# Accessibility of the smart home for users with visual disabilities: an evaluation of open source mobile applications for home automation

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## ABSTRACT
The development of solutions known as "smart homes" has been explored to provide accessible resources to aid in the daily lives of disabled people. In particular, the growth in the development of open-source home automation applications based on Internet of Things (IoT) controlled by mobile devices presents numerous opportunities to boost the development of such aids. However, there is little research into how accessible the interfaces of such mobile applications are to people with visual disabilities. This paper presents an evaluation of six open-source mobile systems for home automation using IoT - Domoticz, Freedomotic, Home Assistant, HomeGenie, Mister House and openHAB. The evaluation was performed by means of expert review of accessibility guidelines using smartphones. The results showed that all the applications evaluated had accessibility problems that could prevent visually disabled users from using them, such as inaccessible controls, vision-dependent features, and lack of textual descriptions of images. The paper points out important adjustments that need to be carried out in order for IoT-based smart home applications to fully accomplish their potential of helping visually-disabled users lead more independent lives at home.

## ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): Evaluation/methodology

## Author Keywords
Accessibility; Assisted Living; Visual disabilities; Smart home

## INTRODUCTION
The use of interactive smart technologies has a significant potential to contribute to helping daily activities of people with disabilities. The appropriate use of devices and resources with adaptations to disabled people can help them perform tasks such as controlling appliances, switching lights and being aware of the state of home components with more independence.

The Internet of Things (IoT) can offer people with disabilities the assistance that they need to achieve a good quality of life. Internet of Things is a term used to describe how everyday objects can use the protocols and technologies developed for the Internet with the purpose of communication between itself and users, making daily activities more efficient. The trend to use interconnected objects in the Internet of Things has a substantial potential to help provide accessibility to using objects that would otherwise be inaccessible to visually-disabled users, for example.

The concept of IoT has the potential to be applied in the most diverse areas, such as business and industrial environments, medicine, and domestic environments. According to Li et al. [16], a context in which IoT deserves mention is the domestic environment. The term Smart Home is used to define a home controlled by a set of interconnected devices that are able to monitor and record information about day-to-day activities of the home residents. The data collected from these daily activities are used to predict people's behavior and prepare the home environment according to the necessities and preferences of each user. A characteristic of technological base that has pushed the IoT research paradigm is the increasing focus on miniaturization, the falling cost of microcontrollers, sensors, electric actuators, and digital wireless communication products, thus allowing you to include new functionalities to ordinary equipment. These components can be connected to devices that already exist, what enables the creation of new applications for home automation.

According to Domingo [8], the first-world report on people with disabilities, published by World Health Organization (WHO) in 2011, estimated that 15% of the world population had some sort of disability. WHO strongly defends the use of IoT as a tool that is able to improve the quality of life of people with disabilities. Furthermore, IoT applications are able to allow that people with disabilities have the same social and economic opportunities as the rest of the population. This


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report also presents a summary of technologies that could be used in Smart Home to help people with disabilities, which are:

- Head-Tracking Devices or devices that use other techniques involving facial movements, eyes movements, brain control, gesture recognition, and equipment for navigation that provides obstacle detection to help people affected by paralysis.

- Voice-controlled interfaces for helping people with visual impairments to control household equipment.

- Touch-screen devices that enable access to graphics information and reading of text content by people with hearing disabilities.

In order to make the implementation of IoT interfaces easier, several applications have been made available to connect a number of devices. Many of them offer interfaces based on mobile applications, which have a significant potential to help users centralize the use of their appliances in web/mobile applications using their mobile phone, for example. By using screen readers available in most smartphones and tablets, visually-disabled users would be able to access the interface of many devices, objects and appliances at home using a more accessible virtual interface available in such applications.

Although many such mobile applications have been developed, there is little evidence about how accessible those applications are in order to be used with screen reading software and other adaptions needed for users with visual disabilities. If such applications are not implemented considering good accessibility practices, users with visual disabilities may still not be able to use them fully to perform the tasks they need to in order to lead fully independent lives with home automation.

Striving to produce more accessible mobile applications is very important, especially as knowledge and research about how to make mobile applications more accessible is relatively more recent than research on Web accessibility [20, 19, 15, 18, 5, 23]. Although some accessibility guidelines are available from smartphone operating systems developers, such as Apple and Android, there are still little awareness-raising about the importance of mobile accessibility and how to help developers implement accessible resources.

The aim of this paper was to perform an evaluation of open-source mobile systems for home automation using IoT. The evaluation examined six applications: Domoticz, Freedomotic, Home Assistant, HomeGenie, Mister House and openHAB. The evaluation was performed by means of expert review of accessibility guidelines using smartphones and screen readers. The aim of the evaluation was to point out current problems encountered in the inspected software products to provide guidance to improve the accessibility of smart home applications.

