Experimental Investigation of Electromagnetic Obstacle Detection for Visually Impaired Users: A Comparison With Ultrasonic Sensing

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***Abstract*—The use of electromagnetic (EM) fields for obstacle detection to aid mobility of visually impaired people is presented in this paper. The method proposed is based on the launch of EM pulses and on the measurement of the reflected signal which explores a region in front of the user of about 3 m. A laboratory system is set up, its performances (detecting the presence and the distance of obstacles) are investigated, and the measurements are compared with the data measured by an ultrasonic obstacle detection system. Results show that, with the EM system, all the obstacles tested (up to a minimum size of 3 cm × 3 cm, at a distance of 3 m) are correctly detected, as well as some specific targets (a chain, a pole, etc.) that are not visible by the ultrasonic system. The EM system has been tested in indoor and outdoor cluttered scenarios at the presence of real obstacles (single and multiple), and in all cases, it detects their presence with a signal-to-noise ratio ranging from 10 to 23 dB. Despite the use of a laboratory system, still not specifically designed for daily use, this paper demonstrates the possibility of adopting EM field pulses for obstacle detection, highlighting advantages with respect to ultrasonic systems and addressing future research activity to design an improved ad hoc EM system.**

***Index Terms*—Electromagnetic (EM) sensor, electronic travel aid (ETA), obstacle detection, visually impaired users.**

I. INTRODUCTION

THE ESTIMATED number of legally blind people in the U.S. is 1.3 million, and the total number of blind and visually impaired is approximately 10 million [1], [2]. Globally, more than 160 million people are visually impaired, and among them, 37 million are blind; by 2030, the number of the blind is predicted to double [3], [4]. Mobility tasks and, in particular, outdoor mobility are among the main issues for these subjects [5], who can be strongly limited in their social and professional life [6].

Blind and visually impaired mobility can be helped by the use of assistance devices such as the following: sighted guides, white or long canes, and dog guides [7], [8]. The white cane is simple, cheap, and reliable and is therefore the most popular device utilized [8]. The cane can only provide an alert for obstacles present in the area scanned by the oscillation of the tip of the cane (< 1 m in front of the user's feet), and most importantly, it does not provide protection against collision with obstacles on the upper part of the body [8]. Moreover, the cane does not allow information to be obtained regarding speed, volume, and distances, which are necessary for safe navigation [8], [9], and therefore, it forces the partially sighted user to always be able to stop suddenly at any moment [10]. In order to overcome such limits, specific electronic travel devices have been proposed, named electronic travel aid (ETA), devised for detection of objects along the user's pathway [11], [12]. However, whatever the ETA, it is only regarded as an ancillary aid to the primary aid which could be the cane or the guide dog. The international guidelines [8], [11] for ETAs require the following:

1) detection of obstacles in the travel path from ground level to head height for the full body width;
2) travel surface information including textures and discontinuities;
3) detection of objects bordering the travel path for shorelining and projection;
4) distant object and cardinal direction information for projection of a straight line;
5) landmark location and identification information;
6) information enabling self-familiarization and mental mapping of an environment.

In addition, ETAs should be ergonomic and easy to operate, reliable, durable, easily repairable, robust, low power, and cosmetically accepted.

The development of electronic assistive devices for the mobility of visually impaired people started in the 1940s. The first electronic mobility aids were made commercially available in the 1960s (Sonich Torch and Pathsounder are some examples [12]). Today, there is a wide range of navigation systems [12] and tools available for visually impaired individuals [14]–[18]. Most of the proposed ETAs are based on the transmission of an energy wave and the detection of echoes from objects present on the user pathway, and a great number of those use ultrasonic emitter/receiver transducers [18], [19]. In [20], two ultrasonic sensors are attached to eyeglasses, and data are transferred to headphones to retrieve the direction and size of the obstacle.

