

# Smart homecare technologies for the visually impaired: recent advances

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**Abstract:** Accessibility and autonomy are fundamental needs for people with visual impairments wishing to enjoy their rights as citizens and to access buildings, premises, and other facilities. Dealing with the possibility of autonomously performing activities of daily living, two main aspects are mandatory: autonomous mobility and living independently. In particular, dealing with autonomous accessibility is strictly related to the possibility to perceive the environment and to gain a realistic and intuitive awareness of ongoing events and hazards. In order to promote living independently, caregivers (whether relatives or assistive services) need to be aware of the user's physical surroundings. The literature is rich in attempts to provide technical solutions to improve quality of life and autonomy for frail people, particularly with regard to the visually impaired. This review summarizes "state of the art" electronic aids for the visually impaired, and aims to highlight the benefits and drawbacks of these aids.

**Keywords:** assistive systems, blindness, multisensor architecture, localization, activities of daily living

## Introduction

Although some progress has been made, disability is one of the most relevant causes of social marginalization. In this paper, some issues regarding the visually impaired are discussed to highlight the dramatic impact of the "worst disability in the world" in terms of social marginalization, as stated by the World Health Organization.<sup>1</sup>

According to the most recent figures, there are hundreds of millions of people with major sight problems throughout the world.<sup>1</sup> People with loss of sight face discrimination and infringement of their rights on a daily basis, be it at work, in trying to find work, or in going to a café, supermarket, or hospital.

The best way to help disabled people in the developing world is to provide them with autonomy. It is vital for blind and partially sighted people to have a good education and more autonomy to give them the skills needed to lead a full life. This is a new life concept, where the blind are not different but have only different abilities.<sup>1</sup>

For visually impaired people, accessibility and autonomy are fundamental needs because for an individual to enjoy his/her rights as a citizen, he/she should be able to access buildings, premises, and other facilities; an accessible environment means that a person will be able to seek employment, receive education and training, and pursue an active social and economic life.

The concept of autonomous accessibility is specifically related to the possibility of gaining a realistic and intuitive awareness of the environment as well as ongoing events

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and hazards. The advantages of tactile-based aids (tactile paths and tactile form of codification of information) are well-known, but there are some drawbacks with these solutions, including:

- social aspects of a tactile path, that could sometimes be interpreted as a mark of inferiority
- poor flexibility and adaptability of a tactile path, ie, modifications and reconfiguration of the environment requires rebuilding of the tactile path, which is expensive and time-consuming
- lack of information provided to the user in emergency circumstances and in the event of a critical situation
- difficulty with regard to a user being able to localize himself/herself inside the path and the impossibility of easily recovering the tactile path in the event that it is lost
- the use of arbitrary codification for exploitation of the tactile path, which is highly demanding
- use of hostile codification to access informative resources (such as notification of pictures, sculptures, flowers, plants, and other stimuli); in practice, the form of codification adopted is often highly demanding, while use of traditional tactile codification (eg, Braille) leads to exclusion of users who do not know the Braille codification.

The literature is replete with technical solutions aimed at improving quality of life and autonomy for frail people, particularly for the blind.<sup>2-6</sup> The development of enabling information and communication technology, including both information and sensing technologies, has provided effective systems and devices to help frail people when performing their activities of daily living (ADL). Such solutions perform in the direction of guaranteeing the right to well-being and active ageing promoted all over the world and also by the Horizon 2020 policy. Two main aspects are addressed by research groups working in this field, ie, autonomous mobility and exploitation in indoor/outdoor environments and frail people being able to live independently.<sup>7-43</sup>

Another key point when dealing with solutions for ambient assisted living, especially for users with depressed sensorial function (eg, the visually impaired), is the development of convenient solutions to convey the information generated by assistive systems to users themselves.<sup>44,46-56</sup>

Changing the way in which the user is provided with information from their surroundings, from artificial coding to natural perception, is necessary to avoid masking of natural echoes (the user must always be able to “visualize” the environment), to improve user confidence in such technologies, and to reduce the amount of training required.<sup>5</sup>

In the following sections, a nonexhaustive but representative review of the state of the art in this field is given, against the efforts dedicated to strengthening these innovations both from the technological and methodological points of view.<sup>2-44,46-56</sup> Since the aim of this review is to address assistive technologies, we do not discuss emerging topics in the field of bioengineering, like the artificial retina, or efforts to develop implantable prostheses able to partially restore vision to blind people.

