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SURVEY

Low-Cost Assistive Technologies for Disabled People Using Open-Source Hardware and Software: A Systematic Literature Review

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ABSTRACT Disabled People deal with a series of barriers that limit their inclusion, empowerment, well-being, and role in society with a special emphasis in low and medium-income countries. One of these barriers is concerning the accessibility and affordability of assistive technologies (ATs) that help to enhance the quality of life of these persons. In this context, this systematic literature review (SLR) analyzes and describes how free and open-source hardware (OSHW) and open software (OSS) are employed in the design, development, and deployment of low-cost ATs. In the SLR process, different ATs were analyzed for disabilities such as visual, mobility, upper body, prostheses, hearing & speaking, daily living, and participation in society. The ATs were designed with diverse OSHW and OSS technologies such as Arduino, Raspberry Pi, NVidia Jeston, OpenCV, YOLO, MobileNet, EEG and EMG signal conditioning devices, actuators, and sensors such as ultrasonic, LiDar, or flex. 809 studies were collected and analyzed from the database Web of Science, GitHub, and the specialized journals in OSHW *HardwareX* and the *Journal of Open Hardware* during the years 2013-2022. In the first part of the SLR, the bibliometric trends and topic clusters regarding the selected studies are described. Secondly, the ATs identified with open source technologies, e.g., sensor-based or computer vision-based, are described along with a complete state-of-art about these based on each disability recognized. Finally, the issues and challenges to this approach are explored including technical factors, documentation, government policies, and the inclusion of disabled people in open source co-creation. The purpose of this study is to inform practitioners, designers, or stakeholders about low-cost (frugal) ATs with OSHW and OSS, and thus promote their development, accessibility, and affordability, contributing to benefit the community of disabled people.

INDEX TERMS Assistive technologies, disabled people, persons with disabilities, adaptive aids, open hardware, open-source hardware, open-source software, computer vision, systematic literature review.

I. INTRODUCTION

Disabled *people or persons with disabilities* must overcome a series of barriers and challenges in daily living that limit their inclusion, empowerment, wellbeing, and role in society all of which are compounded for those living in low-income countries [1]. These barriers include, e.g., accommodation affordability, medical assistance, and accessibility to Assistive Technologies (ATs). According to several reports [1], [2], around 15% of the world's population has some kind of disability, 1 of 5 women is likely to experience some disability during her life, and 1 of 10 children has a disability. This challenge is growing substantially because elderly are more likely to be disabled (more than 46% of older persons – those

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aged 60 years and older are disabled [3]) and the global population itself is aging. It is expected by 2050 that the number of older persons (aged over 60 years) will increase from 850 million in 2013 to 2 billion, and given the likelihood of disability roughly 1 billion people will require some type of AT to make their daily activities independently [2].

There is clearly a need to take actions to improve the quality of life of the burgeoning numbers of disabled people [2]. In this regard, several advances have been made in the field of policies and guidelines from states and governmental agencies. For example, the strategy for disability inclusion of the United Nations (UN) [4] poses several policies that encompass participation, universal design, accessibility, reasonable accommodation, and organizational culture with the aim to foster the development of disabled people. Similarly, the UN Convention on the Rights of Persons with Disabilities (CRPD) [5] indicates general principles for non-discrimination, full and effective participation and inclusion, equality of opportunities, and accessibility. Particularly, the articles 7 (*accessibility*), 19 (*living independently and being included into the community*), 20 (*personal mobility*), and 21 (*freedom of expression and opinion, and access to information*) of the (CRPD) were selected as primary guidelines that orientated this systematic literature review on low-cost or frugal ATs. This study adopts the definition of disabled people or persons with disabilities used by the UN as "people who have long-term sensory, physical, psycho-social, intellectual, or other impairments that, in interaction with various barriers, may hinder their full and effective participation in society on an equal basis with others" [1].

To guarantee the fulfillment of the mentioned principles and articles, ATs play an important role in improving the quality of life, independence, and development of disabled people. ATs are defined as "any item, piece of equipment, or product system, whether acquired commercially off the shelf, modified or customized, that is used to increase, maintain or improve the functional capabilities of the individuals with disabilities" [6], or "any adaptive device or service that increases participation, achievement, or independence of the person with a disability" [7]. ATs allow among other functions, environmental control, enhance mobility, ease of personal care, and dignify and foster the independence of disabled people [6], [8]. ATs encompass technologies for diverse impairments and disabilities such as smart canes or sticks, smart glasses, braille interfaces, smart readers, wheelchairs, prosthetics, exoskeletons for rehabilitation, sign language assistants, indoor and outdoor assistants, accessible toilets, and educational devices [9].

Nonetheless, although ATs have these important functions and impacts, unfortunately, they are not accessible for an substantial percentage of the disabled people in low-income or even medium and high-income countries due to their high costs, and the lack of policies and services regarding their effective access [10]. According to the UN *Assistive Technology for Children with Disabilities: Creating Opportunities for Education, Inclusion and Participation* [10], the costs of purchasing, maintaining, and replacing ATs constitute the primary barrier to their access. In the same study, in a survey among 114 countries, 36% had no financial resources for developing and supplying ATs. In addition, poor or low-quality ATs can be a problem due to the lack of regulation and mechanisms in the countries to guarantee that these technologies meet rigorous standards of security, functionality, duration, and ergonomics [8]. Thus, some strategies have been elicited to overcome the access barriers of ATs that encompass the reduction of the costs of the transactions (those that came from importations and their taxes), the inclusion of the community to provide ATs, and aid to identified vulnerable groups, and the participation of non-profit organizations to increase the accessibility of assistive devices [8].

One approach to reducing the cost of AT is to apply open source principles to their development and distributed digital manufacturing [11]. A recent evaluation on this approach found the financial savings averaged (>94%) compared to commercially-available adaptive aids for arthritis patients [11]. OSS now dominates the software industry but two relatively recent technical innovations have enabled OSHW to flourish: (1) open source electronics and microcontrollers and (2) open source 3-D printers [12]. First, the creation of standardized and easy to learn electronic platforms enabling users to develop electronics to read signals from sensors, carry out signal processing (including feedback control algorithms) and drive actuators in real-time. The most used is the Arduino electronic prototyping platform [13]. These low-cost devices have enough performance to enable an enormous range of applications array of scientific and medical applications [14], [15]. For example, they can be used for everything from making low-cost ultrasound-based navigational aids for the visually impaired [16] to controlling manufacturing equipment like low-cost 3-D printers through the RepRap project (self Replicating Rapid proto-typers that literally fabricated their own components) [17], [18], [19]. OSHW developers contribute by building and freely distributing the files containing software source codes, which are readable by 3-D printers [20]. Then, anyone using freely available OSS and with access to a OSHW fabrication tool can make components of sophisticated products (like AT) that otherwise would require an expensive traditional process of design and fabrication by classical methods [21].

Thus, both free and open-source hardware (OSHW) and open-source software (OSS) can be relevant options that contribute not only to reducing the costs of ATs, and, thus fostering their accessibility, but also promoting the inclusion of disabled people in the processes of decision-making, development, and test of these technologies. OSHW and OSS can accelerate the process of manufacturing ATs, including technologies such as 3-D printing, sensors, and actuators, computer vision, or navigation devices for outdoor or indoor settings. At the conceptual level, the OSHW definition 1.0 [22] states that OSHW is "a term for tangible artifacts – machines, devices, or other physical things – whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things''. In general terms, the principles of transparency, accessibility, and replicability define the main components that are expected in OSHW [23]. Thus, the principles mentioned above involve at least four freedoms in the OSHW community [23]. *Freedom to study*, in the sense, to access documentation that allows understanding of how the hardware works. The documentation can include schematics, 2D, or 3D CAD files. *Freedom to modify*, which includes the possibility to modify the documentation, improve the hardware, or participate in its further development. *Freedom to make* to produce or manufacture a piece of hardware based on the documentation available. And *Freedom to distribute* both the documentation and the physical products fabricated under a free license even for commercial purposes. So, the OSHW statement of principles 1.0 [22] contemplates that the licenses derived from the original work must remain for future modifications, and the license shall allow to manufacture, sale, and distribute the product with these modifications. Besides, the necessary software for the functioning of the hardware must be documented in its main functions and released under an open-source license. These principles and guidelines of the OSHW movement could help to overcome the barriers, shortcomings, and problems that face disabled people concerning the accessibility or affordability of ATs.

In this context, the purpose of this systematic literature review (SLR) is to map and analyze the role of OSHW and OSS in the design and construction of ATs for disabled people in a wide scope of disabilities and impairments such as visual, upper body, prostheses, hearing, and movement. For that, n=415 articles and n=394 open-source projects were analyzed based on the SLR guidelines in the references [24], [25] for the articles, and [26] for the GitHub projects. The studies were retrieved from the database Web of Science (WoS), the journals *HardwareX* and the *Journal of Open Hardware* (JOH), which both specialized in OSHW, as well as GitHub (a large OSS repository) during the years 2013-2022. Several devices commonly used for OSHW were included in the SLR such as Arduino, Raspberry Pi, Beagleboard, or Orange Pi. The motivation to generate this SLR lies in describing the advantages, impacts, and challenges of the low-cost ATs that employ OSHW and OSS, and suggesting actions of improvement to offer a better quality of life and integration for disabled people. Similarly, the extant literature exhibits a lack of studies that examine the implications and impacts of the OSHW-OSS in low-cost ATs for several disabilities which include not only visual impairments or disability.

The main contributions of this study are: (1). Provide a detailed bibliometric analysis and literature review that illustrate the current scope of the OSWH and OSS in the development of ATs; (2). Inform practitioners, researchers, and stakeholders about the technologies in hardware and software used in the creation of ATs; and (3). Describe several opportunities, barriers, and challenges identified in ATs with OSHW and OSS, and suggest opportunities that help to overcome these issues.

The remainder of the article is divided as follows. Section II explains the methodology of the study according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and its limitations. Section III shows the findings and discussion in concordance with the proposed Research Questions (RQs). Finally, section IV outlines the conclusions and final remarks concerning ATs with OSHW and OSS.

II. METHOD

Systematic reviews search to answer a set of questions to identify and reveal current gaps, contrast hypotheses, or expand the scope of topics in a particular knowledge area [25]. The information provided by the systematic reviews allows stakeholders, practitioners, and researchers to make decisions and plan future studies to close breaches based on the collected evidence [27]. Petticrew & Roberts [27] state the first step in the generation of an SLR is to identify if a revision of a particular topic is really needed. Several systematic literature reviews have analyzed and illustrated ATs, for instance, navigation and walking assistants focused on persons with visual disabilities or impairments [28], [29], ambient assisted living solutions for elderly people [30], or prosthetics devices [31]. Then, this SLR searches to complement the previous studies, in the sense to map and analyze the role and implications of the OSHW and OSS in the development of ATs that are accessible to disabled people and contribute in part with the findings of this study to achieve the statements posed in the UN CRPD convention.

This SLR was carried out through the guidelines and steps provided by the authors Gough et al. [25] and Petticrew & Roberts [27], which are summarized as follows: (1) Formulate research questions and conceptual framework; (2) Search and screen for inclusion with eligible criteria; (3) Code to match a conceptual framework; (4) Apply quality appraisal criteria; (5) Synthesize the studies using a conceptual framework or study codes; and (6) Interpret and communicate the findings. Previous steps were accompaniment by the PRISMA guidelines provided by [24] in order to perform the different stages of the review. Fig.(1) depicts the stages of the SLR according to these guidelines. Each one of the mentioned steps will be explained in the following subsections.

A. FORMULATE RESEARCH QUESTIONS

To meet the main purpose of this SLR, several research questions (RQs) were formulated. Table (1) describes these RQs with their respective description.

Initially, to formulate the previous questions were analyzed several documents of non-profit and governmental agencies to identify disabilities, ATs, policies, programs, and the current scenario of the disabled people in the world. Table (2) shows some of them with their description. Also, several systematic reviews were revisited in the process to find gaps in the extant literature.

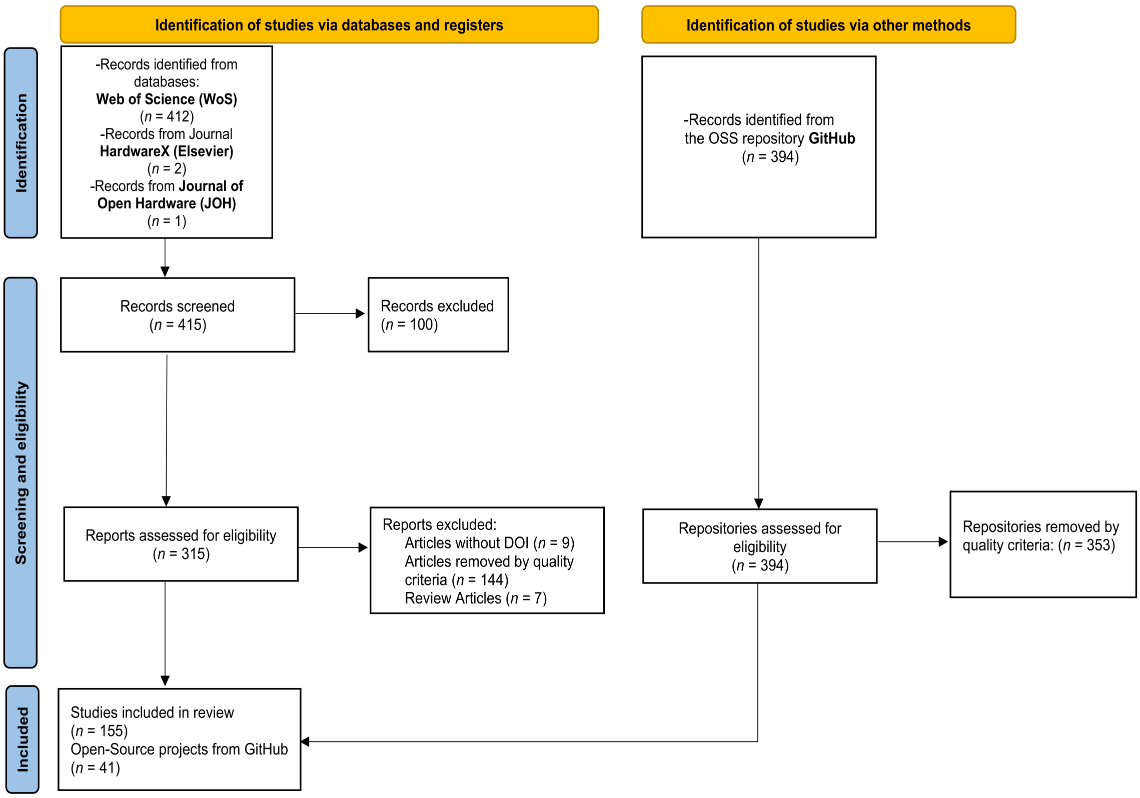

FIGURE 1. PRISMA guidelines for the study adapted from reference [24].

TABLE 1. Description and purpose of the RQs in the SLR.

Research Question (RQ)	Description and purpose
RQ1. What are the main bibliometric trends and research topics in the studies regarding assistive technologies?	Identify relevant studies, authors, journals, publishers, and topics to illustrate how OSHW and OSS are employed for the development of ATs.
RQ2. What kind of disabilities and assistive technologies that use open-source hardware and software are addressed by the studies?	Classify the studies to describe the disabilities and types of ATs that are commonly addressed with open-source hardware and software.
RQ3. What are the main technologies in hardware and software employed by the researchers in the studies?	Identify and examine the main technologies in hardware (sensors, actuators, development boards, etc.) and software (voice, image recognition, navigation, etc.) used or created by the researchers in the studies.
RQ4. What opportunities, issues, and challenges are identified from the assistive technologies that use open-source hardware and software?	Explain the opportunities, challenges, and issues regarding the utilization of open-source hardware and software in ATs. Suggest some actions to improve the ATs and promote their accessibility and affordability for disabled people.