The following sections describe a literature review of accessibility issues encountered in home environments and proposed adaptations, the method used to conduct the study, results and discussion and, finally conclusions and future work.

## ACCESSIBILITY TO HOME ENVIRONMENTS

In this section we describe results from a literature review of research studies describing accessibility issues and solutions to help people with visual disabilities at home.

The use of technologies to aid disabled people at home has a considerable potential to have a positive impact on independent living. In particular, as population aging increases, more and more people can benefit from having good resources to help them in daily activities at home [4].

Dermikan and Olgunt [7] performed a survey involving 161 participants, including adults, elderly and adults with physical and visual disabilities, being 31 visually disabled participants, in order to establish which adjustments in home environments were most relevant to those users. In their findings, they found that the most relevant issues for those users were : "adequate illumination level, ease of use in kitchen, adequate space for approach and use, adequate contrast between essential information and its surroundings, ease of use in accessories and functional vertical circulation"[7].

Gallager and Jackson [12] also investigated issues related to the impact of vision loss and ageing on independent living. The authors highlighted important issues related to the psychological impacts from not being able to carry out daily activities, reduced ability to perform physical exercises and increase in risks of falls. The authors pointed out that a number of important aids can be very helpful to contribute to improvements in the quality of life of people with sight loss at home, such as large-button phones, liquid level indicators, signature guides, talking watches, talking microwaves and talking weighing scales, and others.

In the context of Ambient Assisted Living (AAL), Cunha and Fuks [6], for example, proposed AmbLEDs as resources to help identify and monitor the behaviour of people in care at their homes by sheding light into places when people traverse across different spaces or to alert or remind them about important things that occur in their surroundings.

In another study conducted by Roentgen et al. [22], they produced an inventory of electronic mobility aids for people with visual disabilities encountered in the literature. The inventory identified identified 146 devices, with more details of 21 which were available in the market. The authors showed that many aids were available for people with visual disabilities, but many were not available any more at the time or were only prototypes that could not be used in practice. They pointed out that they found many inadequacies in a large range of products to aid visually disabled users that were not in accordance with specific needs of users.

In a study performed by Slater [24], they reported on issues raised by the Pocklinton Trust in the UK to help people with vision loss have better accommodations in their homes. From their study, they pointed that the main issues encountered by visually disabled people were aggravated when they were older, and included difficulties with cooking, dressing, washing, feeding themselves and using the toilet. Many people with visual impairments (including younger ones) also encountered difficulties with house maintenance. The authors suggested that performing small adjustments in home environments could ameliorate those situations and have significant impact to make people with vision loss (specially older ones) become more independent.

Fisk and Raynham [10] presented a study considering lighting as a technology in the context of people with sight loss. They point out ways in which lighting could help reduce falls and accidents, as well as helping design therapeutical strategies to be used in the rehabilitation of people with vision loss.

Tektonidis and Koumpis [25] presented in their paper a discussion about the provision of assistive technologies to support people at their homes using the principles of Internet of Things. They argued that, in their view, such services for home assistance should include: advisory services, monitoring services, dependable services, accessible interfaces, smart interfaces, orchestration services and third-party services. They proposed the "IOTC4ALL" – Internet of Things and Content 4 (: for) ALL), a framework to help provide smart-home solutions for mobile devices to help disabled people perform their activities at home.

The papers presented in our literature review show that there are important needs for support for people with visual disabilities that can be explored using smart-home strategies. However, it is important to highlight that such technologies will only be effective if delivered from a user-centred perspective and providing accessible and usable interfaces to users with a wide range of abilities.

## METHODOLOGY

This section presents the main methodological approaches used in this study. We describe the sample of mobile applications that was evaluated and how they were selected, the review of guidelines and the functional tests using screen readers.

### Sample of home automation mobile applications

The mobile applications evaluated in this paper were selected in accordance with the requisites: 1) it should be an open source application, considering that we could modify and improve it based on our accessibility evaluation results; 2) it should be a mobile application compatible with Android operating system, the world's most popular mobile platform. 3) it should not depend on any specialized hardware components, because we do not have access to specific control components in our lab; 4) it had to have at least five of the subsequent home automation components: house organization, switch, binary sensor, sensor with data such as temperature chart, sensor of situation as a light status, media player device. These are the most common control components among applications for home automation with IoT.