The literature indicates that, despite good performance of electronic aids, some drawbacks have to be acknowledged, such as:

- high costs
- reliability issues
- poor quality of information provided to the user, in terms of quantity (redundancy) and continuity (existence of dead zones where the user is not assisted)
- inadequate user interfaces (eg, an acoustic interface masking natural echoes, or a vibratory interface conveying information that is poor or difficult to interpret); an interface must be for everyone and for everywhere, in that it should be easy to use and interpret, it should not mask natural echoes, and should be flexible and reconfigurable while conveying a suitable degree of information
- need for highly demanding training.<sup>6</sup>

The above-mentioned drawbacks lead to the visually impaired being diffident about using many of the available solutions.<sup>6</sup> Similar consideration could be extended to other classes of perceptual impairment.

The development of new methodologies overcoming the above drawbacks, for example, by providing blind people with a realistic and intuitive perception of the environment, could solve some of the structural and communication barriers to their use in a concrete way.<sup>2,4,13,18,19,32,44</sup> A realistic and intuitive perception of the environment is mandatory to address their real need of autonomy, to facilitate social inclusion, and to protect them against hazards.

An overview of solutions to assist blind users in mobility tasks is discussed in the next sections, along with innovative methodologies for the detection of ADL. The crucial task of providing the user with a convenient and natural form of information is introduced in the final section.

With the aim of illustrating frontier results produced by recent research activity, the main focus of this paper is on the methodologies adopted to implement smart signal processing rather than on an indepth description of the hardware involved. It should be taken into account these low cost solutions are able to guarantee system performances.

## Assistive systems for autonomous mobility in the blind

Assistive systems for frail people should be able to build awareness of the user's physical status within the environment and provide the user with optimized information allowing for safe and efficient exploitation of the environment. To this end, several technologies have been exploited, including ultrasonic, infrared, laser, and camera devices, while auditory and/or tactile solutions have been used to provide feedback relevant to the user.<sup>7-10</sup>

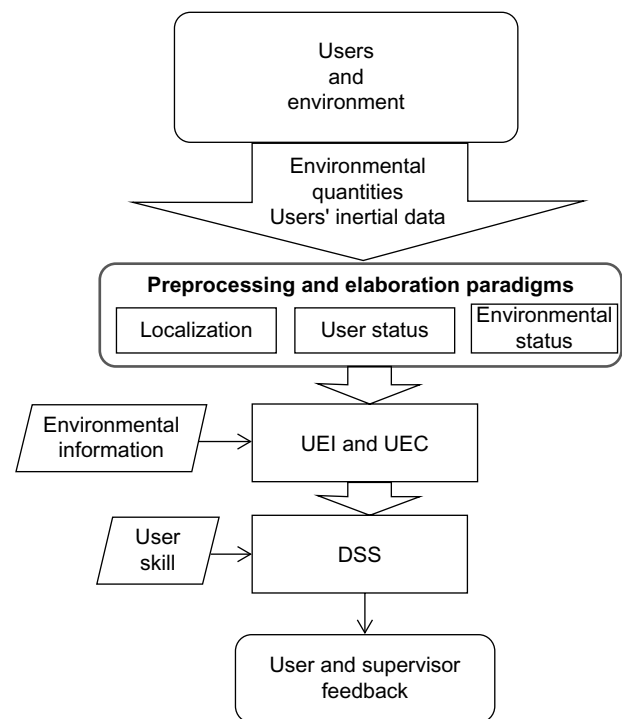
The use of a handheld device based on an ultrasonic beam to detect the distance between the user and obstacles and a vibrational-based user feedback system is exploited by the Miniguide.<sup>10</sup> The possibility of adopting electromagnetic and optical systems to implement travel aids for blind people has been described.<sup>11,12</sup> The Kahru Tactile Outdoor Navigator<sup>13</sup> is a wearable tactile harness-vest display that uses vibrating motors to provide directional navigation instructions to the user. Examples of devices exploiting a camera to perceive the environment and convenient translation of its contents into auditory or tactile perception include the vOICE system<sup>14</sup> and Intelligent Glasses.<sup>15</sup> Other solutions use digital tags, active badges, accelerometers, and other sensing systems to interact with the user once the user gets into the devices' range.<sup>16</sup>

Although notable efforts have been made to develop assistive systems with convenient performance, drawbacks have emerged, such as the discontinuous form of assistance provided to the user, high cost, and sometimes an arbitrary form of information conveyed to the user.