B. SEARCHING CRITERIA

To respond to the RQs proposed, the search was bounded in the timeframe 2013-2022. This interval agrees with the emergence of the main corpus of designs about ATs which include OSHW and OSS. The search string was refined in several attempts to get the major number of relevant studies inside the scope of the SLR. For instance, the first search string incorporated the terms "open-source hardware", "open hardware", "persons with disabilities", "disabled people", and "assistive technologies" with few studies retrieved from the Web of Science (WoS). Then, a second search string was constructed with the most important OSHW devices commonly used in research in the academy and industry based on the systematic reviews [41], [42], [43]. The devices Arduino, Raspberry Pi, Beaglebone, Intel Edison, and Orange Pi were considered in this search string with the Boolean connectors indicated in Table (3). Although the single-board computers (SBCs) Raspberry Pi, or Beaglebone, among others, cannot be deemed strictly OSHW, through their usage many ATs have been developed because the software utilized in those SBCs is of type free-libre open-source software (FLOSS), e.g., Linux, Python, OpenCV, etc. Similarly, the terms disabled person, disabled people, or person with disabilities are *standardized terms* commonly used by the World Health Organization (WHO) and UN in their reports and were included in the search string.

In addition to the primary source selected (the database WoS), other sources were consulted to extend the number of investigations included in the SLR. Thus, the specialized OSHW journals (*HardwareX*, and *Journal of Open Hardware* (JOH)), and the open repository GitHub were considered in the search process as Table (3) illustrates. Although the search

TABLE 2. Documents analyzed to formulate the RQs in function of the key concepts of the SLR.

SLR key concept	Document (Reference)	Description
Assistive Technologies (ATs)	[7], [9], [10], [32], [33]	Documents with the definition of ATs and their classification according to the type of impairment or disability. Reference [33] shows how ATs can help to achieve the UNESCO Sustainable Development Goals (SDG) and reference [10] depicts the shortcomings and gaps regarding ATs for children around the world.
Disabled people or Persons with Disabilities	[2], [5], [34]–[37]	Documents with the analysis of the scenario concerning disabled people in the world. Document [34] specifies the type of disabilities and describes the cultural, social, and economic context of the disabled people in Europe. Document [5] reports the UN CPRD convention. Documents [36], [37] show reports about disabled people from a social perspective around the globe according to the World Health Organization (WHO).
Open-Source Hardware (OSHW)	[22], [23], [38], [39]	Documents or studies about the concept, opportunities, advantages, and limitations of the OSHW. Study [40] defines the factors of success for OSHW projects. Document [39] provides a review of the economic advantages to include OSHW in diverse projects.

string was focused on electronic OSHW technologies also were collected electromechanical ATs, e.g., in prostheses, upper body rehabilitation, and exoskeletons. For GitHub, the searching string was changed because using the previous ones in WoS or the OSHW journals did not generate representative samples as more granular terms were used to describe projects. Moreover, GitHub has a limitation of five Boolean connectors in the search query, which restricted the extension of the search string. Therefore, the search string was based directly on the *disability* and the *OSHW technology* to get an appropriate number of OSS projects. For example, independently several searching strings were considered such as (blind people **AND** raspberry pi, visual impaired **AND** raspberry pi, hearing impaired **AND** raspberry pi, dumb **AND** raspberry pi, mobility **AND** raspberry pi, blind people **AND** arduino, visual impaired **AND** arduino, hearing impaired **AND** arduino, mobility **AND** arduino) and so on for each disability and OSHW in the SLR. Also, in these search strings were included terms like blind, mute, deaf, prosthesis, wheelchair, or dumb that are normally employed by the researchers.

TABLE 3. Description of searching criteria for the SLR.

Aspect	Description
Timeframe	2013-2022
Databases, journals, webpages, repositories	Web of Science (WoS), *HardwareX* (Elsevier), *Journal of Open Hardware* (JOH), GitHub.
Searching String	• **WoS**: ((Disabled people) OR (person with disabilities) OR (visually impaired) OR (deaf) OR (blind) OR (mute) OR (dumb)) AND ("arduino" OR "raspberry pi" OR "beagleboard" OR "orange pi" OR "intel edison") • **HardwareX, JOH**: (Disabled people OR person with disabilities OR visually impaired OR deaf OR blind OR mute OR dumb) • **GitHub**: (*disability* AND *OSHW technology*)
Inclusion Criteria	• Studies that incorporate assistive technologies, OSHW, and OSS for disabled people. • Language: English. • Type of study: Primary research.
Exclusion Criteria	Studies outside the scope of the review: not for disabled people, not employment of OSHW and OSS, not description of the AT, not in English, not primary research, not preprints.
Total records obtained	WoS (412), HardwareX (2), JOH (1), GitHub (394). **Total Records**: 809.

In this way, n=809 records were retrieved from the mentioned sources. N=415 records from the retrieved articles were added to the software Mendeley in the format research information system (RIS) to check duplicates and complete missing information such as authors, DOI, abstract, keywords, or publisher.

C. SCREENING, ELIGIBILITY, AND APPRAISAL CRITERIA

For the articles, the screening process of the n=415 records started with the reading of the title and abstract. Studies outside the scope of the SLR which do not meet the inclusion criteria in Table (3) were rejected. After this process, n=100 records were excluded from the database WoS and the journals *JOH* and *HardwareX*, remaining n=315 articles. The articles were assessed for eligibility, removing those without DOI or with problems of access (n=9), and those that were not primary research, e.g., literature reviews, and surveys, among others (n=7). Then, each one of the remaining articles

TABLE 4. Quality survey to assess the articles and GitHub projects in the SLR.

Survey Questions	Range (1-4)
Q1. Does the study describe clear criteria for the selection of the hardware and software components used in the AT?	(1: strongly disagree to 4: strongly agree)
Q2. Does the study show a method and experiments that allow validating the AT?	(1: strongly disagree to 4: strongly agree)
Q3. Does the study indicate the scope and limitations of the AT developed?	(1: strongly disagree to 4: strongly agree)
Q4. Is the developed AT accessible, replicable, and reusable?	(1: strongly disagree to 4: strongly agree)
Q5. Has the study been cited by other authors?	(1: No, 4: Yes)

was read and evaluated according to a quality criterion (QC) based on a Likert scale survey with the questions depicted in Table (4) in a scale from 1 to 4. These questions were constructed considering the features of the OSHW and OSS, ATs, and the relevance of the studies in the scope of the SLR. Each one of the survey's questions had the same weight, that is, the overall score obtained by an article was based on the average of the score of these questions.

As for the GitHub projects, the screening process of the n=394 retrieved records started with the read of the project's description and information. After, the quality survey in Table.(4) was applied from questions Q1 to Q4. Citations were excluded because this item is more suitable for research articles. A similar procedure has been used in other systematic reviews to evaluate the relevance and quality of the studies, e.g., in [26], [30]. The articles and GitHub projects whose overall score was over 2.8 were selected to be included in the SLR, which resulted in n=155 articles, and n=41 GitHub projects as Fig.(1) shows.

D. DATA EXTRACTION AND ANALYSIS OF THE STUDIES

Data extraction and analysis of the n=155 articles and n=41 GitHub projects obey the Research Questions (RQs) proposed in the SLR. Thus, to respond to the RQ1, some software tools and programs specialized in bibliometric analysis such as VOSViewer [44], Leximancer [45], [46], and Crossref REST API [47] were employed. VOSViewer is a software for bibliometric analysis based on network data that is focused on items and clusters with two overall functions: create maps and visualize them. Leximancer is a text analytics tool that can analyze the contents of collections of documents and visualize their trends in concept maps. The main concepts and the clusters that join the studies in the SLR were analyzed under the lens of these two tools to establish the trends of the collected studies. In this analysis, several words were merged or removed to guarantee the relevance of the clusters and concepts in the analysis. While the software VOSViewer was focused on the keywords of every article with a minimum occurrence of three words, Leximancer was focused on the abstracts of the articles and GitHub projects' description to complement the findings in this part of the SLR.

TABLE 5. Classification of disabilities adopted in the SLR.

Domain	Subdomain
Basic Activity	• Communication • Mobility • Hearing • Visual • Cognition/Remembering • Upper Body • Learning/Understanding
Complex Activity & Participation	• Activities of daily living: Walking around the house, eating, dressing. • Instrumental activities of daily living: Preparing meals, managing money. • Getting along the people: Involve interpersonal interactions and relationships. • Major Life Activities: Include working outside and inside home to earn an income and achieving educational goals. • Participation in society: Include joining in community, religious, leisure, social and sport events.

Regarding the Crossref REST API, this tool allows extracting bibliometric information such as citations, authors, publishers, type of study (journal article, conference proceedings, book chapter), or articles per year, among others. The API was used with Python language to extract the bibliometric features of the studies. To respond to RQ2, each one of the studies was classified according to the disability and AT developed in line with the classification proposed in [34], which is based on the Washington Group on Disability Statistics (WGDS) in the following domains and subdomains in Table (5):

Besides, in each study was identified the stage of development under the classification given by the authors Jones & Richey in [48] as follows:

- *Alpha Prototype*: First version of the prototype that illustrates in a basic form the format, concept, content, or graphics. Sometimes called proof-of-concept.
- *Beta Prototype*: A terminated product that is ready for pilot or test research with complete functionality.
- *Pilot Prototype*: Contains instructor material and short module content for the participants in the study of validation in a training session.

A similar procedure was performed to extract the technologies in hardware and software in the RQ3. Technologies in hardware were organized in the type of board used, e.g., Arduino, Raspberry Pi, etc., type of sensor (LiDAR, ultrasonic, EEG, etc.), or navigation (GPS, iBeacons, RF Tags), etc. The software in the ATs was distributed by disability and functionality, for instance, in image and facial recognition, EEG, text-to-speech, optical character recognition (OCR), and the Internet of Things (IoT), among others. To answer RQ4, a synthesis of the findings in the previous RQs was contrasted with some of the documents in Table (2). This synthesis allowed us to identify the opportunities, problems, and challenges that face ATs with OSHW and OSS. In addition, some suggestions are explored to help to overcome the found issues.

E. REPORTING THE RESULTS

Guidelines proposed by Webster and Watson [49] were considered to write the review in aspects such as identifying relevant literature, review based on a concept-centric approach, tables and figures presentation, tone and structure of the synthesis. Results are presented according to the described Research Questions (RQ). The detailed information of each one of the *n*=155 articles and *n*=41 GitHub projects that condensate the synthesis of the results in the SLR can be found in the following Zenodo link: https://doi.org/10.5281/zenodo.7305175.

F. LIMITATIONS

Throughout the process of the SLR rigorous protocols to collect and analyze the information were utilized, however, there are some limitations. The first one was the databases included in the searching process. The database (WoS) was selected because it centralizes a considerable number of studies about ATs with OSHW and OSS and a relevant corpus of designs to analyze under the PRISMA guidelines was guaranteed. To extend this search other journals specialized in OSHW and the GitHub repository were included. More comprehensive databases like Scopus and Google Scholar may expand this work in future studies to complement its findings.

The second limitation is concerning the searching strings in Table (3). In these, standardized terms such as "disabled people" or "person with disabilities" were used, which are taken in the UN or WHO documents about disabilities. However, other terms and more specific terms (e.g. blind) that are used by the researchers to refer to their developments or intended audiences could have been excluded from the SLR process.

The third limitation was discarding gray literature such as white papers, preprints, or working papers, and also documents that were not in English. This is a restriction based on the features and procedure of the SLR, that is, the limitation of the document sources that the researchers can analyze.

Finally, the fourth limitation is the timeframe of the proposals analyzed (2013-2022). This was not expanded because a large part of designs about ATs was focused on these years and it matches with the rising of OSHW and OSS technologies such as Arduino, Raspberry Pi, NVidia Jetson, and the evolution of computer vision techniques and libraries such as YOLO, CNN, or OpenCV. Nevertheless, some meaningful studies could be outside of the timeframe or could have received citations after the searching date.

III. FINDINGS AND DISCUSSION

A. RQ1. WHAT ARE THE MAIN BIBLIOMETRIC TRENDS AND RESEARCH TOPICS IN THE STUDIES REGARDING THE ANALYZED ASSISTIVE TECHNOLOGIES?

1) BIBLIOMETRIC TRENDS

The number of publications about ATs with OSHW and OSS were increased from 2013 to 2019 with a relative peak in 2019 of *n*=38 proposals as Fig.(2) depicts.

In this year, the studies were related mainly to navigation systems for visually impaired persons, which include canes or smart sticks, wearable devices with ultrasonic sensors, educational devices, and color compensation systems (*n*=25, 65.78%). Similarly, in this year, the authors described robotic gloves and systems for sign language for hearing impaired persons (*n*=6, 15.78%), wheelchairs with gesture recognition and upper body rehabilitation devices (*n*=7, 18.42%). Aside from these designs, the authors employed mainly the single-board computer Raspberry Pi (*n*=17, 44.73%), Arduino (*n*=18, 47.36%), and other hardware devices such as Intel UP2 Board (*n*=1, 2.63%), ESP32 (*n*=1, 2.63%), and ESP8266 (*n*=1, 2.63%).

Concerning the GitHub projects, Fig.(3) shows their distribution per year from 2013-2022. In some cases, for example, in the years 2013-2014 or for 2017, the number of projects that approved the quality criteria was zero. From *n*=41 projects, (*n*=24, 58.53%) addressed vision disability and impairments, (*n*=8, 19.21%) mobility disability which include exoskeletons, prosthetic arms and hands, and wheelchairs, (*n*=8, 19.21%) sign language devices for hearing disability typically with robotic gloves, and (*n*=1, 2.43%) a daily living system for medical assistance that monitors glucose of the patients with some disability. For these ATs, (*n*=18, 43.9%) used Raspberry Pi boards (v.3 and v.4), (*n*=22, 51.16%) Arduino, and (*n*=1, 5.55%) ESP8266 board. Table (6) shows the list of the projects with their respective reference and disability according to Table (5).

In general terms, from *n*=196 ATs between articles and GitHub repositories, (*n*=108, 55.10%) are about ATs for visual disability and impairments, (*n*=40, 20.40%) for movement disabilities in their majority include wheelchairs with hand or gesture control, prostheses, and exoarms, (*n*=23, 11.73%) for hearing or speaking disabilities mainly with sign

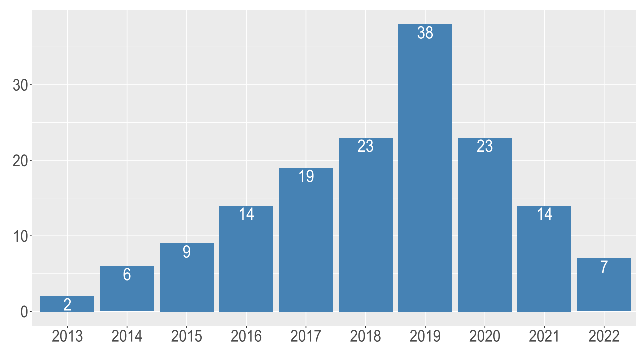

FIGURE 2. Number the articles per year from 2013 to 2022. (*n*=155).

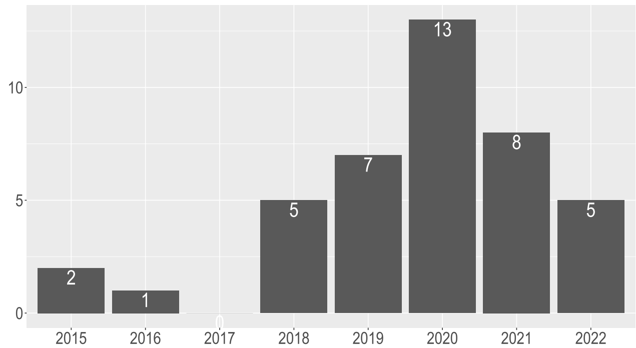

FIGURE 3. Distribution of GitHub projects per year. (*n*=41).

TABLE 6. List of GitHub repositories by disability included in the SLR.