We found twelve open source applications for home automation, which are: aGo Control, Calaos Home, Domoticz, Freedomotic, Home Assistant, HomeGenie, Linux MCE, Mister House, openHAB, OpenMotics, PiDome Home Automation, and Smarthomatic. Among these applications, we discarded Calaos Home, Smarthomatic, and OpenMotics because they did not adhere to requisite 1 mentioned before. The PiDome Home Automation application is available only in alpha version, so we did not use it either. The Linux MCE and aGo Control failured to run on the Ubuntu operating system and the aGo Control Android application did not work fine. We ended up selecting six of the twelve open source applications for home automation. The applications selected included:

- **Domoticz** - A home automation system that lets you monitor and configure various devices [9].
- **Freedomotic** - An open source, flexible, secure Internet of Things (IoT) development framework, useful to build and manage modern smart spaces [11].
- **Home Assistant** - Open-source home automation platform running on Python 3. Track and control all devices at home and automate control [1].
- **HomeGenie** - The open source, programmable, hoem automation server, for smart connected devices and applications [13].
- **Mister House** - a Perl-based home automation software that contains support for all kinds of devices [14].
- **openHAB** - A vendor and technology agnostic open source automation software for your home. [17].

### Review of accessibility guidelines

In order to evaluate the mobile applications for home automation selected in the previous stage, we considered the method of review of guidelines. The chosen approach was a review of guidelines using an adaption of the Web Content Accessibility Guidelines (WCAG 2.0) for Web accessibility [3].

The WCAG establishes a set of Success Criteria that will be either true or false when applied to specific Web content. Considering the indicators from the Web Accessibility Initiative about making the WCAG 2.0 less dependent on technology, we decided to use these guidelines as our approach of accessibility evaluations, after making adaptations to mobile applications content. The success criteria were adapted in order to better fit the context of mobile applications, following previous studies developed by the authors' research group [23]. Success criteria that mentioned keyboard navigation, for example, were adapted to address issues regarding the use of interface components with default screen readers gestures.

The success of criteria of the WCAG 2.0 are divided into three levels, which are A, AA, and AAA. We analysed the 38 success of criteria available at the levels A and AA. Then we adapted the success of criteria to the mobile applications context. After making this context adaptation, evaluators conducted the accessibility inspection using the 38 success of criteria in WCAG 2.0 on the six mobile applications selected for Android. Even if the evaluators do not have any disabilities, they used the same gestures commonly used by visually impaired users to navigate though the applications. For each home automation application we evaluated the following control components: house organization, switch, binary sensor, sensor with data such as temperature chart, sensor of situation such as the light status, and media player device. The evaluators, with the support of an expert in accessibility guidelines, spent between two and three hours to inspect each application.

### Functional evaluation of home automation applications with a screen reader in mobile phones

The last stage of this study was to perform an analysis of accessibility of the six free mobile applications for home automation selected in the previous stage with a screen reader used in mobile applications. The screen reader used in the evaluations was Talkback for Android, the most widely used mobile screen reader by visually impaired users in Brazil.

In the accessibility inspections conducted, evaluators were people who are not visually impaired, but they used the same gestures commonly used by users with visual disabilities to navigate through the applications content in their smartphones. The most common gestures were “swipe right”, which moves to the next interface component and “swipe left” to go to the previous component on the phone screen.

The evaluations were managed using a Moto G (2nd generation) with Android 5.0.2. The evaluations of the Freedomotic, Home Assistant, HomeGenie, and Mister House applications were performed with the Google Chrome web browser, while the Domoticz and openHAB were evaluated though their own Android applications. Considering that most of the smartphones in Brazil runs Android operating system, we evaluated only applications for Android. In December 2015, Android held a market share of 78.62 percent of mobile operating systems in Brazil [21].

The goal of the accessibility inspections was to evaluate if the home automation applications components ensure compatibility with assistive technologies as screen readers and if a WCAG success criteria is either true or false when applied to these applications. For example, during the interaction with a lighting turn on button, we aimed to verify if the Talkback would be able to identify the light state and button function.

After evaluating the selected applications components with the Talkback, we assessed whether it had achieved satisfactory functionality in providing content, function, and state to all users and if it had complied the WCAG 2.0 Guidelines. The results of such assessments are shown in the Table 1.

## RESULTS AND DISCUSSION

This section presents the main results from the evaluations performed and their implications for the use of home automation applications by visually disabled users.

### Accessibility evaluation with a screen reader

In this section, we present the results from the accessibility evaluations of the mobile applications for home automation with Android’s TalkBack, considering the Web Content Accessibility Guidelines adapted to the mobile context as described in the methodology section. We tested the six applications selected in the "Evaluated mobile applications” section, considering the components requisites described in the same section. The first analysis verifies the number of instances of violations of WCAG 2.0 success criteria by levels A and AA. Table 1 shows the results of this analysis for each mobile applications evaluated. As can be seen from Table 1, all applications fails success criteria in both levels.