The main tasks required to implement an efficient and reliable assistive system for the autonomous mobility of frail people are summarized in Figure 1. The system must be able to locate the user, assess environmental hazards, and monitor user status. Moreover, a suitable decision-making system which produces the knowledge on the user-environment interaction is mandatory. Obviously, a suitable way to convey service and security information to the user is a critical feature of each assistive system. The main functionalities of an assistive system for the exploitation of indoor environments are now discussed.

## Absolute and relative indoor tracking systems

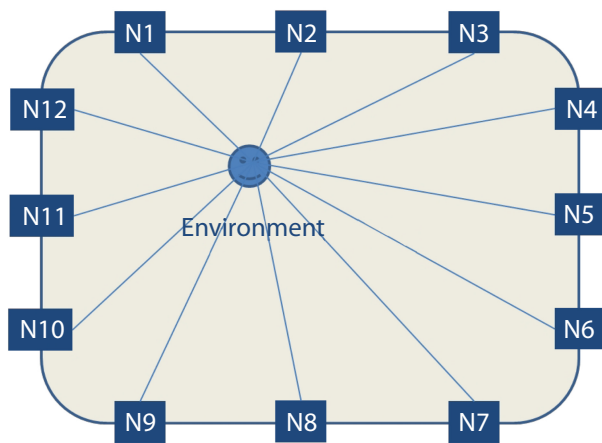
Development of pedestrian tracking systems for indoor application is a challenge for researchers, especially for critical contexts. Two main approaches can be followed, ie, absolute tracking solutions and relative tracking systems.<sup>17-32</sup>



**Figure 1** An approach to implement a smart assistive system for the autonomous mobility of blind people in indoor environments.

**Abbreviations:** DSS, decision support system; UEC, user environment contextualization; UEI, user environment interaction.

Concerning absolute indoor tracking, solutions based on wireless localization systems (such as Bluetooth, ZigBee, and radio-frequency identification) show an accuracy which is often not compatible with assistive purposes in an indoor environment. Moreover, drawbacks of such approaches include the high cost of their initial deployment and power budget. To overcome such drawbacks, a number of technologies have been proposed. As an example, the localization system adopted described by Andò et al<sup>17,18</sup> is based on the continuous interaction between the user module, equipped with an ultrasound transmitter, and a distributed architecture of sensor nodes equipped with ultrasound receivers. This approach, which also exploits smart trilateration algorithms, allows for real time and very accurate estimation of the user's position within the environment.<sup>32</sup> In order to provide the trilateration system with a high degree of redundancy, reinforcing the robustness and the robustness against faults of the system, more than three fixed reference points are usually adopted, as shown in Figure 2.<sup>32</sup> As a first step, the algorithm proposed by Andò et al<sup>17,32</sup> solves the trilateration problem locally, thus obtaining  $M$  estimations of the user's position. The paradigm then performs a statistical analysis of the results to filter least probable solutions and finally processes the remaining results to calculate the optimal estimation. The multilateration



**Figure 2** A two-dimensional trilateration approach with redundant sensor nodes (N).

system ensures a suitable accuracy to the user localization task (in the order of centimeters), as well as robustness (especially when some sensor nodes fail).<sup>17,32</sup>

Despite their good performance, absolute indoor tracking systems require structured environments;<sup>19</sup> inertial tracking can be adopted especially for remote monitoring of frail people in unstructured environments. Such a solution can provide accurate relative positioning information both in indoor and outdoor environments. Although these systems typically suffer for cumulative drift errors, both in walking distance and heading estimations, such drifts can be fixed through a periodic reset by absolute references.<sup>20</sup>

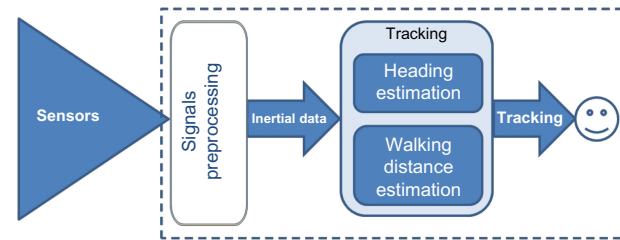
Advances in this context could come from the use of suitable data fusion techniques, often based on extended Kalman filters,<sup>21–23</sup> aimed to improve performance of the navigation system.<sup>20</sup>

Concerning technologies, different solutions have been proposed, eg, standalone customized devices,<sup>24–26</sup> smartphone-based platforms,<sup>27,28</sup> and mixed systems.<sup>29,30</sup>

Although smartphone-based assistive systems could discourage frail people, considering that the cultural heritage in information and communication technology systems is rapidly spreading, such solutions can be very convenient for the safe and efficient exploitation of educational/cultural/job environments.