Disability	GitHub repository reference
Visual disability & impairments	[50]–[73]
Mobility disability	[74]–[81]
Hearing & speaking disability	[82]–[89]
Activities of daily living & environmental control	[90]
Getting along the People & Participation in Society	[78], [82]

language assistants with gloves or computer vision, (*n*=22, 11.22%) for daily life systems with fall detectors, IoT systems for home automation and appliances control, and (*n*=4, 2.02%) for participation in society, which include a sexual health device and a gaming application for disabled people. Specifically, the distribution of the designs by reference according to the type of AT will be discussed in the RQ2. Also, (*n*=85, 43.36%) studies employed Raspberry Pi in its different versions (2, 3, 4 or zero), (*n*=100, 51.02%) Arduino boards, and (*n*=11, 5.61%) other devices such as Nvidia Jetson Xavier, ESP8266, or Intel UP2 Board.

Concerning the type of publications (journal article, proceedings article, or book chapter), Fig.(4) depicts this distribution. In this, the top-10 of most prolific conferences or journals pertaining to citations are described in Table (7). In the table, the conferences and journals of IEEE are the most cited about ATs with OSHW and OSS. Concerning the publishers with more studies, from 155 articles, (47.44%, *n*=93) came from IEEE, (7.096%, *n*=11) from Springer, (6.45%, *n*=10) from MDPI, (5.8%, *n*=9) from Elsevier, and (5.16%, *n*=8) from ACM. By the same token, the top cited articles according to the disability and OSHW are shown in Table (9) as well as the predominance of ATs for visual disability and impairments.

Concerning the GitHub projects, a classification was made according to the stars assigned to each OSS repository by the GitHub members. This information is accessible in the description of the repository and somehow shows the impact of the AT developed [26]. Table (8) describes the repositories

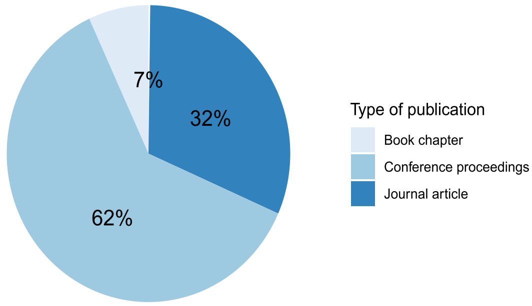

FIGURE 4. Type of publication for the articles in the SLR, (*n*=155).

or projects with a minimum of five starts. *N*=22 from 41 repositories analyzed had scores between 1 to 14 starts.

As for the articles per country, Fig.(5) depicts its distribution, where India with (*n*=31) articles is the most prolific country, followed by Bangladesh with (*n*=26), Malaysia (*n*=9), USA (*n*=9), Indonesia (*n*=7), and Brazil (*n*=7). In turn, from the 41 GitHub projects, (*n*=8) come from India, (*n*=4) from Germany, (*n*=4) from USA, (*n*=2) from Bangladesh, and (*n*=2) from the Philippines. Other developers of several countries such as Indonesia, Nigeria, Korea, Taiwan, Japan, the UK, the Netherlands, and Romania contributed with one GitHub repository. It is important to observe that an important number of the designs were generated in upper-middle-income economies according to the rank provided by the world bank [91]. Also, other countries such as Saudi Arabia, the Philippines, Iraq, Turkey, China, Taiwan, and Spain have provided studies in form of articles for ATs with OSHW and OSS as Fig.(5) illustrates with a range between 3 to 6 ATs.

One aspect to take into account is although the number of designs about ATs is increased in the world, the number of studies on continents such as Africa or South America is low. For example, in Africa, only three designs from Egypt and Nigeria were identified while in South America were identified 11 designs most of them from Brazil. Factors such as the economic resources to research ATs, or the identification and characterization of the real scenario of the disabled people in these continents could generate issues in the accessibility and deployment of ATs. In this sense, research on OSHW and OSS for ATs can contribute in part to overcome the mentioned gaps.

2) RESEARCH TOPICS

Collected studies in the SLR have the cluster map depicted in Fig.(6). In the map, the topics with the most occurrences and links are blind person, camera, image, ultrasonic sensor, smart cane, and wheelchair. Many of the topics depicted in the map are related to technologies for visual impairments and disabilities in the areas of computer vision, image processing, and machine learning according to the 2021 IEEE Taxonomy [108]. These technologies are mainly focused on Optical Character Recognition (OCR), object avoidance, and detection (see clusters 1 and 3 in Table (10)). Typically, previous technologies are presented in devices such

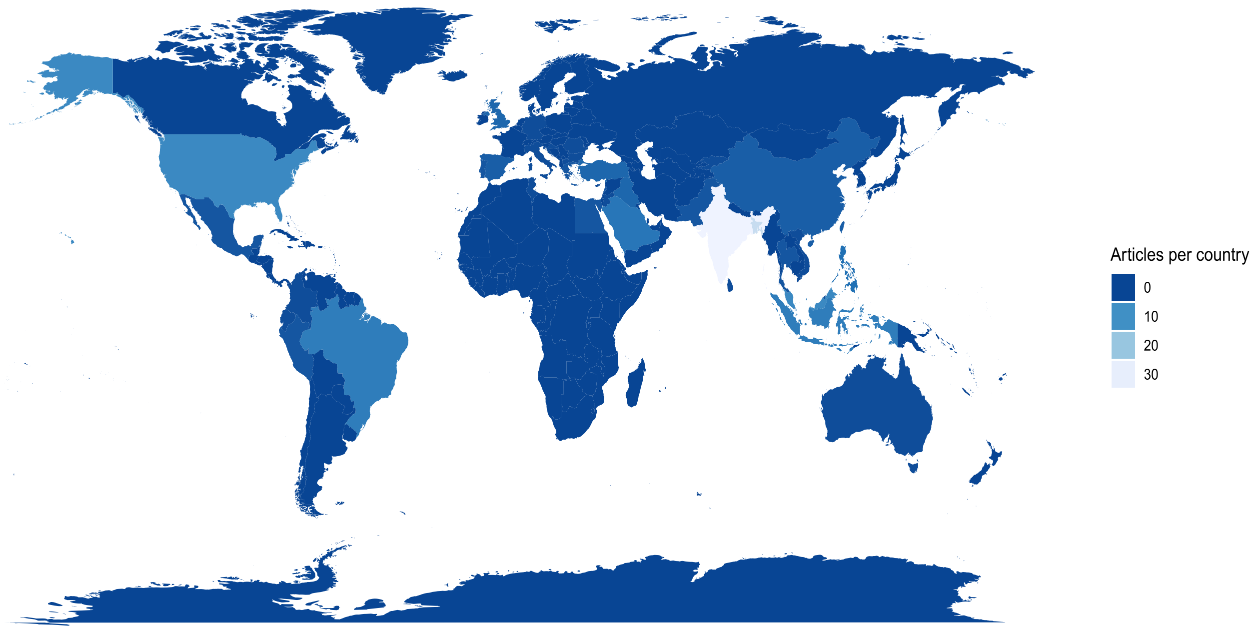

FIGURE 5. Articles per country in the SLR, (n=155).

TABLE 7. Most prolific conferences or journals regarding the analyzed articles.

Conference, journal, or book chapter	Type of Publication	Publisher	Citations	Number of Articles	Article Reference
1. 2016-IEEE conference on advances in signal processing (CASP)	Conference proceedings	IEEE	45	1	[92]
2. IEEE Access	Journal	IEEE	37	3	[93]–[95]
3. Computer methods and programs in biomedicine	Journal	Elsevier	33	1	[96]
4. Procedia Computer Science	Conference proceedings	Elsevier	27	2	[97], [98]
5. Sensors	Journal	MDPI	26	2	[16], [99]
6. 2014-IEEE International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT)	Conference proceedings	IEEE	25	1	[100]
7. Proceedings of the 9th Nordic Conference on Human-Computer Interaction	Conference proceedings	ACM	24	1	[101]
8. 2016-4th international conference on information and communication technology (ICOICT)	Conference proceedings	IEEE	22	1	[102]
9. 2018-2nd International Conference on BioSignal Analysis, Processing and Systems (ICBAPS)	Conference proceedings	IEEE	22	1	[103]
10. 2015 international conference on technologies for sustainable development (ICTSD)	Conference proceedings	IEEE	21	1	[104]

as smart canes, screen magnifiers, reading assistants, banknotes recognition systems, or smart glasses. This information is complemented by the keywords analysis of each article in the cluster map in Fig.(7), where the words with more occurrences are Arduino, Raspberry Pi, visual impairment, ultrasonic sensor, OCR, deep learning, mobile app, and object recognition.

Furthermore, Table (10) describes the keywords and items by each cluster in the map in Fig.(6). In these keywords, apart from those associated with visual disability and impairment,

TABLE 8. Top of GitHub projects scored with a minimum of five stars.

GitHub Developer	Reference	Description	Year	Hardware Technology	Disability-Impairment	GitHub stars
MXGray	[56]	Affordable wearable AI solution for visually impaired users in their day-to-day activities	2019	Raspberry Pi + Intel Compute Stick	Visual	14
akhilaku	[61]	Image-Recognition-and-Classification-Device-for-Blinds	2020	Raspberry Pi + Intel Movidius Neural Compute Stick 2	Visual	9
CymaSpace	[82]	Open source Cymatic Lighting system for Deaf & Hard-of-Hearing to see music	2015	Arduino	Hearing & speaking disability	8
Phirat-Passi	[90]	Synapse AI - IoT CGM (Continuous Glucose Monitory) System	2022	Raspberry Pi	Daily Living activities-Medical system	7
boudhayan-dev	[57]	A low cost reading device for blind people	2019	Raspberry Pi	Visual	6
alokyadav777	[52]	Object detection and recognition for blind persons using Raspberry Pi	2018	Raspberry Pi	Visual	6
ryanmccartney	[75]	Open Autonomous Navigation Platform for Power Wheelchairs	2019	Raspberry Pi-Arduino	Visual	5

TABLE 9. Top-10 of cited articles in the SLR.

Publication Title	Authors	Reference	Citations	Disability-Impairment	OSHW Technology
1. EEG-based brain controlled prosthetic arm	Bright et al.	[92]	45	Mobility, Upper Body	Arduino
2. A facial expression-controlled wheelchair for people with disabilities	Rabhi et al.	[96]	33	Mobility	Raspberry Pi
3. *Loaded Dice*: Exploring the Design Space of Connected Devices with Blind and Visually Impaired People	Lefeuvre et al.	[101]	25	Visual	Arduino, 3-D printing
4. Development of an ultrasonic cane as a navigation aid for the blind people	Kumar et al.	[100]	25	Visual	Arduino
5. Smart guide extension for blind cane	Mutiara et al.	[102]	22	Visual	Arduino
6. Development of Smart Healthcare System Based on Speech Recognition Using Support Vector Machine and Dynamic Time Warping	Ismail et al.	[105]	21	Visual	Raspberry Pi
7. Mind-controlled wheelchair using an EEG headset and arduino microcontroller	Mirza et al.	[104]	21	Mobility	Arduino
8. EyeBill-PH: A Machine Vision of Assistive Philippine Bill Recognition Device for Visually Impaired	Alon et al.	[106]	19	Visual	Raspberry Pi
9. An AI-Based Visual Aid With Integrated Reading Assistant for the Completely Blind	Khan et al.	[107]	19	Visual	Raspberry Pi
10. *MedGlasses*: A Wearable Smart-Glasses-Based Drug Pill Recognition System Using Deep Learning for Visually Impaired Chronic Patients	Chang et al.	[95]	17	Visual	Nvidia Jetson Xavier-Raspberry Pi Zero

appear ATs for mobility disabilities and rehabilitation such as wheelchairs and exoskeletons normally equipped with voice recognition, EOG or EEG systems (see cluster 2). In this category, EEG systems are typically interfaced with

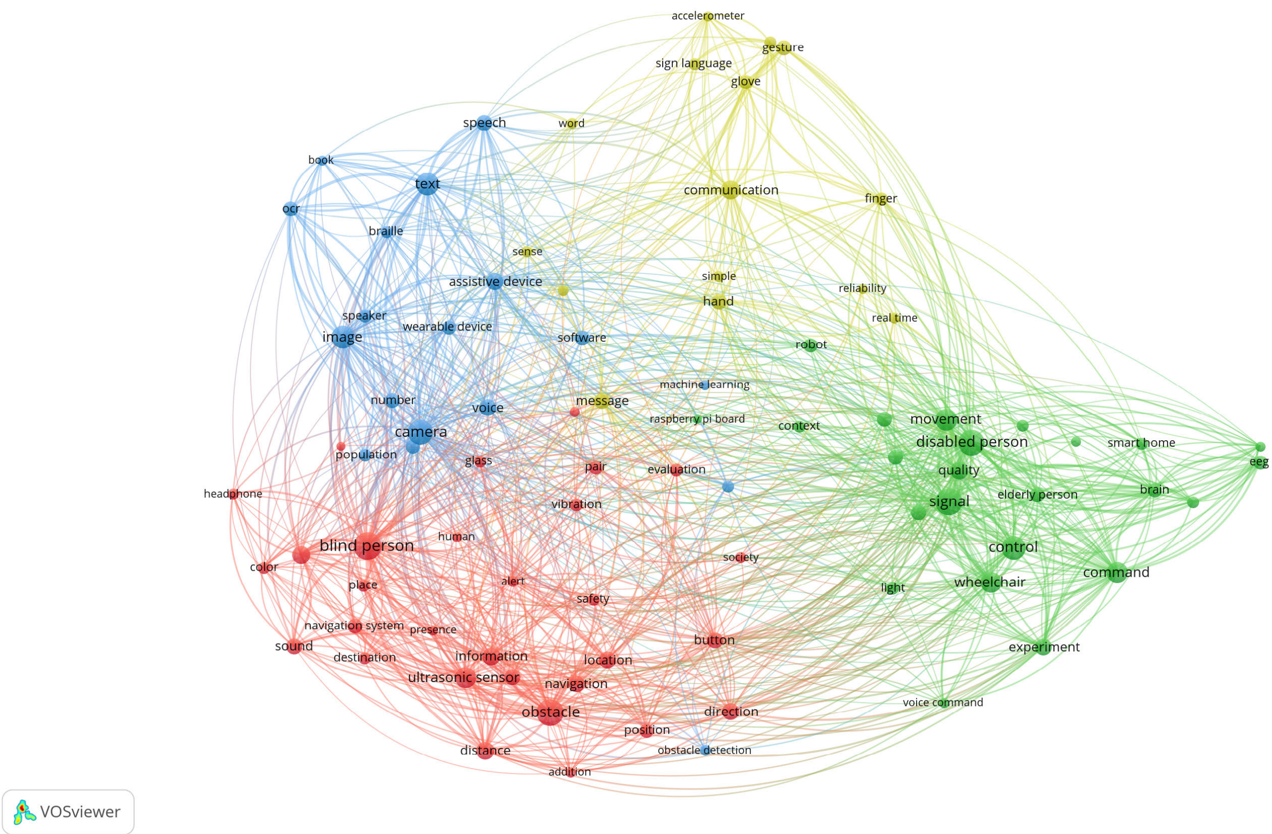

FIGURE 6. **VOSViewer cluster map for the titles and abstracts of the articles in the SLR. (n=155).**

EMOTIV EPOC or NeuroSky MindWave headsets [109], [110], which are cost-effective mobile EEG devices whose processing goes accompanied by MATLAB software to recognize gestures or commands to control the final device, e.g., wheelchair, prosthetic arm, smart home application, among others (see cluster 2). Likewise, ATs for hearing disabilities with gloves and image recognition systems for sign language, and education systems with robotic assistants or voice feedback for chemical education are unveiled in the cluster map (see cluster 4).