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However, testing of the system showed a limited capability to identify and discriminate objects. In a guidance system [21], [22], using eight ultrasonic sensors explore the volume in front of the system, and the avoidance algorithm identifies the obstacle and alerts the user. In this case, the main disadvantages of the system are the following: the audio feedback, the bulky prototype, and long periods of training. In [23], an ultrasonic sensor of 500 g detects obstacles ($> 90\%$ of correct detections) calculating their distance from the user. Stereoscopic ultrasonic sensing was also demonstrated [24] with a wearable system placed at shoulder. The system is wearable and light, with a low-power consumption and a low-cost system, but it suffers limitations for representing 3-D space and for interference with user's hands.

There are also some commercial products available on the market for the mobility of the blind and visually impaired; K-Sonar Cane [12], [25], [26] and miniradar [27] are ultrasonic sonars which detect obstacle distance and provide sound and/or audio messages to the user. Miniguide [12], [25], [28] is a small ultrasonic handheld device that indicates the distance to the closest object; it can be pointed, and via its vibration rate, the presence of the obstacle is signaled. Ultracane [12], [25], [29], [30] is a novel device composed of a cane with embedded ultrasonic range scanners, while LaserCane [12], [31] is a cane using three laser range sensors exploring along three directions in front of the user. Recently, a special device to be attached onto the long cane and based on LED and photodiodes has been proposed with the aim to solve the problem of individuate shoulder-width openings [32]. All of these systems require a mental effort to identify the obstacle with respect to the user's position and/or direction. Despite recent improvements, these devices still present some drawbacks such as the following: limited functionalities, relatively high cost, and limited acceptability by the users.

In general, the recognized limitations [11], [12], [25], [29] of the actual ETAs (commercial systems or prototypes) based on ultrasonic are the following: limited useful range, difficulties of operating on highly reflective surfaces (smooth surfaces), with a low incidence angle $(< 40^\circ)$, and when detecting small openings due to the aperture of the emission cone of ultrasonic waves. Optical ETAs, which do not suffer from these limitations due to their shorter wavelength, however suffer other difficulties such as high sensitivity to ambient natural light or dependence on the optical characteristics of the obstacle surface (transparency or mirrorlike reflection). It is generally agreed that, currently, no available ETA incorporates all the required features to a satisfactory extent.

It is interesting to note that, in the literature, there is a lack of studies which consider electromagnetic (EM) radiation as the physical quantity able to deliver information on obstacle presence for visually impaired users. In fact, EM fields are typically used for identification of obstacles in the long and middle ranges [33]–[35]. On the contrary, a partially sighted person mobility aid system works in a short range without the necessity of a full obstacle characterization.

The main aim of this paper is to investigate the capability of a novel obstacle detection system designed for visually impaired and blind user mobility and based on the measurement of the TOF of an EM pulse transmitted from a wideband antenna and reflected by the obstacle. The system will be compared with an ultrasonic detection system, and their capability to detect obstacle presence will be experimentally tested on selected mobility scenarios, using typical objects found in everyday life and potentially dangerous for the safe walking of visually impaired people [11]. The comparison with an ultrasonic system was considered necessary for two reasons:

1) to assess the performances of the EM system with respect to an existing system;
2) to highlight the peculiarity of the EM system.

As the two systems are quite different, specific attention was devoted to make them equivalent, and this was achieved properly setting some significant system parameters.

The obstacle detection system proposed was set up to carry out a preliminary experimental analysis to investigate the possibility of adopting EM waves for ETAs and to provide useful information for the design of an EM sensor to aid visually impaired users during mobility tasks, possibly allowing them to walk safely and independently.

II. SCENARIO, SYSTEM REQUIREMENTS, AND OBSTACLES

The aim of any obstacle detection system is to permit a visually impaired person to speed up mobility mainly by getting information on the surrounding complex environment. Our system will explore a defined volume in front of the partially sighted user. The scenario we refer to is a 3-D region in front of a walking person, where there may be some obstacles at different heights which can be very dangerous for blind people [11], [32]. In a realistic context, several kinds of situations can be a serious threat, e.g., open windows, public telephones (that are large but attached to a slender pole), low branches, or rears of trucks, and for these cases, the cane is not able to help the person.