In line with the above considerations, our group has developed a fully smartphone-based tracking system for ambient assisted living-oriented architecture.<sup>31</sup>

In order to provide the user with a reliable walking path reconstruction, the approach schematized in Figure 3 aims to reduce the effect of environmental influences on the system estimations. The main feature of this solution resides in the possibility of providing a reliable heading estimation



**Figure 3** Methodology proposed for implementation of a reliable user tracking system designed to reduce the effect of environmental influences on path reconstruction estimation.

also in the presence of serious environmental influence (eg, magnetic field distortion), by exploiting constrained Kalman filters. Moreover, for the walking distance estimation adaptive models, exploiting information on user inertial dynamics, are proposed.<sup>31</sup>

## Building user/environment awareness

An example of a solution to provide blind users with a suitable form and amount of information for safe and efficient living in indoor environments is described in Andò et al.<sup>17,32</sup> The main idea addressed in this work is to define a paradigm to be used when the user and the environment must be mutually aware of each other. The user can be any entity needing to interact with the environment and needing to have context awareness, such as persons, robots, or moving machines. The cognitive sensor network proposed by Andò et al.<sup>17,32</sup> aims to perceive the user within the environment and to monitor the environment itself. Consequently, the cognitive system can gain an awareness of the user–environment interaction, thus providing the user with effective assistance to exploit the environment.

To implement this type of cognitive task, a smart distributed sensor network installed in the environment is used along with a user module. Obviously, a fundamental role is accomplished by paradigms aimed to build awareness of the user–environment interaction.<sup>17,32</sup>

Our RESIMA project<sup>17,18</sup> aims to develop paradigms to assist blind users in indoor environments. The system, which is schematized in Figure 1, is based on a wireless sensor network and an advanced form of signal processing that performs several tasks, such as localization of the user, estimation of user inertia, and monitoring of strategic environment quantities.

An ultrasound-based localization system has been used to perform real time localization of the user with an accuracy of ~4 cm. This localization system exploits an optimization procedure to fix problems caused by a rough installation of the sensor nodes. An example of a user path reconstruction is given in Figure 4.<sup>32</sup> The information acquired is then conveyed

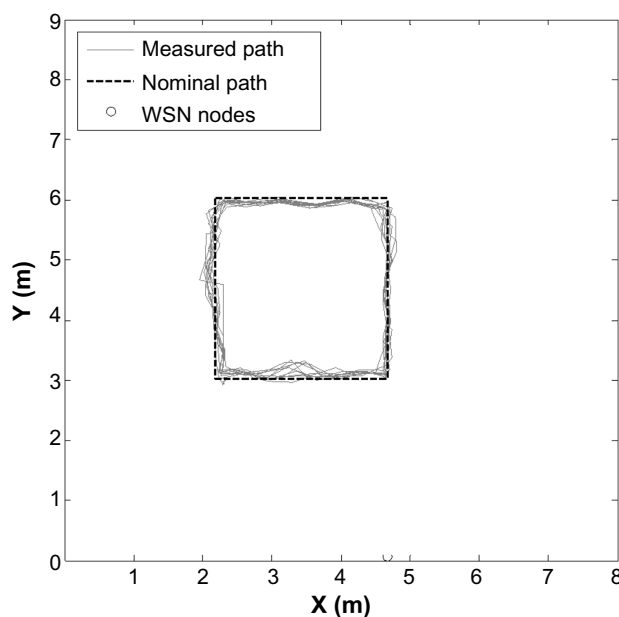
to the user–environment interaction and user–environment contextualization tools which represent the first level of the data integration aimed to improve the user awareness of physical status in respect to the environment.