In the cluster analysis of Fig.(6), apart from the predominance of ATs for visual disability or impairments, two aspects are noticeable in the proposals. The first one is that the OSHW technology (3-D printing, see the blue cluster in Fig.(7)) is employed by the researchers to guarantee accessibility (i.e. economic accessibility [111]) and inclusive design of the ATs for disabled people, which is in concordance with article 7 (accessibility) of the CRPD and the principles of the OSHW in terms of transparency, accessibility, replicability, and democratization of knowledge [112]. However, in counterpart to these principles, as seen in RQ2, only the (16.84%, n=33) proposals from n=196 between articles and GitHub projects are pilot studies that have been validated by disabled people, while the rest are prototypes between alpha or beta stages. The above reveals an issue in the sense that there are a low number of designs deployed and tested with the community of persons with disabilities that limit their opportunity to access and use robust ATs. This may in part be, because of the work started in an online repository is still developing. In addition, the required permissions and regulations for human testing of devices that could be considered medical devices is cost and time prohibitive to many researchers. This is a particularly challenging issue from a legal and ethical perspective (e.g. Who is liable if an AT device design flaw harms someone? On the other hand, is it morally acceptable to withhold open source designs of AT if it can prevent human suffering, injury and in the most extreme cases death?) The open source approach here may be a particular benefit as people with disabilities can download and fabricate devices for themselves if they need or want them. The second issue that arises, is that although the studies in the SLR were classified by disability, no ATs were identified for cognitive and learning disabilities. This trend opens a discussion about other fields of exploration of ATs, OSHW, and OSS, including AI and machine learning techniques for these types of disabilities.

The evolution of the keywords from 2013 to 2022 is shown in Fig.(8). A large part of the ATs was developed from 2017 to 2019, while new technologies in the fields of machine learning and AI for object recognition started to be developed in 2019 commonly including real-time computer vision with OpenCV [113] and Tesseract [114] in Python

TABLE 10. Cluster information of the Fig.6 with their respective keywords.

Cluster	Keywords	Items	Cluster Color
1	Blind person, Information, Navigation system, Smart cane, Ultrasonic sensor, Vision, Obstacle, Distance	30	Red
2	BCI, Brain, Wheelchair, Signal, Quality, Home appliance, EEG, Elderly person, Disabled person, Control, Command	24	Green
3	Computer vision, Machine learning, Wearable device, Voice, Text, OCR, Camera, Assistive device, Speech	18	Blue
4	Accelerometer, Gesture, Flex sensor, Sign language, Communication, Glove, Hand	15	Yellow

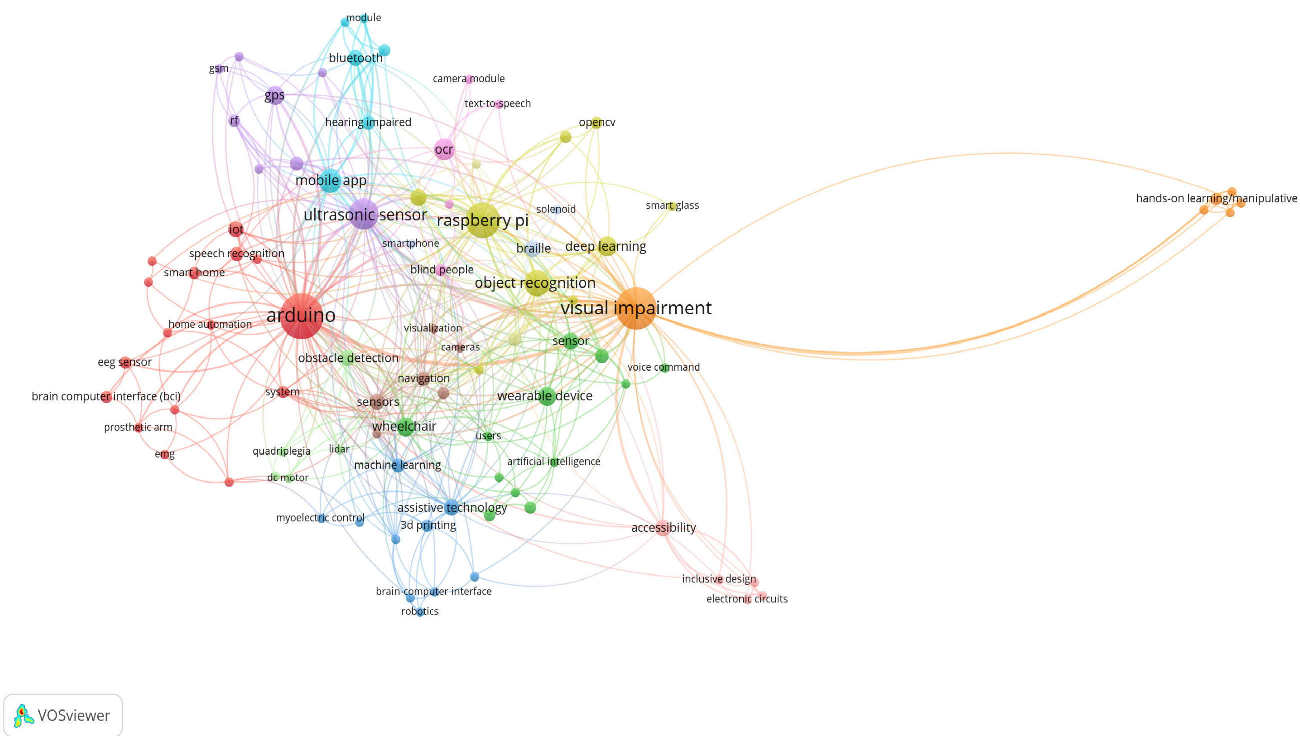

FIGURE 7. VOSViewer cluster map for the keywords of the articles in the SLR. (n=155).

Language. Also, Google products such as Google Cloud Vision API [115], Google Speech Recognition [116], and TensorFlow [117] are employed by the researchers in their designs. Parallelly, the evolution of these new technologies has been supported by the improvement of the OSHW, in this case, mainly Raspberry Pi with the incorporation of new multicore processors, RAM options (2GB to 8 GB), Bluetooth and Wi-Fi modules, which allowed to increase the computational efficiency to meet the technical requirements of the software applications in the mentioned fields. Moreover, to increase the processing capabilities of the Raspberry Pi, the researchers have included special hardware accelerators for neural networks and AI such as Intel compute sticks [118] or Intel Movidius neural compute sticks (see the GitHub projects [56], [61]). IoT applications for home automation regarding activities of daily living and monitoring of disabled people and elderly people with platforms such as ThingSpeak [119] or Blynk [120] were typically developed between 2019 to 2020. For blind persons, the navigation assistants (see cluster 1) evolved from only sensor-based with ultrasonic sensors, GPS, and smartphones, usually with Arduino boards towards computer vision-based systems to recognize objects, faces, obstacles, and medicines, commonly using Raspberry Pi in its versions (v.3, v.4, and Zero).

Fig.(9) shows the concept map produced by Leximancer, which analyzed the abstracts of the articles and projects' descriptions in the GitHub repositories. The Leximancer maps are configured by the concepts of system, people, research, blind, Raspberry Pi, and wheelchair, among others, that reinforce the findings of the cluster analysis of the previous figures with the additional concept of *accuracy*. In this case, several studies that employ image and gesture recognition, and voice detection describe the accuracy of the methods employed in them through several techniques and software tools such as Convolutional Neuronal Networks (CNNs), Support Vector Machines (SVMs), Haar cascade

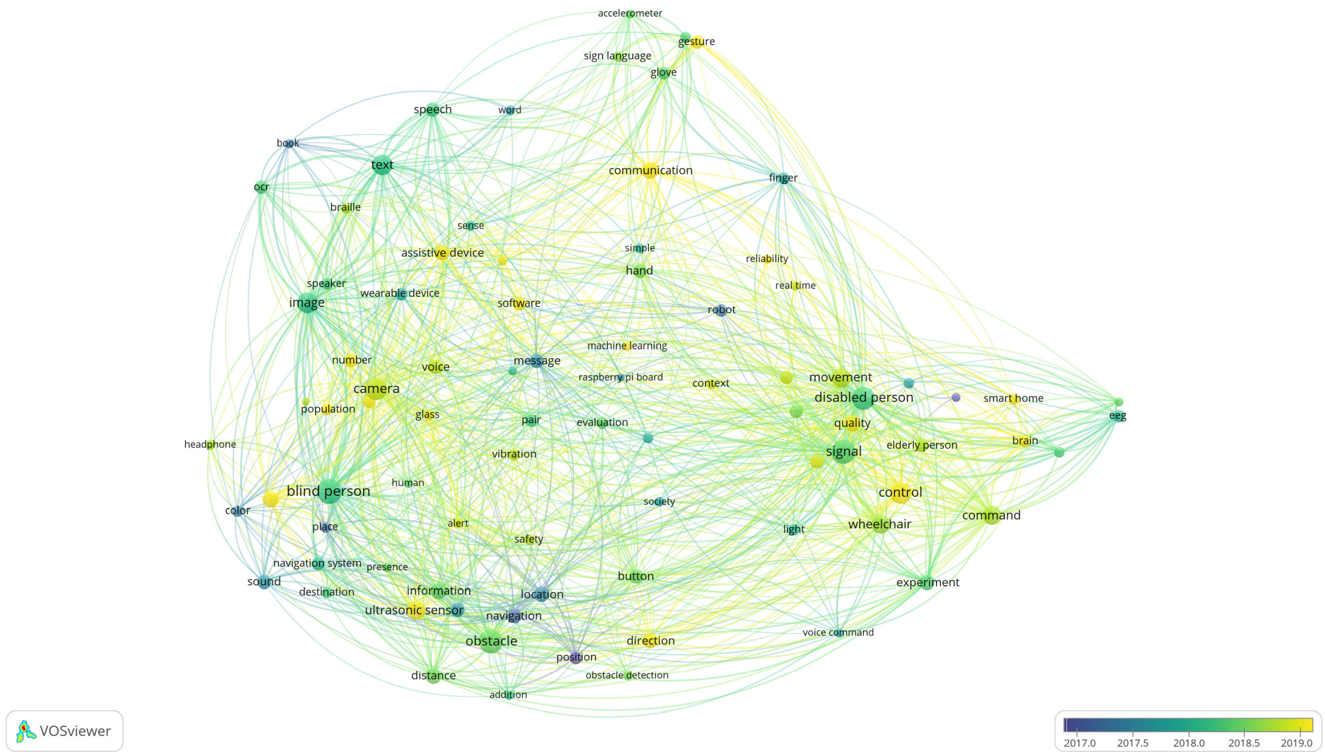

FIGURE 8. **Map of the keywords' evolution from 2013 to 2022 in the articles of the SLR. (n=155).**

classifier, or Speeded Up Robust Features (SURF) method. For instance, ATs developed for visual disabilities report an accuracy between 63% and 95.1% utilizing CNNs and You Only Look Once (YOLO) [95], [121], 88% to 90% for SURF method [94], 90% for blob detection algorithm [122], 84% for Google Cloud Vision API [123], and 85% for Tesseract [124] which is a tool for OCR applications. Similarly, ATs for mobility disabilities using EEG and EMG signals report an accuracy between 80% employing both SVMs [125] and NeuroSky MindWave headset [92], 83% with the Receiver Operating Characteristic (ROC) [126], and 97.1% for detection of facial expressions through Viola-Jones algorithm [96]. As for voice recognition, ATs for mobility and hearing disabilities using the hardware tool EasyVR shield [127] describe an accuracy between 80% to 95% [128], [129]. At last, ATs for hearing disability report 99.1% of maximum accuracy implementing CNNs with MobileNetV2 in image detection for a hand gesture authentication system [130].

The previous maps illustrate the themes addressed by the studies in the SLR and provide a perspective of the ATs developed with OSS and OSHW. In the following section will be entailed a complete state-of-art of the most representative articles and GitHub projects in the SLR.

B. RQ2. WHAT KIND OF DISABILITIES AND ASSISTIVE TECHNOLOGIES THAT USE OPEN-SOURCE HARDWARE AND SOFTWARE ARE ADDRESSED BY THE STUDIES?

As indicated above, ATs with OSHW and OSS entail a diversity of disabilities in both domains, basic activity, and complex activity & participation according to Table (5) with a predominance of systems and devices for visual disability and impairments (n=106, 54.08%) from 196 designs. Each type of ATs will be described in the next subsections in compliance with the disability or impairment identified in the SLR.

1) VISUAL DISABILITY AND IMPAIRMENTS

Table (11) illustrates the ATs recognized in the studies for visual disability and impairments, which were classified as articles and GitHub projects. It is also worth mentioning that from 106 studies for visual disability and impairments, (n=65, 61.32%) are *walking assistants*, which include smart canes or sticks for obstacle recognition based on ultrasonic and infrared sensors, smart glasses with computer vision for obstacle and facial recognition, or indoor and outdoor navigation assistants with GPS, RFID, or iBeacons support. In addition, (n=13, 12.26%) are *OCR devices*, whereas (n=5, 4.71%) are *Braille interfaces*.

Concerning the walking assistants, the studies [16], [100], [102], [134], [135], [137], [143], [144], [161] report smart sticks or white canes for disabled people using sensors and computer vision techniques according to the convention pointed out in the review about walking assistants in reference [29]. It is important to notice that the authors interchange the terms smart stick or white cane in their works. So, in this SLR both terms are employed to describe the studies.

As for sensor-based devices, in [100] a white cane for obstacle and pothole detection is presented based on an ultrasonic sensor and feedback to the user through a beep

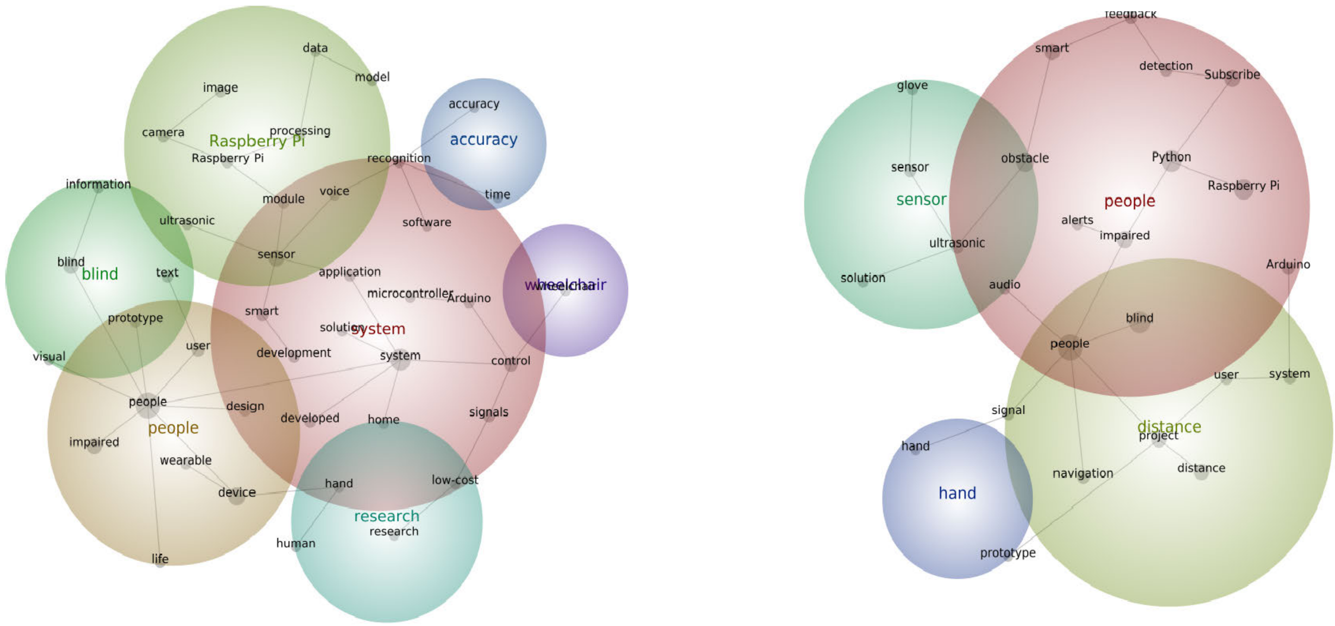

FIGURE 9. Concept map for the studies produced with Leximancer. Left: Map of the articles, Right: Map of the GitHub projects.

that has been interfaced with ZigBee protocol in a range between 50 cm to 105 cm. The prototype was designed employing Arduino and it was tested with n=10 non-blind users. As conclusions of the study, the authors remarked that new additional trials and the incorporation of GPS are needed in the project. In [16] a low-cost ultrasound-sensing based device is presented with a cost less than USD 24. The device was tested with n=5 non-blind users. A similar prototype with an ultrasonic sensor for obstacle detection was designed and tested with n=9 blind users in [102], where the authors applied a satisfaction survey for the white cane with an acceptance rate of 73.5%. Also, this prototype provides feedback to the user through voice commands. In [137], the authors describe a white cane with an ultrasonic sensor for obstacle, pothole, and water detection. The device can detect objects until 70 cm. Zahir et al. [149] show a low-cost device (USD 27) with ultrasonic sensors and vibration motors to provide feedback to the user depending on the obstacles detected. Other studies with white canes have included low-cost GPS with the accompaniment of ultrasonic sensors in order to geolocate disabled persons and help them to navigate in outdoor settings. For instance, in [131], [135], the authors developed two Android Applications (apps) with speech recognition and GPS support. With the apps, the users can indicate their destinations and the smartphone with voice commands guide them through the route or path. Besides, the authors added some ultrasonic sensors to detect obstacles and agile the navigation of the person. Some analogous ATs with navigation through GPS and ultrasonic sensors are described in the references [134], [144].