**Instances of violations of success criteria by level**

| *Applications* | *Level A* | *Level AA* | *Total* |
|---|---|---|---|
| Domoticz | 50 | 20 | 70 |
| Freedomotic | 217 | 125 | 342 |
| Home Assistant | 121 | 94 | 215 |
| HomeGenie | 35 | 28 | 63 |
| Mister House | 42 | 45 | 87 |
| openHAB | 66 | 37 | 103 |

**Table 1. Summary of number of instances of success criteria violations by levels A and AA.**

Table 2 presents the number of different success criteria violated per each application. As shown in Table 2, the Freedomotic application violated the largest number of success criteria. The Freedomotic interface is an image of the house map with its components, what makes it difficult for people with visual disabilities to navigate through the application and find all the features desired. Most of the components tested in the Home Assitant appiclation were unlabeled, that is why it was the second application that violated more different success criteria. It was also the second application that violated the success criterion 2.4.6, "Headings and Labels"more often that others, losing only for the Freedomotic application. The Mister House application drew with Home Assistant, violating a total of seventeen success criteria. In the Mister House application, the success criterion 4.1.2, "Name, Role, Value", is the most damaging violation for users with visual disabilities, because some control modes such as alarm do not enable compatibility with screen readers. Thus the state of those control modes cannot be accessed by people who depends on screen readers to use mobile applications.

**Number of different success criteria violated**

| *Applications* | *Level A* | *Level AA* | *Total* |
|---|---|---|---|
| Domoticz | 8 | 3 | 11 |
| Freedomotic | 11 | 8 | 19 |
| Home Assistant | 12 | 5 | 17 |
| HomeGenie | 5 | 5 | 10 |
| Mister House | 9 | 8 | 17 |
| openHAB | 6 | 4 | 10 |

**Table 2. Summary of number of different success criteria violated per application.**

Table 3 and Table 4 show, respectively, the number of instances of success criteria violations for levels A and AA, listing the most frequently violated success criteria for each application. As can be inferred from Table 3, success criterion 1.1.1 - "Non-text Content", 1.3.3 - "Sensory Characteristics", and 4.1.2 - "Name, Role, Value"presented a total of more than one hundred violations each one. In Table 4, success criterion 2.4.6, "Headings and Labels"was violated multiple times by all applications.

The number of violations of accessibility criteria in the evaluated applications is alarming. This shows that there is a strong need for improvements in open source applications for home automation should they meet the expectation of improving the lives of disabled people.

In the case o Brazil, in particular, the deployment of such solutions commercially can also be characterised as breach of federal law. Recently, Law 13.146/2015 [2], known as the Brazilian Law of Inclusion, expanded the obligation of providing accessible Information and Communication Technology (ICT) resources from only governmental agencies to all companies operating in the country. Unless significant changes are made in the applications, they would not be ready for deployment as solutions to home accessibility.

### User scenario and tasks

In the following, we discuss the main tasks that were performed in our accessibility evaluations of home automation applications with Android's TalkBack. Here we also explain which accessibility guidelines (WGAC), that were described in the methodology section, were violated by each task.

*Scenario*: A blind user lives in a residence and needs help to manage daily tasks with home automated living. He controls various devices in his home by using websites or applications in his mobile device. His house has two floors connected by a flight of stairs. On the first floor are the kitchen and the living room. On the second floor are the kids bedroom and his bedroom. Each bedroom has its own bathroom. All rooms have RGB (coloured) light, light switches, door, blinds, and air conditioning. The house has a security alarm.

*Task 1*: It is dinner time. I will cook a special meal tonight. Let's turn on the kitchen lights every day at night.
All six home automation applications have at least one light

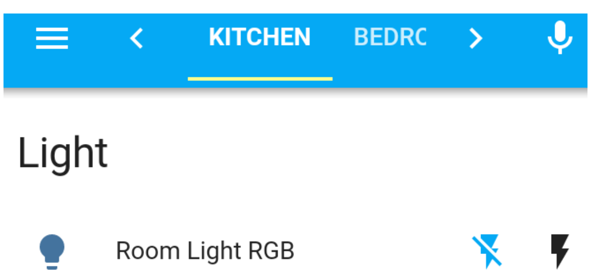


**Figure 1. Kitchen light switch from the Home Assistant application.**

switch feature. As shown in the Figure 1, the button switch aims to turn on or turn off the rooms lights according to a schedule or event. In the Home Assistant application, the light switch fails Success Criterion (SC) 1.3.3 - "Sensory Characteristics: Instructions provided for understanding and operating content do not rely solely on sensory characteristics of components such as shape, size, visual location, orientation, or sound", SC 1.4.1 - "Use of Colour: Colour is not used as the only visual means of conveying information, indicating an action, prompting a response, or distinguishing a visual element", and SC 4.1.2 - "Name, Role, Value: For all user interface components (including but not limited to: form elements, links and components generated by scripts), the name and role can be programmatically determined; states, properties, and values that can be set by the user can be programmatically set; and notification of changes to these items is available to user agents, including assistive technologies".
The light switch is represented by two lighting icons, one is a grey turn off button and another one is a blue turn on button. The icon colour indicates the light status and the icon shape indicates its function. The light switch does not provide information conveyed with colour, shape, and value through another visual means, therefore, users with visual disabilities cannot perceive the information and access instruction for using the button.