The system has to give information on the presence, location, and, possibly, the nature of the obstacles immediately in front of the subject, exploring in elevation a region from ground-to-head level and in azimuth an area corresponding to the subject's body; this explored volume has also been determined as significant for blind users in [32]. The minimum distance or range over which this information is needed is a comfortable stopping distance at normal walking speed [11], [32]. The volume explored in this study is a parallelepiped in front of the subject of 3 m of length, 1.5 m of width, and 2 m of height. Such dimensions are a compromise between the necessity, in a real system, to give sufficient information to the user and the need to limit meaningless alarms. For a quick identification of obstacle location, we have considered three different subvolumes of the scenario:

1) leg zone: volume in front of the subject in contact with the walking surface;
2) trunk zone: volume in front of the subject's trunk;
3) head zone: volume in front of the subject's head.

The present study aims to analyze the signal reflected from different types of obstacles placed at a different distance, level,

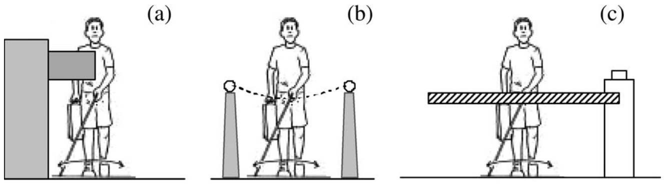


Fig. 1. Examples of obstacles for visually impaired mobility not detectable by the cane: (a) An open drawer, (b) a horizontal chain, and (c) a car parking barrier.

and position inside the aforementioned volume. The obstacles are classified in terms of shape, material, and positions. In particular, three different geometries are investigated: one dimensional, like a suspended chain, bidimensional, like a door, and tridimensional, like a box or a basket. The materials considered are the following: plastic, metal, and wood. The objects are placed directly in front of the system and off center. The type of materials and the dimensions are chosen in order to stress the capability of the system to detect an object. In the case of the EM system, the most reflective material is metal, whereas the least reflective is plastic, and therefore, these two limit situations can be regarded as the best and worst cases.

All the objects used to test the feasibility of the system respond to the characteristic to be likely to be found during indoor/outdoor traveling (basket, door, and pole) and/or to have a high offensive potential because an unexpected impact with them (chain, door, and pole) can cause injury. The obstacle selected are:

1) A plastic basket: This case is a typical situation that a person can very often encounter in an indoor environment. The basket is considered a threat for safe walking because it can throw a blind person off balance. Moreover, it is particularly significant since the material has a very low reflection coefficient to the EM signal allowing us to analyze the sensibility of the system.
2) A suspended chain: If not properly detected, this object can be very dangerous, and the person may fall and get injured.
3) An open door: This can also be a dangerous situation and difficult to detect from distance by ultrasonic systems because the reflected signal is strongly affected by its orientation. Moreover, the presence of the wall, which creates a high reflected signal, may mask the presence of an open door.
4) A plastic pole: This particular object was chosen because it is a typical object that can be found on a pathway as an isolated element or support. In this case, we again chose a plastic material because it represents the worst case situation for EM wave reflection.

The influence of the materials was investigated considering three obstacles having the same rectangular shape and dimensions but made of different materials: wood, plastic, and metal.

Finally, real indoor/outdoor scenarios [similar to the examples shown in Fig. 1(a)–(c)] have also been tested to verify the ability of the EM system to detect single or multiple obstacles, not always detectable with the cane, in a cluttered environment.