Furthermore, two wearable navigation assistants composed of ultrasonic sensors, voice commands, and vibration motors to provide feedback to the user are explained in documents [142], [147]. Specifically, the second study exposes a smart glove built with Arduino Lilypad and an ultrasonic sensor that was tested with n=2 blind users. The authors indicated that the prototype needs some improvements such as obstacle detection in function of the walker speed, employment of RFID tags for indoor settings, and the usage of reflective materials or leds for low light environments. Also, for navigation in outdoor settings, the researchers in [148] proposed a system based on iBeacons. In this technology, the system reads the current location of the users according to the ID of the iBeacon and compares it with Google Maps, providing feedback with voice commands. As a recommendation, the authors of the studies that used ultrasonic sensors mentioned that the white canes or smart sticks should have an angle between 15° to 45° regarding the floor to get better results for obstacle and pothole recognition. In general terms, sensor-based walking assistants are in their majority white or smart canes with ultrasonic or infrared sensors and GPS or RFID support that have been built with Arduino boards or in a few cases with Raspberry Pi [143], [145], [147], [148].

Regarding walking assistants that include computer vision techniques, the studies [94], [107], [121], [152] show ATs developed mainly with Raspberry Pi and Pi Cameras. In [107], the authors present an AI system composed of smart glasses with a camera and an ultrasonic sensor for obstacle detection. The system has the possibility to detect and recognize objects and persons, and it serves as an OCR engine. The system was evaluated with n=60 blind users (30 males and 30 females), where the overall score of satisfaction in a range of 0 to 20 was 14.5, which demonstrated that AT was considered by the users as helpful. The authors established a cost of USD 68 to implement the assistant. Likewise,

TABLE 11. Type of ATs analyzed for visual disability and impairments.

Type of Assistive Technology (AT)	Subclass	Article reference	GitHub project reference
1. Walking Assistants	Sensor-based (ultrasonic and infrared sensors with GPS, iBeacons, RFID tags, etc.). Typically, white canes or smart sticks.	[16], [100], [102], [131]–[149]	[51], [54], [64], [73]
	Computer vision-based. Typically, smart glasses or white canes.	[93], [94], [107], [121], [150]–[161]	[52], [53], [56], [61], [65], [72]
2. Braille interfaces and devices	–	[145], [162]–[165]	–
3. Educational devices and materials	–	[101], [166]–[171]	[62]
4. OCR reading and dictating assistants	–	[123], [124], [172]–[176], [176]–[179]	[57], [63], [66]
5. Color detection and compensation	–	[180]–[182]	–
6. Systems for detection of visual impairments	–	[122]	–

in [94], a hybrid approach is implemented to detect obstacles, manholes, and staircases based on ultrasonic sensors and a camera. Ultrasonic sensors are used to detect staircases while the camera was employed to detect manholes. The system was trained with 138 image samples of manholes and staircases. The accuracy of the device is between 88% to 90% for the detection of the mentioned elements. Complementary, an IoT system is described in [152] that is composed of a white cane and a smart cap. The white cane can detect obstacles, chuckholes, and water. The smart cap with the camera recognizes objects and provides feedback to the user. The system was evaluated by n=21 non-blind users with the System Usability Scale (SUS), where 86% of the participants recommend the system. Finally, in the section on walking assistants, the works [121], [161] show system for object and face detection to assist visually disabled or impaired persons based on YOLO. In this case, the accuracy of recognition for the objects and faces oscillated between 78% to 100%.

The second type of AT in the category of Visual Disability and Impairments in the SLR was the Braille devices and interfaces. In [162], a low-cost Braille keyboard (USD 43.45) with Arduino is presented (in comparison a commercial Braille Keyboard can cost USD 2000). Similar work was developed in [163], wherein is depicted a Braille Keyboard which can communicate with an Android app using Bluetooth protocol. The authors conclude that is necessary to incorporate a database in SQL to support different languages as well as to perform trials that allow testing the feasibility of the proposed solution. The studies [164], [165] focus on Braille devices evaluated by blind users. In the first study, the authors exposed a Braille system for the writing and reading of grade 1 students. The system was evaluated by n=20 persons (10 teachers, 10 blind students) had an acceptance rate of 91% for the teachers, and 85.3% for the students. In the second work, the authors present a Braille system in Arabic that was tested with students from four to eight years old. The system presents a number or letter that the user must replicate through the interface and afterward the system evaluates his-her progress. The authors pointed out some improvements such as include diacritics marks and Arabic words.

The third type of AT is related to educational devices and materials for visually disabled or impaired students. In references [166], [167] are described two educational devices to teach the concept of pH with Arduinos through an electrode and color sensor, respectively. In these ATs, which cost USD 85, the pH scale is transformed to a musical tone that the user can recognize. Another device to teach chemistry in the field of calorimetry with an Arduino is depicted in [168]. Although it should be pointed out that professional lab-grade calorimeters can be fabricated using a similar approach [183], [184]. The USD 43 device made to be inclusive is composed of a thermistor, and the temperature is converted to speech in two languages (Portuguese, and German) that the user can select. In [169] an USD 284.58 robot is illustrated that helps to support walking activities for visually disabled students. The robot can detect obstacles and objects, providing feedback to the users. In further work, the authors want to evaluate if the feedback provided by the robot is adequate for visually impaired persons. In [170] more than a device or AT, the experience to teach and design educational materials for Arduino concepts in a community of blind students is explained. The educational materials include piezo tactile schematics, and both component diagram and circuit description feedback. Some troubles regarding the conceptual understanding of the materials are manifested by the authors that suggest the need to collaborate with blind instructors which know the context of the blind students. N=8 blind students participated in the experiments. In the same way, in [171] a set of activities are described with tactile graphic schematics that were created with the help of experts and physical computing instructors. Also, the study [101] shows an interactive tool called *Load Dice* to support co-design activities for visually impaired students who can explore its features employing sensors (humidity, temperature), and a haptic interface. The device was tested by $n=11$ users of which four were blind people. The authors indicated that a wider audience should be considered to understand the implications of the device for visually disabled users. It should be noted that the studies [166], [167], [168] contain repositories with the information about the implementation of the AT which can help to strengthen the principles of the OSHW community concerning accessibility and replicability of the devices.

The fourth type of AT for visual disability is regarding OCR assistants for reading and dictating purposes. Studies [172], [173], [174], [175], [176] show some OCR systems with text recognition accuracy between 83.3% and 98%. Typically, these devices employ Raspberry Pi and an OCR engine known as *Tesseract* [114], which is an open-source library initially developed by Hewlett-Packard Laboratories in Bristol that employs Otsu's thresholding method. With this tool, the text of an image is extracted and afterward is synthesized to speech generally using Google Text-to-Speech Engine (GTTS) [116]. In this set of articles, the authors of references [174], [175] describe some enhancements to their developments such as appending a higher resolution camera to increase the accuracy of text extraction, reduce the noise of the speech using signal processing techniques, and implementing a method to identify mathematical equations through the application of parallel core processing techniques in the Raspberry Pi. Specifically, study [174] was tested by a blind user. In the same line, authors in [172] developed an OCR system with its preprocessing algorithm to improve the processing speed of Tesseract with a detection accuracy of 98%. In this case, the system uses the Text-to-Speech engine eSpeak [185]. An alternative OCR wearable device (glasses) that uses cloud computing through Google Vision Cloud API [115] for text and object recognition with an ultrasonic sensor for obstacle detection is addressed in [123]. Moreover, the AT was tested with 500 images, and the authors state that the system has an overall accuracy of 84%. Another OCR device for educational purposes is depicted in [186] with a cost of USD 330. In this system, the images are captured and processed independently through an OCR engine. Authors refer to some improvements to the system such as including multilingual support, GPS, and video processing. Lastly, the study [177] shows a comparable IoT OCR device to the reference [123] with Google Vision Cloud API.

The fifth type or category of AT analyzed for visual disability is the color detectors. The works [180], [181] show two ATs for color detection based on Arduino boards. In the first study, the authors outline a wearable color detector mounted in a glove with voice feedback to the user through Bluetooth protocol and a headphone to inform the detected color. The cost of the device is USD 50, and the authors mentioned that further studies will be conducted to get a more reliable and cost-effective device. In the second reference, a similar device to detect colors is illustrated with support in different languages such as English, Thai, Vietnamese, and Chinese. The device was tested by $n=15$ visually impaired students. For this case, the cost of the device is USD 87, and the authors pointed out that future research will be focused on a wearable device with a sleep mode to save battery in order to increase the autonomy of the AT. By the same token, the reference [182] develops a system to compensate colors that uses Ishihara plates to detect color impairments. The AT shows a compensated color image in function of the deficient color that the person does not identify. The efficiency of the color compensation oscillated between 70% to 90%. The system was tested by $n=8$ visually impaired persons.

To detect visual impairments, the authors in [122] explain a system to detect three types of visual impairments, namely, strabismus, blind spots, and blurry vision for rural areas, employing Raspberry Pi, and OpenCV with blob detection algorithm. The AT was tested in several trials (3-5) to identify the impairments of $n=19$ volunteers. The authors conclude that a variation of the illumination can conduct to get a better result for the computation of sight sensibility. This last system belongs to the sixth type of ATs for visually disabled persons as shown in Table (11). At last, the studies [187], [188] depict some lessons learned and aspects regarding the angle of detection, measurement distance, etc. to have in mind in the ATs that use ultrasonic sensors.

2) MOBILITY DISABILITY

Devices for mobility disability represent the second category of ATs that emerged in the analysis and synthesis of the SLR. This category is compounded of three overall ATs: Wheelchairs, rehabilitation equipment for the upper body, and prostheses. Concerning the wheelchairs, these were developed for persons with medium to severe mobility impairment. The first kind of wheelchair uses electroencephalogram (EEG) signals to handle or command their movements through Emotiv Epoc or NeuroSky Mindwave headsets [104], [189], [190]. In these cases, the headsets with a signal conditioning circuit take the EEG signals that are processed in third-party software such as Emotiv SDK, MATLAB, or ThinkGear SDK for .NET. In addition, Arduino is used as an end device interfaced with the motors or sensors to process the commands to move the wheelchair according to the signals sent by the previous software. Commonly, a laptop is mounted in the wheelchair to process the EEG signals that came from the eye's blinking or movement. In function of the previous action, a command is generated in the wheelchair. The authors of these developments pointed out some improvements to their designs such as including navigation sensors, speed control, and the need to perform more trials to determine the robustness and functionality of the ATs. Complementary in [191], the authors present a USD 210 wheelchair controlled by EOG signals with an average accuracy of 90%. The device can reduce in 83% the accessibility costs of the wheelchairs available commercially.

The second kind of wheelchair employs computer vision techniques with gestures to identify the command of the user. In the study [96], the authors developed a Human

Machine Interface (HMI) to detect the emotions or facial expressions of the users which can command the movements of the wheelchair. The facial gestures are detected with a smartphone camera installed on the wheelchair. The system was designed with neural networks, OpenCV, and Raspberry Pi, and counted with an accuracy of 98.6% in the different trials. As improvements, the authors indicated the need for a rear camera to detect and avoid obstacles. A similar work was deployed in [192]. In this case, the authors designed a wheelchair with two modes of operation: manual and automatic. In the manual mode, the user can handle the wheelchair with a joystick. In the automatic mode, an object detection system created with Raspberry Pi, TensorFlow, and OpenCV allows to recognize and avoid obstacles. The authors stated that for indoor environments the wheelchair is safe but for outdoor settings more sensors and trials, and a balancing of the force in the wheelchair's motors are needed.

The third kind of wheelchair is handled with voice commands. The works [97], [128], [193] show designs in this regard. In the first study, the authors describe the feasibility to develop a wheelchair with Raspberry Pi. The second study describes a wheelchair controlled with voice commands and a magnetic device that is composed of a dental retainer with a magnet. A command for handling the wheelchair is sent by the disabled person according to the tongue movement with the magnet. Speech recognition is based on an *EasyVR* board. The accuracy of the speech detection is between 98%-100% with a latency of 20 ms. The system was tested on a person with disability. At last, the third work addresses a wheelchair with voice command using Google Speech Recognition API. The accuracy of the device in the trials was 90% with a latency of 1.2 secs.

The fourth kind of wheelchair that uses an accelerometer, 3-D printing, and a joystick was developed in the work [194]. Through the hand gestures of the user detected with the accelerometer, the wheelchair can be handled to go forward or backward. The device was created with an accessible design employing a 3-D printer. The authors mentioned that more trials must be conducted as well as, the consideration of making a wireless hand band, which would reduce the invasiveness in the user. The wheelchair was tested on a person with dexterity disabilities. Similarly, the study [195] depicts an OSHW wheelchair with a cost of USD 267 and the complete files in software and hardware to replicate it. The wheelchair is controlled by head motion through Python and MATLAB. The reaction time of the wheelchair was 100 ms and the AT was evaluated by 10 users.

Concerning equipment for upper body rehabilitation, reference [196] describes a compact single degree of freedom robotic system known as PARS that costs USD 170.12. The system is interfaced to an ESP8266 that sends the force signals through User Datagram Protocol (UDP) to a simulator that counts with several levels of difficulty to help the patient with the treatment. The authors manifested that the parameters of the simulator should be altered by consulting medical experts in the field according to the features of the patient. It is worth mentioning that this study has an open repository where the design information can be downloaded to replicate the system. Another system to monitor rheumatoid arthritis patients with a cost less than USD 100 is presented in [197]. The system is composed of a glove with flex and force sensors to monitor this last variable in the fingers and to establish a diagnosis of the person. The authors highlighted the need for this kind of device because the diagnosis in many cases for rheumatoid arthritis is subjective and slow. Also, the authors pointed out as further work the inclusion of machine learning algorithms to adapt the system to the patient characteristics. Diego et al. [198] detail a USD 400 system for arm and hand rehabilitation created in 3-D printing. The movements of the system are coordinated by an Android APP. The authors pointed out some improvements such as adding more degrees of freedom to the joints in the arm, the shoulder, shoulder blade, and the wrist.

