




Despite this, the user evaluated the system with an average of 92.5, which is quite high, even higher than the previous tests with the able-bodied participants, in which the overall mean was 89.9. In fact, according to (BANGOR; PHILIP; JAMES, 2009; BROOKE, 1986), the products evaluated in the 90 point range are considered exceptional.

As recommended by Begum (2014), in this work the methodology of UCD for the design of new products was used in order to put the needs and desires of the user first. This way, it was possible to understand, study, design, build, and evaluate the system from the user’s point of view.

# 6 CONCLUSIONS

This work presented an assistive system based on eye gaze tracking for controlling and monitoring a smart home using internet of things, which was developed following concepts of user-centered design and usability.

The proposed system allowed a user with disabilities to control the everyday equipment of her residence (lamps, television, fan and radio). In addition, the system allowed the caregiver to monitors remotely the use of the system, in real time, by the user. The user interface developed here allowed some functionalities to improve the usability of the system as a whole.

The experiments were divided into two steps. In the first step, the assistive system was assembled in an actual home, where tests were conducted with 29 participants (group of able-bodied participants). In the second step, the system was tested for seven days, with online monitoring, by a person with disability (end-user).

Results of Usability (SUS) showed that the group of able-bodied participants and the end-user evaluated the assistive system with a mean of 89.9 and 92.5, respectively.

## 6.1 CONTRIBUTIONS

Such as aforementioned, the focus of this work was the development of a human-machine interface based on eye tracking for controlling and monitoring a smart home using internet of things. Briefly, the contributions of this PhD Thesis are:

- Development of a web application, based on free software, that can be accessed from any computer connected to the Internet;
- Adaption of a residence, transforming conventional equipment of people's daily life into equipment connected and controlled by the internet;
- Increase of the autonomy of people with disabilities in performing day-to-day tasks, allowing them to control equipment of the house through an appropriate interface to their physical condition;
- Long-term usability pilot tests conducted with the end-user, in her own home, reducing the possibility of abandonment of the assistive technology.

## 6.2 PUBLICATIONS

### 6.2.1 Papers in Journals

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#### 6.2.4 Awards

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## 6.3 FUTURE WORKS

This work presented an assistive system based on eye gaze tracking for controlling and monitoring a smart home, using the internet of things, which was developed following concepts of user-centered design and usability. Although some relevant results have been found, by testing the system in an actual home and then conducting long-term testing with an end-user (person with severe disabilities), it is very important that several other tests be done in several other end-user homes (people with disabilities). Currently, the PhD student in Biotechnology, Mariana Midori Sime (Occupational Therapist), has been testing this system, having conducted experiments in more than five houses so far.

It is important to emphasize that although the concept of multimodality has not been explored in this Thesis, once it has opted to focus on eye tracking to perform tests in users' homes, several other forms of human-computer interactions (HCI) can be explored in the future, such as voice recognition, brain-computer interface (BCI), electrooculography (EOG), surface electromyography (sEMG), etc. In other words, the use of eye tracking should be seen as an accomplishment of the system and not as a limitation.

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