*Task 2*: Which colour should we choose for the kids bedroom RGB light?
In order to choose a RGB light colour, the user has to click

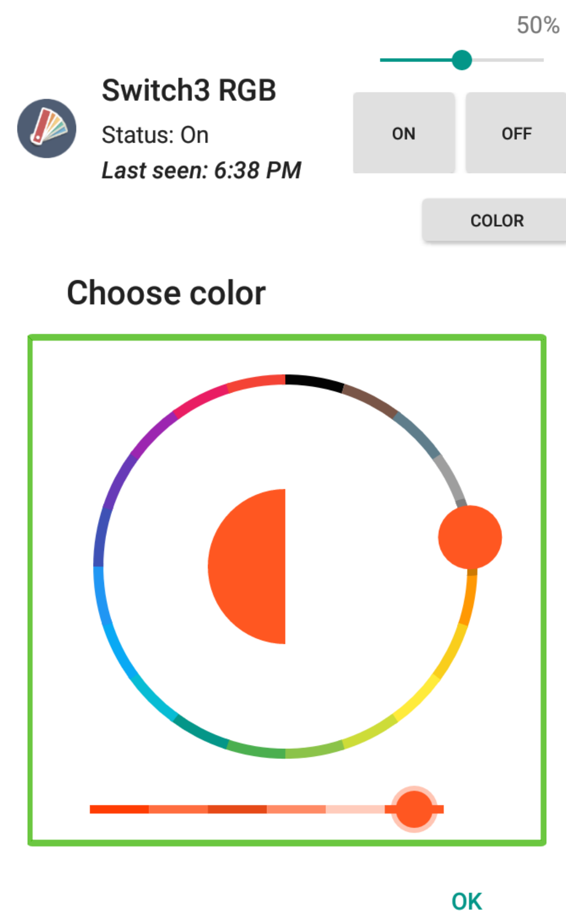


**Figure 2. Switch RGB color button and choose colour slider from the Domoticz application.**

at the colour button showed in the Figure 4.2, choose a colour using the colour slider, and then click at the OK button. The RGB light component was present in three of the home automation applications, which are Domoticz, HomeGenie, and openHAB. The choose colour window fails SC 1.1.1 -

| Guideline Level A | Number of instances of success criteria violations | | | | | |
|---|---|---|---|---|---|---|
| | *Home Assistant* | *Domoticz* | *Freedomotic* | *Mister House* | *openHAB* | *HomeGenie* |
| 1.1.1 Non-text Content | 26 | 11 | 47 | 10 | 20 | 6 |
| 1.3.1 Info and Relationships | 1 | 0 | 1 | 6 | 0 | 9 |
| 1.3.3 Sensory Characteristics | 20 | 8 | 47 | 6 | 17 | 4 |
| 1.4.1 Use of Color | 30 | 11 | 4 | 6 | 8 | 4 |
| 2.4.3 Focus Order | 1 | 8 | 47 | 0 | 1 | 0 |
| 3.2.1 On Focus | 5 | 9 | 6 | 0 | 0 | 0 |
| 4.1.2 Name, Role, Value | 25 | 1 | 55 | 8 | 19 | 12 |

**Table 3. Summary of number of instances of success criteria most violated per application in level A.**

| Guideline Level AA | Number of instances of success criteria violations | | | | | |
|---|---|---|---|---|---|---|
| | *Home Assistant* | *Domoticz* | *Freedomotic* | *Mister House* | *openHAB* | *HomeGenie* |
| 1.4.3 Contrast (Minimum) | 19 | 9 | 2 | 6 | 10 | 1 |
| 1.4.4 Resize Text | 8 | 2 | 1 | 0 | 0 | 2 |
| 2.4.6 Headings and Labels | 30 | 16 | 55 | 11 | 23 | 16 |
| 2.4.7 Focus Visible | 29 | 0 | 44 | 11 | 3 | 8 |
| 3.2.3 Consistent Navigation | 0 | 0 | 10 | 3 | 0 | 0 |
| 3.2.4 Consistent Identification | 0 | 0 | 10 | 5 | 0 | 1 |
| 3.3.3 Error Suggestion | 8 | 2 | 0 | 6 | 0 | 0 |