Finally, in this section, the studies [92], [125], [199] depict upper body prostheses. In [92], the authors propose an arm in 3-D printing controlled by EEG signals that are sent to Arduino utilizing ZigBee protocol. The performance of the arm was evaluated by three users, however, the accuracy of the device was between 20% to 80%, which means that the device must be optimized with extensive training time that allows controlling the arm more accurately. Similarly, the authors in [125] show a bionic arm controlled by the EEG signals of the eye blinks using two techniques in MATLAB: Supported Vector Machines (SVMs) and Linear Discriminant Analysis (LDA). The accuracy of the arm with these techniques is over 97%. The study [199] depicts a hand made in 3-D printing and controlled by Electromyographic (EMG) signals in real-time. The fingers are moved through servomotors, middle phalanxes, and hinges. The movement is detected by EMG sensors installed on the arm of the patient. After, these signals are characterized to generate the control of the fingers. The device was tested by a disabled participant with congenital disorders of the musculoskeletal system. The average error of recognition was 8.43% for relaxed muscles, 16.10% for half tensed muscles, and 5.21% for fully tensed muscles.

Concerning the GitHub projects for mobility disability, consult the following references which include wheelchairs controlled by EEG signals and image recognition [75], [76], hand prosthesis, and an exoskeleton [74], [77].

3) HEARING AND SPEAKING DISABILITIES

The third category of ATs is focused on hearing and speaking disabilities. The category is compounded by electronic hand gloves for sign language [200], [201], speech-to-text devices [202], [203], computer vision-based systems for lip and sign detection [130], [204], and devices with complementary support for mutism, or speaking disability [202], [205]. In this way, the studies [200], [202], [205] show systems to support communication with persons with hearing and speaking disabilities. In [202] is described a wearable device to show text in an LCD according to the speech recognized.

The device uses the Google text-to-speech recognition API to convert the speech into text through an app called *ANKON* designed by the authors. In a similar way, the work [205] presents a device to communicate with deaf-mute persons through two modes: the first one is based on the conversion of text to vibrations in Morse code. The second one is based on the gestures of a glove that wear the person with a disability. The authors indicated the need to improve the time delay between the voice and Morse code conversion and reduce the extra noise of the ambient that can affect the results of voice recognition. The authors in reference [200] explain an electronic hand glove for sign language. The system reproduces through audio files several words such as ''hello'', ''goodbye'', ''yes'', ''no'', ''thanks'', etc., depending on the voltage values of the flex sensors in the fingers of the glove. Another electronic glove is illustrated in [201] for American Sign Language (ASL). The glove contains flex sensors and an accelerometer. Each sign is transformed into text and voice, using an LCD and a speaker.

Concerning computer vision-based devices, the works [130], [204] report systems in this regard. In [130], the authors expose an authentication system based on image recognition and edge computing for the identification of hand gestures. The model achieved an accuracy of classification of 99.1% and a processing time of 280ms. The performance of the classification algorithm was compared with CNN MobileNet V2. The system counts with an open repository (GitHub) with the classification models implemented. In [204], a lip-reading system for disabled people is depicted. The system takes images of the face's person and uses a Multi-Task Cascade Convolution Network (MTCNN) to detect the words expressed. The accuracy of the device was 86.5% with a processing time of 7.2 secs. The database for the system was constructed based on the voice pronunciation of six volunteers with 6000 samples. Other studies that employ SVMs and artificial neural networks with MATLAB to recognize the gestures of the ASL and transform them into speech through flex sensors and accelerometers are depicted in [98], [206], respectively.

Regarding GitHub repositories, the reference [83] shows a glove with flex sensors using Arduino while reference [82] illustrates a device to help *see* music for mute or deaf persons through LEDs and Arduino.

4) ACTIVITIES OF DAILY LIVING AND ENVIRONMENTAL CONTROL

ATs for activities of daily living and environmental control allow the person's actions such as eating, drinking, dressing, recognizing currency, and take the control of home appliances. The first AT in this category is composed of devices or systems for smart home appliances. For instance, in [105], the authors created a speech recognition system to control appliances at home based on the Dynamic Time Wrapping (DTW) technique and machine learning through SVM. The system needs a smartphone with an application developed by the authors. The control of the devices in the home is performed with a Raspberry Pi. The accuracy of the system with SVM was 97%. One limitation of the systems is the difficulty of speech recognition if the user's voice is affected by illness. Similar work with Arduino is presented in [207]. In this case, the authors used Google speech recognition API and Bluetooth protocol to send the different commands to turn on lamps and fans in a house.

A second AT allows monitoring the disabled people to prevent falls and accidents at home. The studies [208], [209] show these systems which are based on Wireless Sensor Networks (WSN) and a computer vision-based method to detect falls known as Motion History Image (MHI). Also, the systems launch an alarm in case of detecting a fall or a potential hazard. Both works employ Raspberry Pi to communicate with IoT systems or perform image processing.

A third AT was created by persons with medium to severe mobility impairments or disability [210], [211]. The first investigation describes an Electrooculogram (EOG) system with BIOPAC [212] data acquisition unit to capture the ocular signals and process them with Fast Fourier Transform (FFT) through MATLAB. The device moves a cursor in a Graphical User Interface (GUI) to turn on a light system. The second work shows a development to perform daily living activities based on EEG signals (blinking). According to the number of eye blinks is executed an operation such as turning on a lamp, fan, or open a door. The accuracy of blink detection was over 80%. As improvements, the authors mentioned the integration of a voice command selection.

In addition, other types of ATs such as banknotes and drug pills recognition systems have been identified. In [95] a wearable device known as *MedGlasses* allows to recognize the drug of the patient and monitor his/her health state with an app. The researchers employed R-CNN with a database of 4000 images to detect the drug pills with a reported accuracy of 95.1%. Other medical systems to monitor glucose, and communicate with the caretakers of the person with disabilities were identified in the studies [90], [213]. Concerning this last study, the system allows to send notifications to smartphones and control a GUI to interact with home appliances. As for the wheelchair controlled by the system, the authors implemented a coupling to handle it in 3-D printing.

In [99], [106], and [214] the authors illustrate banknotes recognition systems with backpropagation neural networks, SURF method, MobileNet v2, and Viola-Jones algorithm. As for the first work, the nominal error reported was 1.6% with neural networks while the recognition accuracy for the second work with the SURF method was 69.25%. The authors in this last study pointed out the necessity to improve the detection algorithms as further work. At last, the work [215] describes a mechanized toilet for disabled persons with Arduino.

5) GETTING ALONG THE PEOPLE AND PARTICIPATION IN SOCIETY

Four additional designs were analyzed that can benefit the well-being of disabled people in the fields of entertainment,

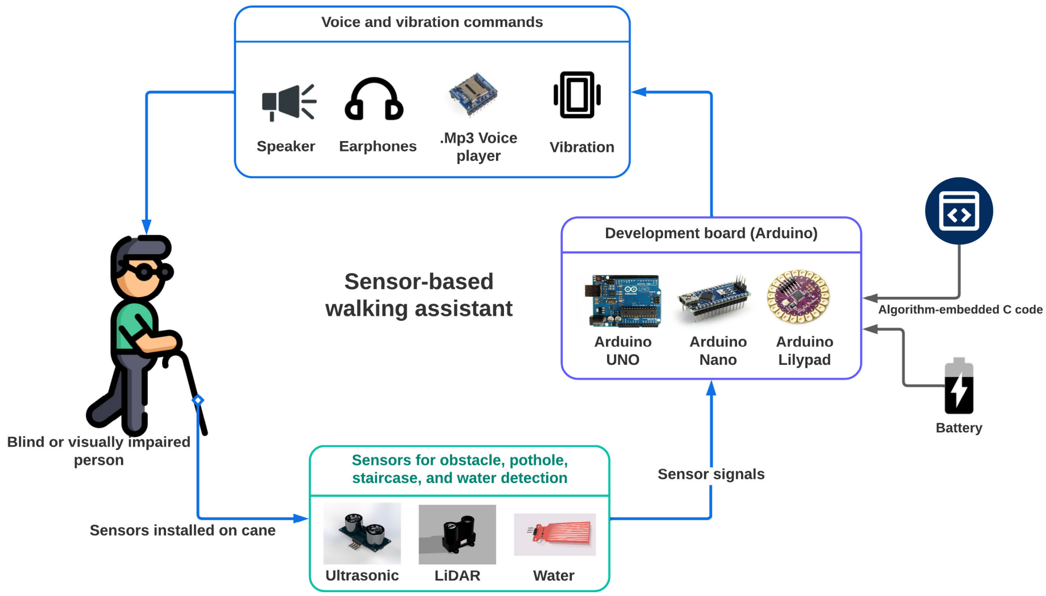

FIGURE 10. System architecture employed for sensor-based walking assistants.

sports, and sexual health. A video game designed in Unity3D considering usability, economic cost, and adaptability is reported in [216]. The game whose principal action is navigation and walking was tested with n=12 blind users (6 males, 6 females). In addition, the game system is composed of a white cane interfaced with an Arduino that sends its movement signals to the game. As improvements, the authors propose the design of a new experiment with more participants and consider more advanced techniques to evaluate player performance and preferences. For sports, in reference [217], the authors expose an Electronic Travel Aid (ETA) system known as *EyeVista*. The system can recognize obstacles, end-line identification, and track detection for athletes. As future work, the authors indicated the design of an embedded system that replaces the current Raspberry Pi computer installed in the device. A third device is created for sexual health [218]. In this case, a mind-controlled sex toy (neurodildo) for people with disabilities was created using 3-D printing. The device counts with a vibrator and some electrodes to provide electrical stimulation. The vibrations of the device are controlled by an EEG headset and an Arduino which allow the interaction between two users. Finally, [219] is a tourism assistant to facilitate information to blind or visually impaired users that have no experience on the semantic web.

C. RQ3. WHAT ARE THE MAIN TECHNOLOGIES IN HARDWARE AND SOFTWARE EMPLOYED BY THE RESEARCHERS IN THE STUDIES?

Figs.(10) to (12) show the architectures for *walking assistants*. For the sensor-based, typically the researchers employed sensors such as ultrasonic, LiDar, and water detection, installed on the cane or stick of the person. The signals of these sensors are interfaced to the Arduino boards using in some cases signal conditioning circuits with operational amplifiers. The early versions of these assistants notified the person with vibration or voice commands generated through vibration motors or speakers, respectively (see Fig.(10)). An improved version of these assistants incorporates smartphones with GPS to track the location of the blind or visually impaired person. In these cases, as Fig.(11) depicts, the authors created apps in Android with voice recognition utilizing Google speech-to-text API that indicates obstacles, potholes, puddles, and the current location of the person with the help of the Google Maps API. The signals and events detected in Arduino are sent to the app through a Bluetooth module, usually with HC-05 or RN-42 modules. To reduce the size of the hardware devices and make wearable walking assistants, the authors have decided to include boards such as Arduino Lilypad or Nano in their designs. Regarding computer vision-based walking assistants, Fig.(12) shows their overall architecture. For these designs, the authors used Raspberry Pi (3, 4, zero) because of its processing and peripheral features. A Pi Camera of 5MP or 8MP is installed on a cap or glasses and sends video frames or images to the Raspberry Pi. After, a computer vision API, system, or method such as OpenCV, TensorFlow, YOLO, Google Vision API, or SURF, among others, generally with CNN or R-CNN processes the image to recognize objects and faces, and notify the user. More sophisticated computer vision-based assistants [154], [158] use cameras such as ZED 2 or Asus Xtion Pro, specially designed for AI applications and to track objects. Notice that in some cases the architectures shown in Figs.(10) and (12) are mixed to provide more functionality to the AT. Another application of computer vision in ATs for visual disability and impairments is associated with the OCR reading and dictating assistants.

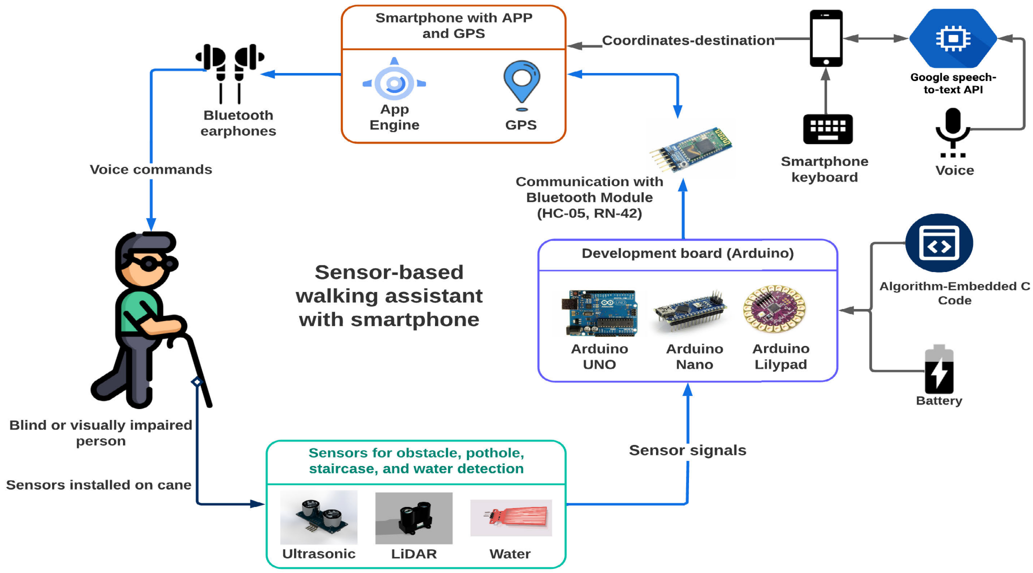

FIGURE 11. System architecture employed for sensor-based walking assistants with smartphone and GPS support.

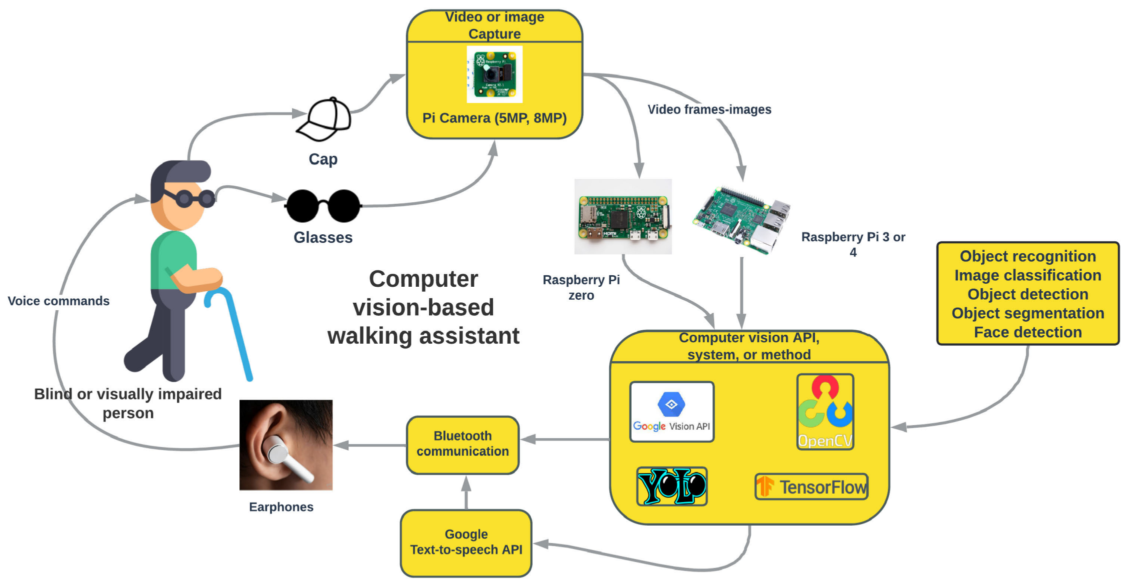

FIGURE 12. System architecture employed for computer vision-based walking assistants.