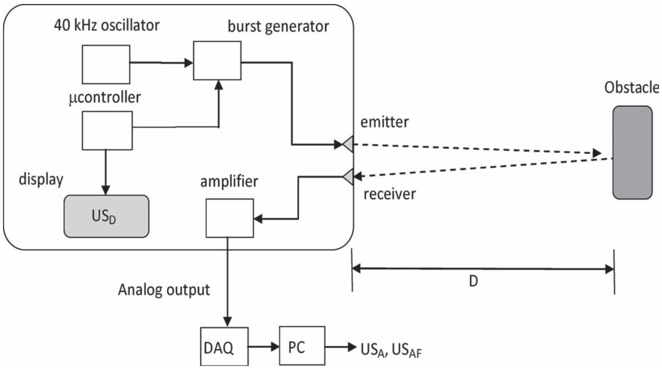


Fig. 2. System diagram of the ultrasonic obstacle detection sensor.

III. OBSTACLE SENSING SYSTEMS

A. *Ultrasonic Obstacle Detection System*

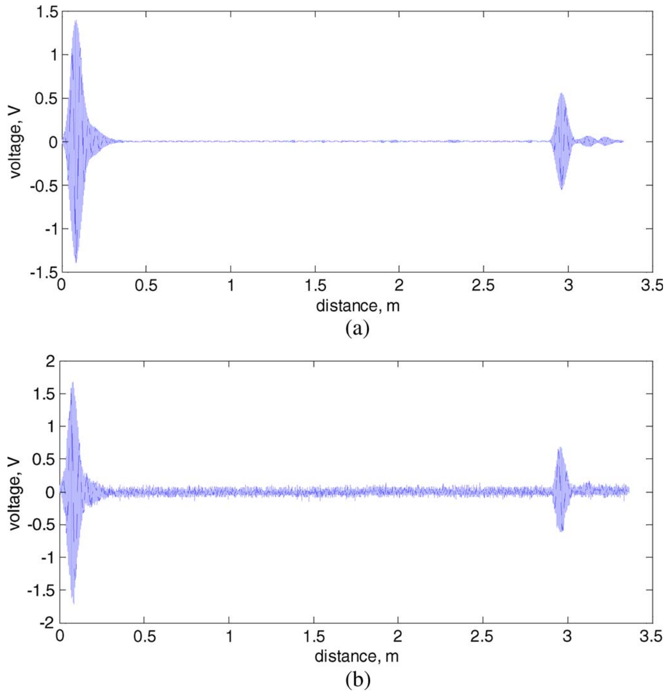
Obstacle detection systems for the visually impaired users based on the ultrasonic have been already proposed in the past [12], [18]–[30]. The operating principle is based on the transmission of the ultrasonic wave (single pulse or train of pulses) and the reception of the wave reflected by the obstacle. The distance from the obstacle is indirectly determined by the measurement of the TOF [37], [38]. TOF is defined as the time t that elapses between transmission and echo reflection. The distance D between the ultrasonic sensor and the obstacle can be calculated as

$$D = \frac{v_s t}{2} \tag{1}$$

where v_s is the sound velocity and t is the time needed for the ultrasonic pulse to travel to the obstacle, be reflected, and come back to the receiver. Therefore, if the sound speed is determined precisely, the accuracy of the measured distance depends mainly on how accurately the TOF is measured. In all our experiments, tests were carried out at 20 °C and at about 50% relative humidity; therefore, we have $v_s = 342$ m/s [37], [38].

The ultrasonic obstacle detection system works at a frequency of 40 kHz. It uses two custom-made ultrasonic transducers; one transducer is used to emit a short burst (0.2 ms of duration), while the other receives the obstacle-reflected echo. The emitter is fed by the burst generator, while the receiver output signal is first amplified and then directed to a microcontroller which calculates the distance D between the ultrasonic system and the obstacle by (1). The output from the amplifier was acquired using a 12-b 500-kS/s analog-to-digital acquisition board. In a standard configuration (using the microcontroller to calculate the distance D), the measurement range is limited from 0.12 to 3 m, and the explored field of view is about ±30° in front of the emitter. Fig. 2 shows the scheme of the ultrasonic obstacle measurement system.