**Table 4. Summary of number of instances of success criteria most violated per application in level AA.**

"Non-text Content: All non-text content that is presented to the user has a text alternative that serves the equivalent purpose", SC 4.1.2 - "Name, Role, Value: For all user interface components (including but not limited to: form elements, links and components generated by scripts), the name and role can be programmatically determined; states, properties, and values that can be set by the user can be programmatically set; and notification of changes to these items is available to user agents, including assistive technologies", and SC 2.4.6 - "Headings and Labels: Headings and labels describe topic or purpose".
Besides being unlabeled and not providing alternative text, the colour slider does not provide important information to assistive technologies and does not allow itself to be controlled by assistive technologies. As the colour component does not enable compatibility with screen readers such as Talkback, it cannot be used by people with visual disabilities.

*Task 3*: Let's increase the air conditioning temperature of the living room to thirty degrees over the winter.

The air conditioning feature is available in the Domoticz,

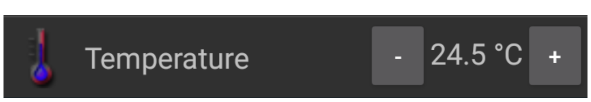


**Figure 3. Temperature control component from the openHAB application.**

Freedomotic, Mister House, and openHAB applications. The temperature component is controlled by the minus and plus buttons, which decrease and increase the air conditioning temperature of a room where the air conditioning system is located. The air conditioning temperature feature fails SC 1.1.1, "Non-text Content: All non-text content that is presented to the user has a text alternative that serves the equivalent purpose", SC 4.1.2, "Name, Role, Value: For all user interface components (including but not limited to: form elements, links and components generated by scripts), the name and role can be programmatically determined; states, properties, and values that can be set by the user can be programmatically set; and notification of changes to these items is available to user agents, including assistive technologies", and SC 2.4.6, "Headings and Labels: Headings and labels describe topic or purpose".
The temperature control buttons are non-text content and do not have a text alternative to present the button purpose to the user. Furthermore, the buttons are unlabeled and does not provide a cue to finding and navigating content. Thus the application does help people who use screen readers by ensuring that labels are meaningful when read out of context.

*Task 4*: It is very sunny today, we must check the weather before going out.

The weather chart shows the weather forecast for the current day and the next coming days or months. The weather chart was found in the HomeGenie, Mister House, and openHAB applications. The weather forecast component fails SC 1.3.1, "Info and Relationships: Information, structure, and relationships conveyed through presentation can be programmatically determined or are available in text"and SC 2.4.6, "Headings and Labels: Headings and labels describe topic or purpose".
The background colour of the weather chart is used to indicate that several weather indicators are related to each other. These relationships should be made to be perceivable to all. However, the weather chart does not provide means to programmatically determine the weather indicators' relationships. Therefore, users who are blind using a screen reader do not benefit when the information conveyed trough color is not available in text.

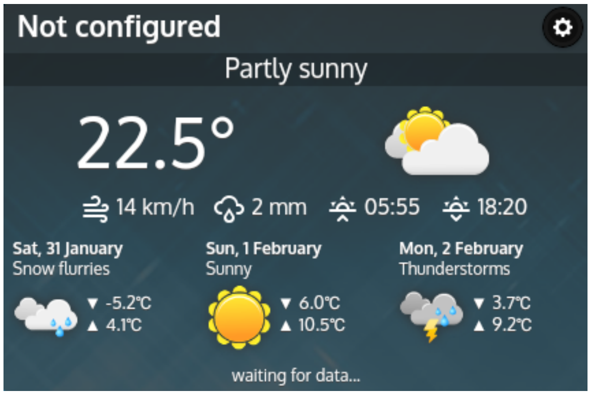


**Figure 4. Weather information from the HomeGenie application.**

In addition, the plus and minus arrows close to the temperature values as shown in the Figure 4 are all unlabeled. Since the arrow description is not provided, it is difficult for users with visual disabilities to understand the relationships between different parts of the content.

*Task 5*: Did you arm the alarm? We cannot forget to arm the alarm before going out.
The security alarm system allows the user to arm and disarm