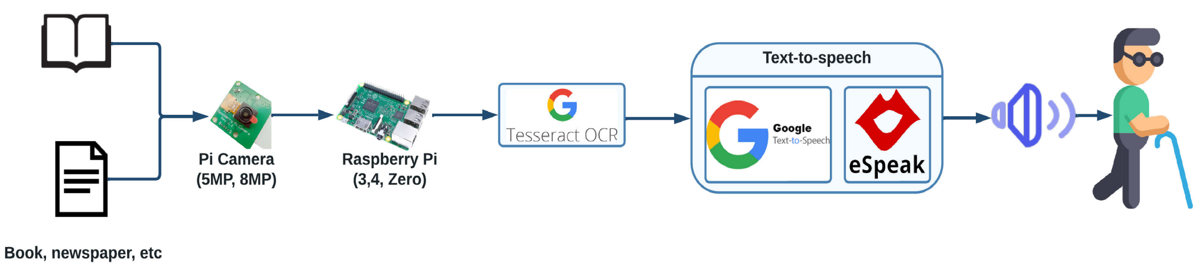

FIGURE 13. System architecture employed for OCR reading and dictating assistants.

For these systems, Fig.(13) outlines their architecture. In this, a tripod or similar structure is installed with a Pi camera to capture text and images from books, newspapers, etc. The images are processed by a Raspberry Pi,

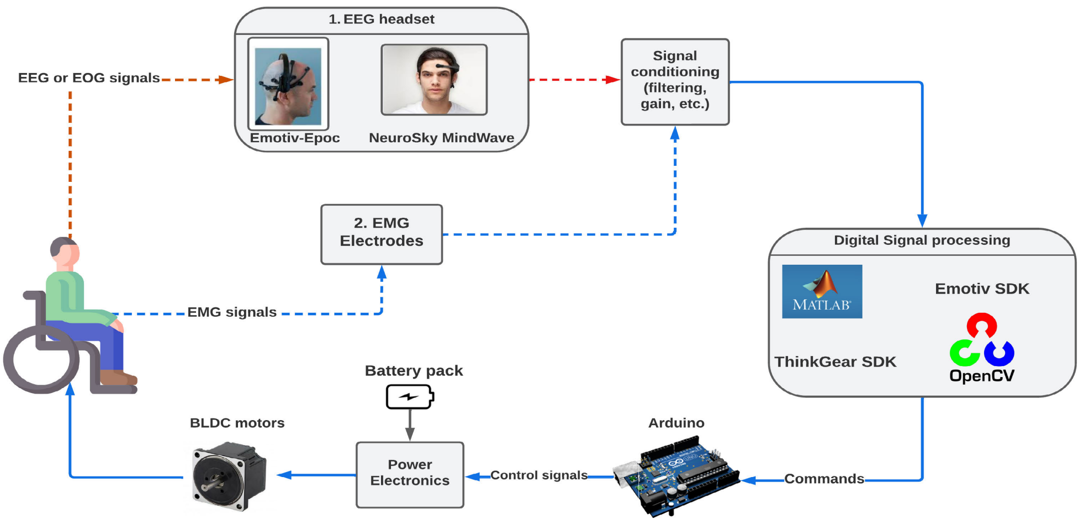

FIGURE 14. System architecture utilized for wheelchairs handled by EEG, EOG, or EMG signals.

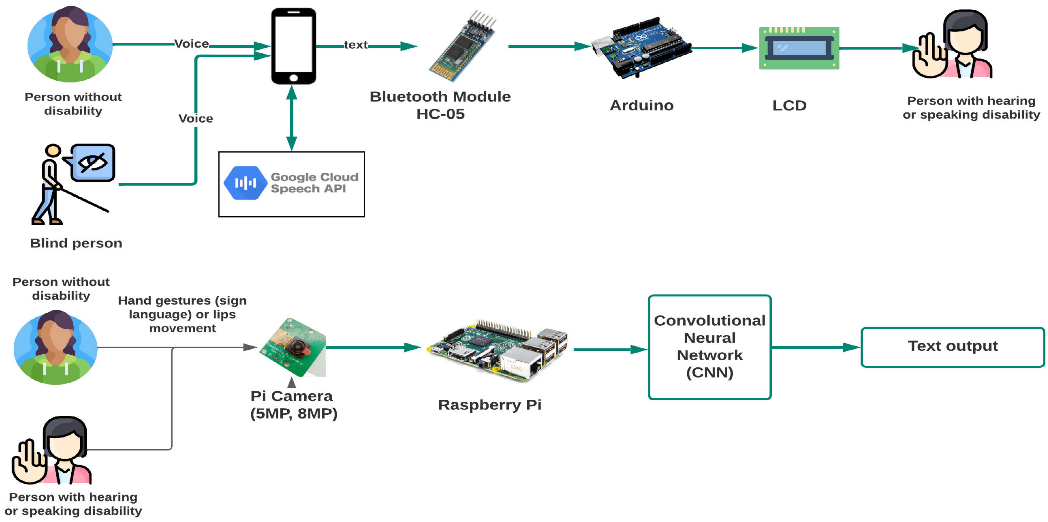

FIGURE 15. System architecture applied for hearing & speaking ATs.

commonly with the package Tesseract OCR. This software recognizes the text in the images, which is sent to a text-to-speech engine or API such as eSpeak, GTTS, PocketSphinx, or Flite.

Concerning color detection and compensation, these devices employ Arduino with RGB sensors type TCS230 or TCS3200 with .mp3 modules to reproduce the sound of the color. For the systems that detect visual impairments, the authors incorporated Raspberry Pi and Pi camera with OpenCV through blob detection algorithm. With respect to mobility disability, Fig.(14) describes the typical architecture for the *wheelchairs* designed to detect and process EEG, EOG, or EMG signals. There are two scenarios to process these signals. In the first one, to collect EEG and EOG signals, authors utilize EEG headsets type emotiv-EPOC or Neurosky Mindwave with signal conditioning circuit, which basically filters the signals of the person with disabilities. In the second scenario, EMG signals are collected with electrodes, and after these signals are filtered and adjusted with a gain provided by an instrumentation amplifier.

Once the signals are conditioned in any of the two scenarios, they are sent to MATLAB, OpenCV, or to special SDKs such as Emotiv or ThinkGear created by the manufacturers of the headsets. In these software are identified certain patterns for eye blink, relaxation, or muscle movement. With these patterns and their processing, some commands are transmitted to Arduino which operates as an end device to perform the control of the BLDC motors installed in the wheelchair. Besides, to avoid obstacles and hazardous situations, the wheelchairs are equipped with ultrasonic (HC-SR04) sensors, GPS, and in some cases with voice detection shields such as EasyVR. For this last case, the AT does not use EEG headsets

TABLE 12. Main technologies in hardware used by the researchers according to the disability and AT.

Disability-Assistive Technology (AT)	Hardware Component	Description-Type (bold)	URL- Supplier Example	Approx. Cost (USD)
Visual Disability and Impairments: Walking Assistants (Sensor-based) such as white canes or smart sticks	**HC-SR04**	Low-cost ultrasonic **sensor** to measure distances (2cm to 400cm)	https://bit.ly/2IyCF4v-Adafruit	$3.95
	Garmin LIDAR-Lite	LiDAR **sensor** to measure distances (3cm to 400cm)	https://bit.ly/3Q3nZMM-Adafruit	$59.95
	HMC5883L	Triple axis compass magnetometer **sensor** module for arduino 3V-5V	https://ebay.to/3BUd0kz-Ebay	$3.67
	SIMCOM SIM800	Complete quad-band **GPRS/GPS module** for embedded applications	https://bit.ly/3oTkBrQ-Indiamart	$4.42
	NEO-6M Module	U-blox 6 **GPS module** for embedded applications	https://amzn.to/3zxLdnb-Amazon	$18.99
	Arduino UNO R3	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	HC-05	5V wireless **Bluetooth RF Transceiver**	https://ebay.to/3Jtk5tZ-Ebay	$3.45
	aPR33A series C2.x	**Voice Playback** and Recorder Kit	https://bit.ly/3QdmbAV-Research design lab	$11.09
	WTV020	**Audio module**, sound player for Arduino	https://ebay.to/3BEt49S-Ebay	$2.53
Visual Disability and Impairments: Walking Assistants (Computer vision-based) such as smart glasses or white canes	**Pi Camera**	High quality 8 megapixel Sony IMX219 **image sensor** custom designed add-on board for Raspberry Pi	https://bit.ly/3Jq4rQ4-Adafruit	$29.95
	ZED2	First **stereo camera** that uses neural networks to reproduce human vision, bringing stereo perception to a new level	https://bit.ly/3vB3tKU-Stereo Labs	$449
	Raspberry Pi (V.3, V.4) with 2GB or 4GB	**Single-board computer** made by the Pi Foundation	https://bit.ly/32wU4nQ-Adafruit	$55
Visual Disability and Impairments: Braille interfaces and devices	**Arduino UNO R3**	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	Solenoids	Medium Push-Pull **Solenoid** - 5V or 6V	https://bit.ly/3zrXfhS-Adafruit	$7.50
	LCD	Standard **Liquid Crystal Display (LCD)** 16x2	https://bit.ly/3JtnU27-Adafruit	$9.95
	Raspberry Pi (V.3, V.4) with 2GB or 4GB	**Single-board computer** made by the Pi Foundation	https://bit.ly/32wU4nQ-Adafruit	$55
	HC-05	5V wireless **Bluetooth RF Transceiver**	https://ebay.to/3Jtk5tZ-Ebay	$3.45
Visual Disability and Impairments: Educational devices and materials	**Arduino UNO R3**	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	Sensor started kit	Arduino **sensor kit**	https://bit.ly/3oQj7hI-Alibaba	$13.04

TABLE 12. ***(Continued.)*** **Main technologies in hardware used by the researchers according to the disability and AT.**

Disability-Assistive Technology (AT)	Hardware Component	Description-Type (bold)	URL- Supplier Example	Approx. Cost (USD)
Visual Disability and Impairments: Color detection and compensation	**TCS 3200-TCS230**	Color recognition **sensor**	https://bit.ly/3d6M4n7-Mouser	$7.90
	ThaiEasyModule MP3	.mp3 **voice playback** module	https://bit.ly/3BJJ8Hm-ThaiEasyElec	$16.50
	HC-05	5V wireless **Bluetooth RF Transceiver**	https://ebay.to/3Jtk5tZ-Ebay	$3.45
	Arduino UNO R3	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
Visual Disability and Impairments: Systems for detection of visual impairments	**Pi Camera**	High quality 8 megapixel Sony IMX219 **image sensor** custom designed add-on board for Raspberry Pi	https://bit.ly/3Jq4rQ4-Adafruit	$29.95
	Raspberry Pi (V.3, V.4) with 2GB or 4GB	**Single-board computer** made by the Pi Foundation	https://bit.ly/32wU4nQ-Adafruit	$55
Mobility Disability: Wheelchairs	**Emotiv EPOC headset**	**EEG headset**	https://www.emotiv.com/epoc-x/-Emotiv	$849
	Neurosky MindWave Mobile 2 EEG Headset	**EEG headset**	https://store.neurosky.com/-Neurosky	$109.5
	EV3SB	Audio IC Development Tools **EasyVR Module**	https://bit.ly/3BLpHOe-Mouser	$42.90
	Flex sensor	Industrial motion & position sensors-**flex sensor**	https://bit.ly/3SvvkpU-Mouser	$12.95
	HC-05	5V wireless **Bluetooth RF Transceiver**	https://ebay.to/3Jtk5tZ-Ebay	$3.45
	ASMC-04B	Robot Servo with high torque and support 12V-24V	https://amzn.to/3JF4Wpp-Amazon	$57.99
Mobility Disability: Exoskeletons & Prostheses	**MyoWare 2.0 Muscle Sensor**	**EMG signal conditioning circuit**	https://bit.ly/3JB1Kep-Mouser	$39.95
	Neurosky MindWave Mobile 2 EEG Headset	**EEG headset**	https://store.neurosky.com/-Neurosky	$109.5
	131:1 Metal Gearmotor 37Dx73L	**DC Motor** with encoder	https://bit.ly/3BNuI93-Pololu	$47.79
	Arduino UNO R3	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	100kgf Linear Actuator	Medium-Duty **Linear Actuator** with Feedback	https://bit.ly/3QrQza8-Pololu	$259.95-273.95
	Micro servo	Micro **servo** 3.7 g	https://bit.ly/3dgdirH-Pololu	$4.95
	Flex sensor	Industrial motion & position sensors-**flex sensor**	https://bit.ly/3SvvkpU-Mouser	$12.95

TABLE 12. *(Continued.)* **Main technologies in hardware used by the researchers according to the disability and AT.**

Disability-Assistive Technology (AT)	Hardware Component	Description-Type (bold)	URL- Supplier Example	Approx. Cost (USD)
Hearing & Speaking Disability	**Pi Camera**	High quality 8 megapixel Sony IMX219 **image sensor** custom designed add-on board for Raspberry Pi	https://bit.ly/3Jq4rQ4-Adafruit	$29.95
	SIM 900 GSM module	SIM900 **gsm module** Shield Development Board Quad-Band Module	https://bit.ly/3Syvf4z-Aliexpress	$6.35
	HC-05	5V wireless **Bluetooth RF Transceiver**	https://ebay.to/3Jtk5tZ-Ebay	$3.45
	Flex sensor	Industrial motion & position sensors-**flex sensor**	https://bit.ly/3SvvkpU-Mouser	$12.95
	ADXL345	I2C-SPI **accelerometer**	https://ebay.to/3SIY9zk-Ebay	$24.95
	Miniature vibration motor	**Vibration motor**	https://ebay.to/3vLlgiN-Ebay	$2.20
	Arduino UNO R3	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	Raspberry Pi (V.3, V.4) with 2GB or 4GB	**Single-board computer** made by the Pi Foundation	https://bit.ly/32wU4nQ-Adafruit	$55
	USB microphone	**Microphone**	https://ebay.to/3Q8rHEM-Ebay	$12.35
Activities of daily living & Environmental control	**Pi Camera**	High quality 8 megapixel Sony IMX219 **image sensor** custom designed add-on board for Raspberry Pi	https://bit.ly/3Jq4rQ4-Adafruit	$29.95
	Neurosky MindWave Mobile 2 EEG Headset	**EEG headset**	https://store.neurosky.com/-Neurosky	$109.5
	EOG100C	**Electrooculogram Amplifier amplifies corneal-retinal potential**	https://bit.ly/3Qr9JNv-Biopac systems	Request quote
	Arduino UNO R3	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	Raspberry Pi (V.3, V.4) with 2GB or 4GB	**Single-board computer** made by the Pi Foundation	https://bit.ly/32wU4nQ-Adafruit	$55
	Nvidia Jetson TX2	**Single-board computer for AI applications**	https://ebay.to/3bAG3if-Ebay	$274.81
Getting along the People & Participation in Society	**Pi Camera**	High quality 8 megapixel Sony IMX219 **image sensor** custom designed add-on board for Raspberry Pi	https://bit.ly/3Jq4rQ4-Adafruit	$29.95
	Arduino UNO R3	**Open-source electronics platform** based on easy-to-use hardware and software	https://bit.ly/3JrQSj2-SparkFun	$27.95
	Raspberry Pi (V.3, V.4) with 2GB or 4GB	**Single-board computer** made by the Pi Foundation	https://bit.ly/32wU4nQ-Adafruit	$55
	Emotiv EPOC headset	**EEG headset**	https://www.emotiv.com/epoc-x/-Emotiv	$849
	Miniature vibration motor	**Vibration motor**	https://ebay.to/3vLlgiN-Ebay	$2.20

TABLE 13. List of main software employed by the authors. Descriptors: V: (Visual Disability & Impairments), M: (Mobility Disability), H&S: (Hearing and Speaking Disability), ADL&EC: (Activities of daily living & Environmental control), PS: (Getting along the People and Participation in Society).