The user–environment interaction tool is designed to perceive the user’s interaction with obstacles and services available in the environment. As schematized in Figure 5, this task is accomplished by exploiting knowledge of the user’s position and a map of the environment. The user–environment contextualization tool builds information on anomalous and dangerous events, due to users’ failures or hazards in the environment. To this end, the user–environment contextualization tool analyzes the user’s status as respect to their status in the environment.

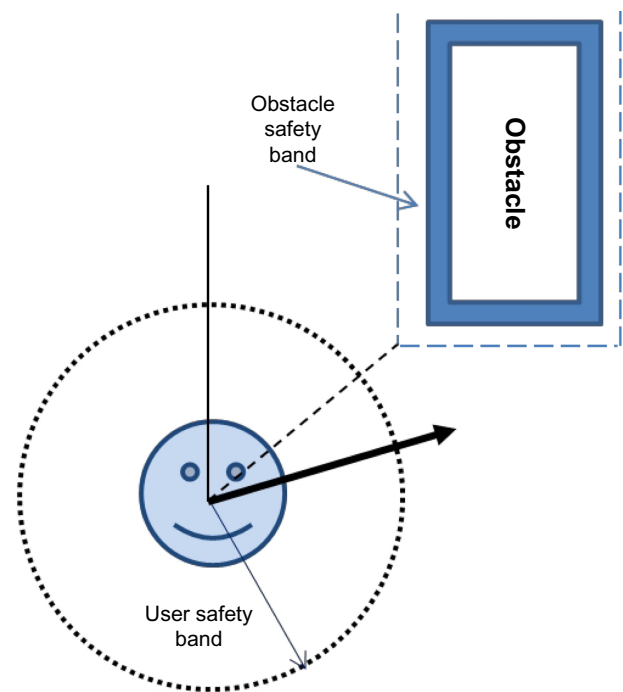
Information generated by the user–environment interaction and user–environment contextualization tools are then exploited by a decision support system. The decision support system provides information to the user for a safe and effective site exploitation and to the supervisor to manage hazards or specific user requests. The possibility of providing the user with an effective form of assistance represents the main advantage of the RESIMA system against currently available solutions.<sup>17,18</sup>

## Smart sensing solutions to detect ADL

ADL includes a wide set of actions characterizing people’s habits especially in their personal living spaces. Monitoring of ADL can be considered mandatory for frail



**Figure 4** Example of results obtained by the trilateration algorithm.  
**Abbreviation:** WSN, wireless sensor networks.



**Figure 5** Schematization of the approach adopted to implement user–environment interaction functionality. Two safety areas, around the user and the obstacle, are defined to improve the performance of the assistive system in providing the user with alert notifications.

people, in order to guarantee effective and safe independent living.<sup>33</sup> Negotiation of stairs, user posture, falls, sitting, standing up, and lying down are common activities to be detected. In falls in particular cause a lot of injuries among frail people.

The availability of reliable and user-friendly solutions for monitoring of ADL would be very useful for gaining a real time awareness of the user’s condition and to provide the required assistance. From a technological point of view, both customized devices<sup>34–36</sup> and smartphone-based platforms have been proposed in the literature for ADL monitoring.

Although smartphones are not always readily accepted by frail people due to the skill required to operate these devices, ADL detectors based on such a platform do not require user interaction and the smartphone can be conveniently positioned on the user’s body. Conversely, some of the features of smartphones like automatic dialing and powerful signal processing are very strategic for the implementation of ADL monitoring.<sup>37,40</sup>

Dunkel et al<sup>37</sup> have addressed the use of smartphones and complex processing paradigms for downfall detection. A smartphone-based architecture for monitoring of human physical activities and its application to assist frail people is described in Franco et al;<sup>38</sup> the possibility to estimate trunk position during bipedal stance in remote rehabilitation contexts, by exploiting signals from a gyroscope and an accelerometer embedded in a smartphone, is addressed by

the same authors.<sup>38</sup> Investigation of human falls based on the inertial sensing feature of smartphones is presented by Tacconi et al.<sup>27</sup> A smartphone-based fall detection system, using threshold algorithms to process user acceleration and heading information is described by Quang Viet et al.<sup>40</sup> A paradigm for interpretation of body movement exploiting a built-in triaccelerometer in smartphones is presented in He et al<sup>41</sup>, Fahim et al have proposed<sup>42</sup> a solution to the problem of independent living by frail users, which exploits sensors deployed in the environment (on different objects) and the communication, storage, and processing features of smartphones supporting cloud-based signal processing.