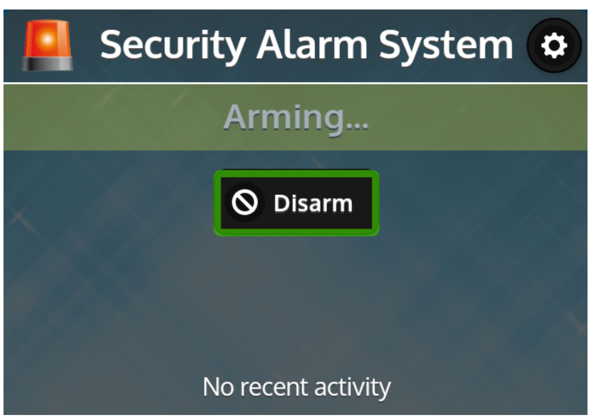


**Figure 5. Security alarm system from the HomeGenie application.**

the alarm when he is at home or out. The alarm component is available in the HomeGenie and openHAB applications. This feature failures to SC 1.4.1 - "Use of Colour: Colour is not used as the only visual means of conveying information, indicating an action, prompting a response, or distinguishing a visual element"and SC 4.1.2 - "Name, Role, Value: For all user interface components (including but not limited to: form elements, links and components generated by scripts), the name and role can be programmatically determined; states, properties, and values that can be set by the user can be programmatically set; and notification of changes to these items is available to user agents, including assistive technologies". The state control of the arm and disarm alarm button is not programmatically determined, and notifications about change of state are not sent to users and assistive technologies. Missing value information on user interface does not enables compatibility with screen readers used by people visually disabled.

*Task 6*: I like to listen to music while I am studying, but the current playlist is not good. Can you skip to the next song, please?
The media player component allows that users play songs

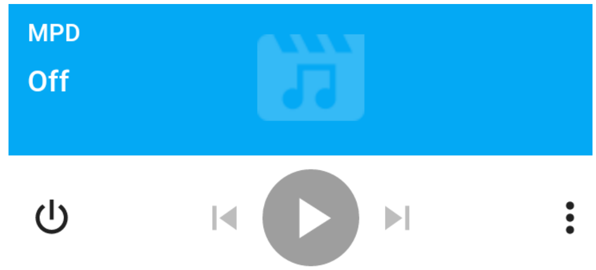


**Figure 6. Media Player component from the Home Assistant application.**

at a specif time or event. It is present in the Mister House and Home Assistant applications. The media player control failures to SC 1.3.1, "Info and Relationships: Information, structure, and relationships conveyed through presentation can be programmatically determined or are available in text"and SC 2.4.6, "Headings and Labels: Headings and labels describe topic or purpose".
The background colour of the media player component indicates that the music control buttons are related to each other. However, there is no text alternative to ensure that this information is understood by everyone. Thus the media player controls relationships are not perceivable to users with visual disabilities. Moreover, the previous button, play button, and next button of the media player are unlabeled and thus do not ensure compatibility with assistive technologies and by ensuring that labels are meaningful to them.

*Task 7*: It is already dark in the July season. Let's open the blinds a little bit.
The blinds are controlled by a slider component that allows


**Figure 7. Blinds slider control from the openHAB application.**

the user to determine what percentage of the blind should be open or closed. The blinds feature is available only in the blinds components. The blinds control component failures to SC 1.4.1 - "Use of Colour: Colour is not used as the only visual means of conveying information, indicating an action, prompting a response, or distinguishing a visual element", and SC 4.1.2 - "Name, Role, Value: For all user interface components (including but not limited to: form elements, links and components generated by scripts), the name and role can be programmatically determined; states, properties, and values that can be set by the user can be programmatically set; and notification of changes to these items is available to user agents, including assistive technologies".

When a user opens or closes some blinds, the blinds icon changes its colour to inform a status change. However, there is no text alternative or another visual means to ensure that all users can access this information that is conveyed by colour. Furthermore, assistive technologies as screen readers cannot keep up to date on the status of the blinds component.

*Task 8*: Also, increase the bedroom light luminosity to 100%, please.