It must be observed that the echo detected differs from the originally transmitted burst; in fact, due to attenuation and diffraction, echo is usually reduced in amplitude. In order to operate with a sufficiently high signal, a signal amplification is performed before signal acquisition (by the data acquisition (DAQ) board) and/or microcontroller processing and automatic



(a)

(b)

Fig. 3. Examples of reflection signal from a metal obstacle at 3 m. (a) Received signals. (b) Effect of the bandpass filter.

distance calculation by (1). The microcontroller also acts as a trigger for the generation of the emitted burst; in particular, these bursts are generated each 18 ms in order to allow a maximum explored range of approximately 3 m. The distance D to the obstacle is automatically calculated and displayed by the microcontroller using threshold reflected burst detection and implementing (1) (digital output), or it can be measured by the analysis of the analog signal after acquisition by the DAQ board (analog output).

In Fig. 3(a), we report an example of reflected time signal received and amplified, after obstacle reflection (a metal plate) at a distance of 3 m. It is possible to observe direct coupling between the emitter and the receiver; this phenomenon sets the lower limit for the measurement range of the ultrasonic detection system, affecting the detection of very close obstacles (< 0.12 m). As a further improvement of system performance, a software bandpass filter (39.5–41.5 kHz) was applied on the signal acquired by the DAQ board in order to reduce the effect of the noise [Fig. 3(b)].

B. EM Obstacle Detection System

The use of EM pulses seems to be a suitable technique for the application to a realistic mobility scenario for a partially sighted user. In fact, in our case, the user can stand still or walk at an acceptable speed (although not very high, < 1 m/s). Even if the detection system is mounted on the stick, and it is moved by the user in order to explore the volume of the space in front, (thereby intrinsically performing a space scanning like a real surveillance radar), mechanical motion is far slower than the speed of the EM pulse. A short time-domain pulse is reconstructed by applying an inverse Fourier transform to frequency-domain measurements [39]. This can be achieved by performing N frequency measurements, starting from the lowest frequency $f_{\min}$ up to the highest frequency $f_{\max}$, with a constant frequency step Δf. In our case, we selected the following: $N = 1601$, $f_{\min} = 1$ GHz, $f_{\max} = 6$ GHz, and $\Delta f = 3.12$ MHz. The main advantage of this approach is that the measurement is very accurate at each frequency, even using a low transmitted power. The request that the antenna position (and consequently the position of the visually impaired user) should remain unchanged during the frequency sweep is largely achievable by a modern sweeper (sweep time over many gigahertz provided in a few milliseconds). On the basis of the aforementioned considerations, we built an experimental setup schematized in Fig. 4 to replicate the EM detection system in our laboratory.

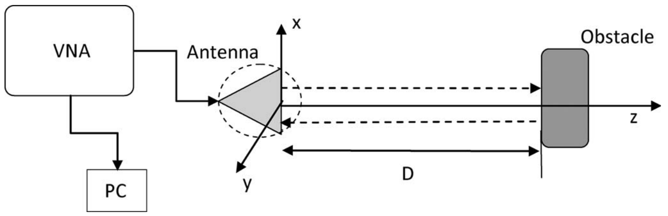


Fig. 4. System diagram of the EM obstacle detection sensor: The antenna illuminates the obstacle and captures the reflected signal.