Software	Disability					Description	Link
	V	M	H&S	ADL&EC	PS		
Tesseract OCR	✓					Open-source OCR engine	https://bit.ly/2QCrkaC
Google cloud text-to-speech API	✓		✓			Synthesizes natural-sounding speech by applying powerful neural network models	https://bit.ly/3P8n77Y
Pocketsphinx Python-CMU Sphinx	✓	✓				Open-source Toolkit For Speech Recognition	https://bit.ly/3p2qNha
Player	✓					Free Software tools for robot and sensor applications	https://bit.ly/3d21OYq
OpenCV	✓	✓		✓	✓	Real-time optimized Computer Vision library	https://bit.ly/2VY2Paw
Google speech-to-text API			✓			Accurately convert speech into text with an API powered by the best of Google's AI research and technology	https://bit.ly/3P6pPuV
Neurosky ThinkGear SDK for .NET		✓		✓		Adds new interfaces to access data from NeuroSky devices	https://bit.ly/3bzPwpS
Emotiv BCI		✓			✓	Trigger events with your thoughts using BCI's Mental Commands detection. Compatible with Emotiv EPOC EEG headsets	https://bit.ly/3A5WxIG
SimpleCV		✓		✓		Open-source framework for building computer vision applications	https://bit.ly/3A5WxIG
eSpeak	✓		✓			Compact open source software speech synthesizer for English and other languages	https://bit.ly/3bAeGEO
Google cloud vision API	✓					Derive insights from images with AutoML Vision. Detect emotion and understand text with pre-trained Vision API models	https://bit.ly/3bAf5XQ
TensorFlow Object Detection API	✓	✓				Create accurate machine learning models capable of localizing and identifying multiple objects	https://bit.ly/3BMdPeY
YOLO	✓					Real-Time Object detection library	https://bit.ly/3QnGxqE
OpenNI2		✓				Allow accessing and processing different sensor modules and cameras such as ASUS Xtion, PrimeSense Carmine, or Microsoft Kinect	https://bit.ly/3vPSGwD
Azure Text Analytics API	✓		✓			Mine insights in unstructured text using NLP—no machine-learning expertise required	https://bit.ly/3Sye7fp
Blynk		✓				IoT platform	https://blynk.io/
Unity 3D					✓	The complete solution to create and operate real-time 3D experiences	https://unity.com/

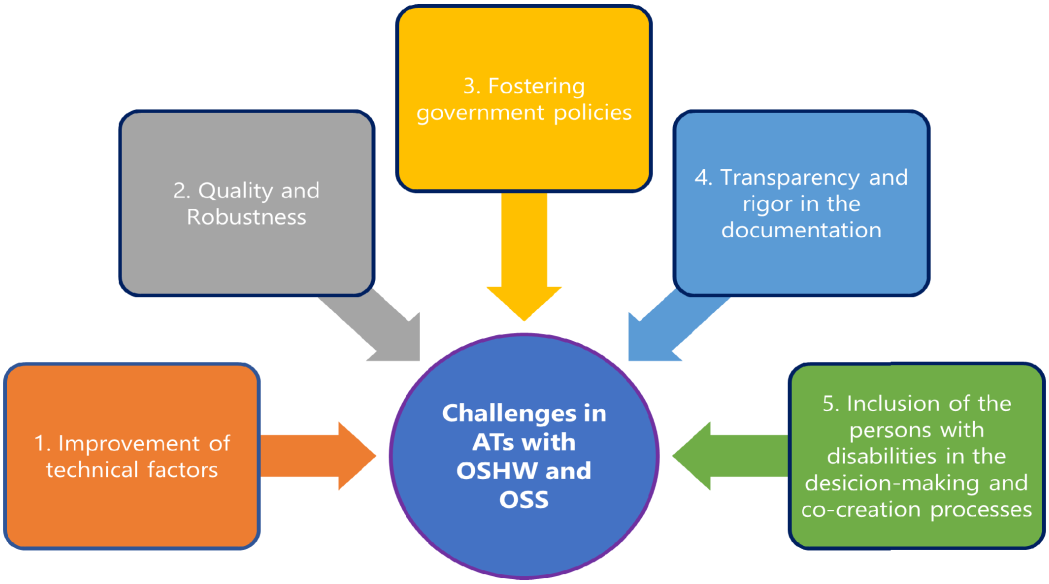

FIGURE 16. Challenges identified in the ATs with open-source hardware and software.

or EMG electrodes but rather the voice commands directly handling the movements of the wheelchair.

As for *prostheses*, some researchers employ EEG headsets [92], [125] while others utilize specialized EMG sensors and conditioning circuits such as MyoWare Muscle Sensor [220]. For the studies with EEG, the authors designed prosthetic hands and arms with 3-D printing, Arduino, and servomotors. For *exoskeletons*, the authors equipped their designs usually with linear actuators and EMG sensors [221].

About ATs for *hearing and speaking disabilities*, Fig.(15) portrays their overall architecture. In the same way as the wheelchairs, three schemes for these ATs were identified. In the first one, a person without a disability or a blind user generates words that are collected in a smartphone and transformed into text with the Google cloud speech API. The text identified by this API is sent to an Arduino through a Bluetooth module (HC-05) and is represented in an LCD to be read by the person with a hearing or speaking disability. In the second scheme (computer vision-based), the hand gestures or lips movements of the user are recorded with a Pi camera to detect patterns using CNN or MTCNN techniques in a Raspberry Pi [130], [204]. Once the CNN processes the video, it is generated a text output for diverse purposes such as security authentication or communication with non-disabled persons. In the third scheme, some gloves with flex sensors and accelerometers were created and characterized. According to the position of the fingers for sign language in these gloves, the flex sensors produce a voltage that is read by an Arduino to produce a text in an LCD in function of the sign or word expressed.

Respecting ATs for *daily living activities and environmental control*, to perform actions of home appliances, the authors utilize Arduino, Google speech recognition API, and EEG headsets. The EEG headsets are employed when users have mobility restrictions to turn on a fan or lamp at home. Also, to detect falls or hazardous situations in which the person with disabilities can be involved were implemented systems to monitor the persons with Pi cameras and Raspberry Pi. For the drug pill recognition system in [95], it was incorporated a Pi camera, Raspberry Pi zero, and the SBC NVidia Jetson TX2 with an R-CNN technique. Similarly, for the banknotes recognition systems, the researchers employed Pi cameras and Raspberry Pi with the SURF method and Viola-Jones algorithm as described.

In the technologies for ATs in the field of *getting along the people and participation in Society*, in the references [216], [217], [218] were used Arduino, Raspberry Pi with Pi camera, Unity 3D, and 3-D printing.

To complement the previous information, Tables (12) and (13) show the principal technologies in hardware and software that we found in the studies mentioned above. Aside from this information, a description, link, and in the case of hardware components both an approximate cost and a supplier example are depicted. The intention of providing this information is that stakeholders, practitioners, or designers of ATs can identify software and hardware which can be incorporated into their designs or products easily.

D. RQ4. WHAT OPPORTUNITIES, ISSUES, AND CHALLENGES ARE IDENTIFIED FROM THE ASSISTIVE TECHNOLOGIES THAT USE OPEN-SOURCE HARDWARE AND SOFTWARE?

While the studies in the SLR show that OSHW and OSS can contribute to the accessibility and reduce the barriers of cost and implementation of the ATs, that otherwise would require an expensive traditional process of design and fabrication, several challenges outlined in Fig.(16) were detected. Each

TABLE 14. List of Beta and Pilot prototypes for each disability according to the articles included in the SLR.

Disability	Type of study (Reference)	
	Beta Study	Pilot Study
Visual disability & impairments	[16], [93], [95], [124], [141], [156], [166], [167], [169], [171], [225]–[229]	[94], [101], [102], [107], [122], [133], [136]–[140], [142], [144], [146], [152], [157], [158], [160], [164], [165], [168], [170], [174], [181], [182], [216], [230]
Mobility disability	[194]–[196], [198], [199], [221], [231]	[96], [97], [189], [232]
Hearing & speaking disability	[204]	–
Activities of daily living & environmental control	[95], [106], [211], [233]	–
Getting along the People & Participation in Society	[217], [219]	[216], [218]

one of these with some suggestions to overcome them are described below:

1) *Improvement of the technical factors*: In several studies in the SLR, in special, those related to computer vision, the researchers and developers have manifested the need to improve the latency and accuracy of object detection in the algorithms and libraries employed. The reported detection accuracy in most cases is between the range of 63% to 99.1%. The processing time can, however, oscillate between hundredths of seconds to seconds which can be a critical factor, especially, in systems that detect hazardous situations, e.g., transit signals, falls, obstacles, and vehicles. In other cases, factors such as illumination, noise level, and the size of the image dataset have been mentioned by the researchers as improvements in their designs. For Arduino-based systems, one recurrent aspect is the reduction of the device's size to make it more compact and wearable for disabled people. In addition, references [222], [223], [224] can help the designers to enhance the techniques and methods employed in computer vision-based systems or devices. Besides, Table (13) describes the software, some of them open source, for several disabilities identified. For wearable and portable ATs, recommend to review the works [16], [95], [101], [133], [158].
2) *Quality and Robustness*: Although the technical factors exposed before are important, also the quality and robustness of the ATs affect their affordability. From n=155 designs exposed as articles, various are between *Beta* and *Pilot* prototypes according to the classification given by Jones & Richey in [48], that was explained in the section II-D. In this sense, (n=31, 20%) are pilot studies, while (n=30, 19.35%) are beta studies. The rest are *Alpha* prototypes sometimes called proof-of-concept, which evidences an issue in the testing of ATs. Table (14) shows the list of beta and pilot studies for the articles. Generally, the authors employ the descriptor "low-cost" to describe their developments, but in many of the studies, the cost of the AT is not explicit, which makes the identification of the economic accessibility of the AT challenging.
   Regarding the GitHub projects in Table (6), n=10 are beta prototypes [51], [56], [57], [61], [65], [72], [75], [76], [78], [90], n=2 are pilot prototypes [62], [82], whereas the rest (n=29) are alpha prototypes.
   Notice that in some disabilities, the number of pilot and beta studies is low, which can limit the evaluation of the quality and robustness of the ATs. Even, the researchers in the pilot and beta studies have indicated the need to perform more trials with disabled people due to that several experiments to test the ATs have been conducted typically with non-disabled persons. In addition, the trials have been conducted with n=1 to n=60 participants. Nonetheless, one aspect to take into account is to investigate and enhance the ATs to become pilot prototypes and final products. Similarly, the main corpus of ATs is focused on basic activities in compliance with Table (5). More research should be conducted, for instance, on ATs for learning disabilities and complex activity & participation. Regarding this last aspect, no AT that aid with learning or cognitive disabilities was identified. An exploration can be done in virtual reality, wearable devices, sensors, assisted AI ATs, educational devices, and biocompatible 3-D printing.
3) *Fostering government policies*: Research and potentiation of the ATs should be promoted by governmental agencies. More funds to implement and deploy robustness ATs with the help of disabled people and policies for effective access to the ATs can be boosted from these agencies, especially, in low or medium-income countries [10]. Also, ensure and improve the quality of the supply chain and its costs for the development of ATs. Respecting government policies on open-source with several experiences in some countries, there are four studies to review [234], [235], [236], [237].
4) *Transparency and rigor in the documentation*: While several works were found that meet the specifications for OSHW concerning documentation, including the bill of materials (BOM), and located in open repositories, a large portion of the articles analyzed lack

these requirements. Apart from the BOM, as mentioned by the authors in [238] in the document *Identifying the factors affecting the replicability of open-source hardware designs*, the lack of quality in the documentation and its accessibility can conduct to bias in the degrees of freedoms to study, modify, make, or distribute in this case ATs with OSHW and OSS. ATs should comply with four factors mentioned by the same authors: quality, completeness, accessibility, and ease of manufacture and assembly [238]. In principle, the documentation with OSHW and OSS should be uploaded in an open repository, for instance, *zenodo*, *ohwr.org*, *osf.io*, or *GitHub* as it is mandatory in some journals in the field of OSHW such as *HardwareX* or the *Journal of Open Hardware* (JOH). Aside from these elements, on one hand, it is necessary that more studies with OSHW and OSS are presented to OSHW specialized journals, or that the researchers publish their results in open repositories accessible by designers or practitioners. In addition, designers and researchers are encouraged to present their ATs to meet the OSHWA Certification of Open-Source Compliance (https://certification.oshwa.org/). In part, by complying with the above aspects, the three principles of openness in open-source hardware could be guaranteed: *Transparency, Accessibility, and Replicability* [38].

Even though much information concerning the hardware structure can be extracted from the studies, many of the documents lack software diagrams, e.g., flow, UML, etc., that help to understand the functioning of the AT. In this sense, apart from the Github projects indicated in Table (6), the following studies count with an open repository: [130], [158], [166], [167], [168], [169], [195], [196], [225]. Many of the studies collected and analyzed in the SLR have the potential to be complete ATs that help disabled people, but still, it is needed to improve the transparency and rigor of the information depicted in these studies. Then, ATs with OSHW and OSS could become more replicable for other designers or researchers.

5) *Inclusion of the disabled people in the decision-making and co-creation processes*: An interesting article about the maker movement entitled *Is the maker movement inclusive of ANYONE?: Three accessibility considerations to invite blind makers to the Making World* by the author Seo [239] questions if the democratization of making and the principles of the maker movement really mean for "everyone", especially, for the community of persons with some type of disability. There are obvious difficulties in matters of documentation accessibility for blind users in the maker movement. This example is provided because the maker movement with the advent of DIY (Do-It-Yourself) electronics can influence the proliferation and research about ATs that employ OSHW and OSS. It was clear that in several of the pilot studies, the disabled people were not included until the final stage of prototype testing and not during the process. This is an important point because the opinions of the disabled persons throughout the process from conceptualization to the design can aid to improve substantially the quality, affordability, and accessibility of the ATs. Ideally, the disabled persons could be enabled by an open source approach that allows them to become co-creators of their own AT. Regarding the co-creation of ATs and successful empowerment of persons with disabilities with this approach, consult the reference [240].

These aspects are current challenges of the ATs with OSHW and OSS, but they can mean an opportunity to enhance the well-being and quality of life of disabled people.

IV. CONCLUSION AND FINAL REMARKS

In this study, OSHW and OSS were shown to foster the design and deployment of low-cost assistive technologies that can benefit disabled people. Several ATs for diverse disabilities such as visual, mobility, upper body, hearing & speaking, among others, were described, as well as the diverse OSHW and OSS technologies employed in their construction from 2013-2022. An important corpus of designs from the database WoS along with specialized journals in OSHW, and GitHub was collected and analyzed. The SLR, found OSHW and OSS can contribute to the accessibility and affordability of ATs that can benefit disabled people. These can catalyze the design and deployment of low-cost ATs, which could be sensor-based or computer vision-based. The diversity of the technologies uncovered in the SLR provide clear evidence that it is possible to design, construct and even commercialize ATs that meet high-quality criteria standards.

While it is clear that an open source approach is promising for the design and fabrication of ATs, some challenges remain. At the technical level, the improvement of the computer vision techniques and libraries, and the robustness of the ATs are critical as they play an important role in the assurance of the quality and affordability of the ATs. More trials that involve disabled people should be conducted to establish such robustness and quality, allowing the evolution of the ATs from alpha to pilot prototypes. Also, various aspects of OSHW and OSS such as the transparency in the documentation, the detailed description of hardware and software components in open repositories, with clear open source licenses and their accessibility influence the replicability and deployment of the ATs. Designers and researchers of ATs are encouraged to present their studies in journals specialized in open-source hardware that have rigorous criteria to consider any hardware under the descriptor of "open-source hardware". Moreover, ensuring that the technologies and documentation are inclusive provide the potential for disabled persons to be inside the decision-making process and co-developers of the AT rather than take part only in the final testing stage of the ATs. Disabled people can suggest meaningful improvements in ATs from their perspective which can help to expand the scope of the ATs for low or medium-income countries.

The purpose with this SLR was to inform and describe in detail the different ATs created with OSHW and OSS, and map the current state-of-art of these, encouraging in this way to researchers or stakeholders to create and design ATs that can improve the quality of life and well-being of disabled persons. This appears possible to the extent that the government, researchers, the marker movement, and people with disabilities work together in the co-creation and deployment of ATs.

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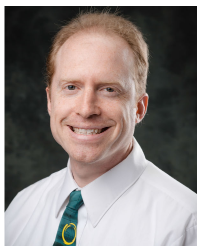

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