In the Mister House application, the light luminosity is con-

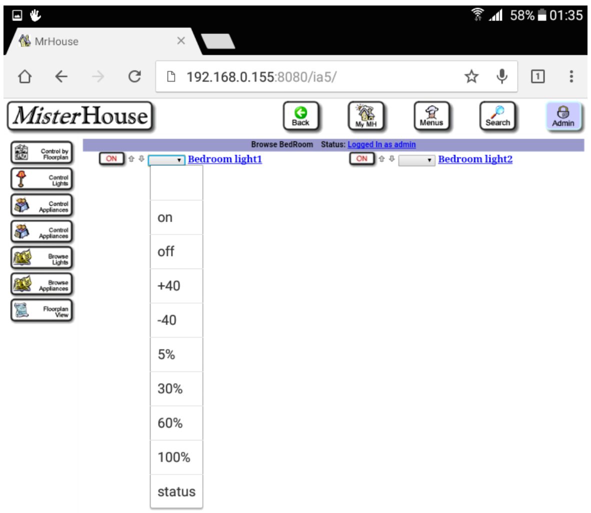


**Figure 8. Bedroom light luminosity dropdown list from the Mister House application.**

trolled by a dropdown button. In some other applications the luminosity feature is represented as a slider component. The light luminosity was tested in the Freedomotic, HomeGenie, Mister House, and openHAB applications. The luminosity component failures to SC 4.1.2, "Name, Role, Value: For all user interface components (including but not limited to: form elements, links and components generated by scripts), the name and role can be programmatically determined; states, properties, and values that can be set by the user can be programmatically set; and notification of changes to these items is available to user agents, including assistive technologies", and SC 3.2.4, "Consistent Identification: Components that have the same functionality within a set of Web pages are identified consistently". The state of the luminosity button cannot be programmatically determined and then it does not enable compatibility with assistive technologies as screen readers. Thus users with visual disabilities do not have access to notifications about change of state ant the current state of the lumninosity dropdown list. Moreover, the lighting icons have the same functionally, but their text alternative and icon symbol are not consistent, what makes difficult for users who depend on text alternatives to find a desired function.

*Task 9*: Check if the switch of the door lock is closed, please.

The door sensor allows to control the doors of all rooms in the house according to a schedule or event. When a user double clicks at the door icon, it changes its state from closed

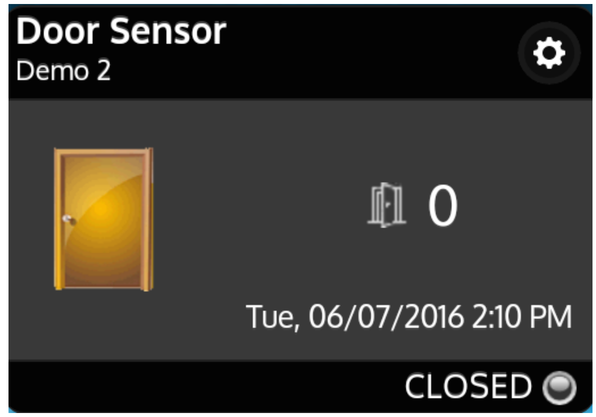


**Figure 9. Door sensor from the HomeGenie application.**

to open and vice versa. This interface component is available in the Domoticz, Freedomotic, and HomeGenie applications. The door sensor failures to SC 1.1.1, "Non-text Content: All non-text content that is presented to the user has a text alternative that serves the equivalent purpose", SC 1.3.3 "Sensory Characteristics: Instructions provided for understanding and operating content do not rely solely on sensory characteristics of components such as shape, size, visual location, orientation, or sound", and SC 2.4.6, "Headings and Labels: Headings and labels describe topic or purpose". The door icon is unlabeled, what make it impossible to find by people who use screen readers. Furthermore, the door symbol cannot be accessed through the use of a text alternative. So a person who cannot see the door picture will not have the text alternative recognized by screen readers.

The study performed yielded valuable contributions in terms of understanding the challenges and opportunities to provide more accessible smart home mobile applications.

Important issues were identified using the WCAG-based inspection. However, it is worth noting that performing empirical studies with disabled users would be very important in future studies to unveil other issues that are not currently covered by the literature in the field. This is particularly important considering the little existing evidence of empirical findings to support accessibility guidelines for mobile applications.

From the results presented in the present paper, we could identify that performing such studies, especially considering the home environment, would have a substantial potencial to explore important design issues to help visually-disabled users lead more independent lives.

## CONCLUSIONS AND FUTURE WORK

This paper presented an investigation on the accessibility of open source mobile and web applications for home automation using Internet of Things (IoT) principles. The evaluation was performed to highlight problems that could hinder the access of people with visual disabilities, mainly using screen readers.

Using Internet of Things and resources to make homes smarter has long been a promise to provide solutions to help disabled people to become more independent and to perform their tasks. However, if accessible systems are not effectively provided for them, such goals cannot be accomplished, and those technologies can become yet another barrier to their use of the home.

The results presented in this study showed that the accessibility of six web and mobile applications for home automation using IoT had very poor performance in the accessibility evaluations. The applications Domoticz, HomeGenie and openHAB had a slighter lower number of violations of accessibility requirements. However, they still presented serious issues that would prevent users with visual disabilities from performing a number of tasks at a "smart home".

Despite the vanguard approach of those applications in their goals of innovation, they present issues that are common to problems encountered in many mobile apps and websites. It would be very important that the developers and community involved in the development of such applications devote time and effort to improve the accessibility of these applications.

As future work, we intend to perform usability tests of the open source applications evaluated with visually-disabled users, in order to deepen the understanding of the accessibility issues encountered in smart home environments.

We also plan to conduct qualitative studies with visually-disabled users in Brazil to understand specific needs to develop home automation solutions tailored to the Brazilian context.

Finally, we plan to implement a proof-of-concept home environment with IoT objects interconnected in a real setting and operated via mobile devices. After the implementation, we plan to test and verify the implications and requirements to make it more accessible to people with visual disabilities.

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