The obstacle is illuminated using a broadband antenna. In our case, we used a double-ridge horn antenna matched from 700 MHz up to 18 GHz. This antenna exhibits a half-power beam of about 38° in the E plane (i.e., the $x-z$ plane in Fig. 4) and of about 30° in the H plane (i.e., the $y-z$ plane in Fig. 4), similar to the ultrasonic sensor beamwidth. A vectorial network analyzer (VNA) is used to measure the reflection coefficient at the antenna input. The built-in sweeper sets up 1601 frequencies, equally spaced in the band: 1–6 GHz. The "impulse-low-pass" function was set on the VNA to recover the time-domain response. The equivalent pulse feeding the antenna is practically a Gaussian with a unitary amplitude and a duration τ of 0.4 ns (calculated at 50% of the pulse amplitude), corresponding to 12-cm spatial resolution, similar to the ultrasonic one. Since the same antenna is used to receive the pulse reflected by the obstacle, it is important to verify the duration of the antenna time response that limits the minimum distance for obstacle detection. To better clarify this aspect, in Fig. 5, we report the time-domain response measured in the case of a 2 m × 2 m metal plane, placed at a distance D of 3 m from the antenna.

Two peaks are well evident in the early time response, with a time difference Δt of about 1.32 ns. The first peak corresponds to the initial coaxial–waveguide transition of the antenna, while the second corresponds to the antenna aperture (time difference Δt in Fig. 5). The peak caused by the reflection on the obstacle is revealed at 21.8 ns; considering the time difference between this time value and the peak relative to the antenna aperture (the peak at 1.86 ns), we obtain a value that is twice the distance between the antenna aperture and the obstacle.

The presence of the double peaks caused by the antenna response limits the obstacle detection for distances < 28 cm. Such very close range is not of interest for the blind's mobility, with an obstacle being too close within that range to avoid

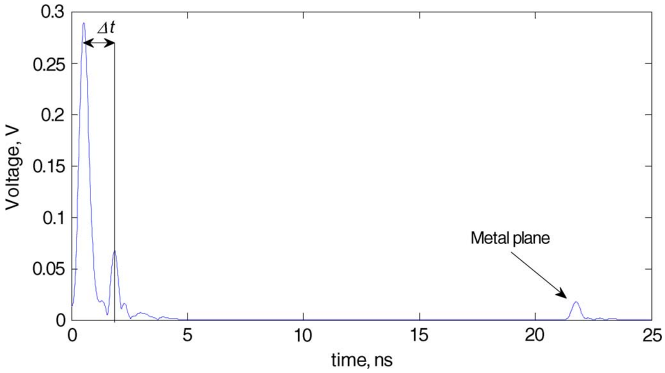


Fig. 5. Time response determined by a metal plane placed at 3 m: The corresponding pulse is at 21.8 ns.

the impact. The same problem is also present in the ultrasonic system due to the coupling between the transmitter and the receiver [Fig. 3(a)], as well as in most of the ETAs.

C. Definition of the Systems' Equivalence

The intrinsic differences between the two systems in terms of physical behavior, dimension, costs, and dynamics make it necessary to verify their equivalence in terms of measurable parameters. In order to assure the equivalence of the two systems, we focused on the following three parameters.

1) antenna beamwidth, to assure the same explored region (about 30°);
2) pulse duration, to assure the same spatial resolution (about 12 cm);
3) signal to noise ratio (SNR), to assure a similar detection threshold.