The smartphone-based platform addressed by Andò et al<sup>43</sup> is aimed at providing effective solutions for ADL detection in ambient assisted living contexts. The main task of the assistive system proposed is to acquire awareness of common ADL, such as avoidance of falls, negotiation of stair, and sitting, in order to provide frail users with a suitable degree of assistance. Advantages of the system developed are the use of a fully smartphone-based solution, the hip position of the device, as well as the possibility to recognize falls from other ADLs. However, the advantage of the proposed approach is the possibility to separate prevention of falls from other ADL and to classify among different kind of falls. The former is a relevant task in the remote monitoring of impaired people, while the latter is mandatory when implementing diagnostic or rehabilitation tasks. The strategy adopted to detect ADL exploits the cross-correlation between the body acceleration and ADL signatures. This approach makes the system robust against external influences. Moreover, two classification algorithms are proposed to process the extracted features (cross-correlation values). The first algorithm exploits a threshold mechanism while the other is based on principal component analysis. In order to implement an adaptive threshold definition mechanism for different application contexts, the system sensibility and specificity have been taken into account. In order to test the system, simulated intentional actions were performed by healthy subjects.<sup>43</sup> The subjects were asked to wear the system on their right hip and to perform a sequence of tasks. As discussed by Andò et al,<sup>43</sup> the results obtained highlight the good sensitivity of the proposed methodology along with a reasonable specificity. The latter assures a negligible amount of false positive notifications, especially in discriminating falls from other activities. This platform could be exploited in both indoor and outdoor contexts, such as living environments, museums, hospitals, and public sites as well as for monitoring of patients recently discharged by the hospital.

## Providing the user with an efficient form of information

The way assistive systems provide the information to blind people is key to improving their self-confidence and autonomy. Examples in the state of the art reveal that the information is often codified in arbitrary forms, by tactile or auditory perception. Efforts in developing nonvisual forms of presentation are also described.<sup>44</sup> Gibson (1966) defined haptics as “the sensibility of the individual to the world adjacent to his body by use of his body”.<sup>45</sup> Our opinion is that haptic user interfaces play a fundamental role in the framework of assistive systems for the visually impaired. A state of the art survey on haptics is available in Varalakshmi et al,<sup>46</sup> while a comprehensive review of haptic methods for data visualization is given in Panëels and Roberts.<sup>47</sup> A few examples of interesting results are briefly discussed here.

Moustakas et al<sup>48</sup> have proposed a force-field haptic rendering method for converting videos of three-dimensional maps into haptic data. An haptic interface for orientation and mobility training of blind users is proposed in Schloerb et al.<sup>49</sup> A haptic system for the visually impaired exploiting a smartphone platform is presented in Akhter et al.<sup>50</sup> A solution allowing the visually impaired to remotely identify objects of interest and to navigate through natural environments is proposed in Horvath et al.<sup>51</sup> Other haptic solutions to assist impaired users have also been reported,<sup>52-54</sup> and also applications dedicated to children.<sup>55</sup>

The development of a haptic cane has been described by Andò et al.<sup>5,56</sup> The device exploits a tactile interface to provide the user with information on imminent obstacles and their position within the environment. The system basically consists of a short cane with an embedded ultrasound sensing strategy to perceive the position of an obstacle and an active handle.<sup>5,56</sup> The handle implements a natural haptic codification strategy, which conveys to the user's palm a sensation similar to the one provided by a traditional long white cane.

The results of a study by Andò and Ascia<sup>5</sup> was dedicated to understand the sensation provided on the user's hand palm by a traditional white cane bumping against obstacles. It has been observed that different kinds of bumps produce different hand palm solicitations. The haptic cane, proposed in<sup>5</sup> exploits such map of correspondence to reproduce into the user hand palm sensations similar to those perceived by a white cane. This functionality has been implemented by a distributed actuation system embedded on the cane handle.

The main advantage of the proposed solution is being able to provide the user with a natural form of codification regarding the position of a detected obstacle, rather than an arbitrary form of codification. This methodology will be

valuable from a social point of view, giving autonomy to blind people performing mobility tasks. In particular, the user can achieve information on the environment without a physical interaction with objects and other people.

## Disclosure

The authors report no conflicts of interest in this work.

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