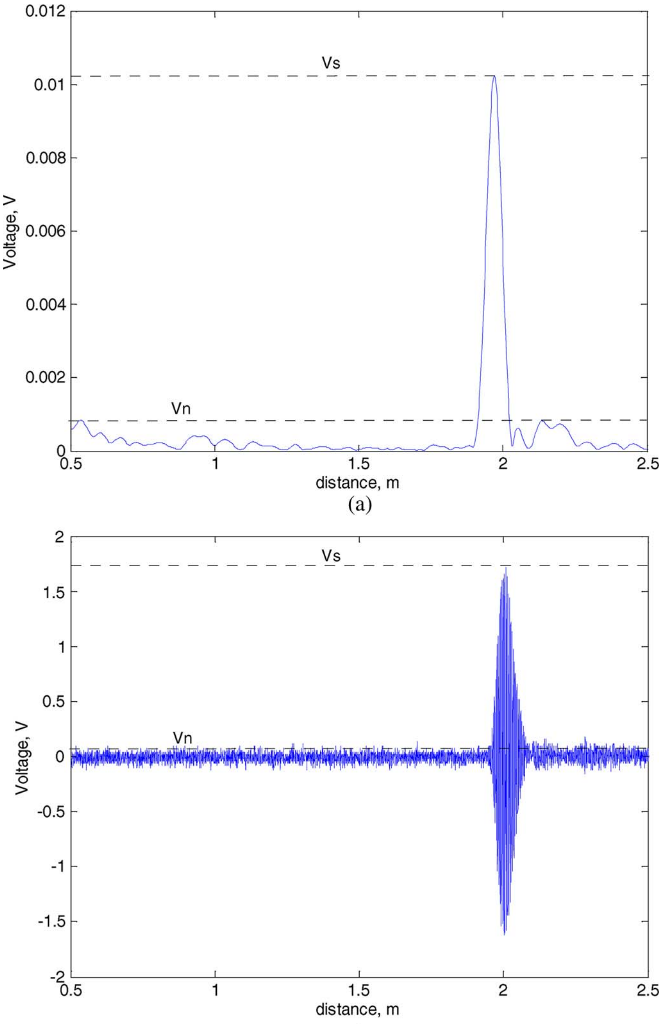
The equivalence of the first two parameters has been guaranteed by the settings given in the previous section, whereas the third one is discussed in the following. As shown in Fig. 6, both signals emerge from the background noise. V_s has been defined as the magnitude of the reflected peak, while V_n is the amplitude of the background noise.

The noise has two components that can mask the sought echo pulse: the thermal one due to the electronics and the sensor impulse response that could last for a long time.

In the EM system [Fig. 6(a)], the noise level due to the thermal effect is lower than the antenna impulse response, so the thermal component can be neglected, and consequently, V_n is defined as the maximum peak due to this response; on the other hand, for the ultrasonic system, the nature of the noise is mainly thermal, so it is more appropriate to define V_n as the root mean square of the background noise level [Fig. 6(b)]. The SNR (SNR_{dB}), for both the systems, has been defined as

$$SNR_{\mathrm{dB}} = 20\log_{10}\left(\frac{Vs}{Vn}\right). \tag{2}$$

The test obstacles are metallic (same reflection coefficient for ultrasonic and EM waves) and characterized by a 2-D extension and progressively decreasing sizes, placed at distances of 1, 2, and 3 m.



(a)

(b)

Fig. 6. (a) EM and (b) ultrasonic reflected echoes for a metal plate of 25 cm × 25 cm placed at a distance of 2 m.

In Table I, SNR_{dB}'s, measured at different distances and for obstacles of different dimensions, are reported. In particular, the result of (2) for the EM sensor and the ultrasonic sensor are in the third and fourth columns, respectively, as a function of the distance D. Comparing these two columns, the systems can be considered equivalent in terms of SNR_{dB} $(differences < 3\ \mathrm{dB})$ in the case of objects with a large area $(dimensions \geq 0.50\ \mathrm{m})$, whereas for smaller obstacles, the ultrasonic system exhibits better performance. This behavior can be explained because the wavelength of the ultrasonic signal (8.5 mm) is shorter than that of the EM one (5–30 cm); for the latter, the dimensions of the smaller tested obstacles are comparable with the wavelength.

For both systems, it is possible to improve the SNR_{dB} by implementing two different algorithms for signal processing.

1) For the EM system, we calculate the difference between the obstacle time response and the free-space antenna response, so that most background noise is cancelled.
2) For the ultrasonic system, we used a 39.5–41.5-kHz bandpass filter to the analog signal reducing the thermal noise.

TABLE I
SNR_{dB}'S MEASURED FOR OBSTACLES OF DIFFERENT AREAS, AT 1, 2, AND 3 M OF DISTANCE: EFFECT OF THE SIGNAL PROCESSING [(EM) EM SENSOR AND (US) ULTRASONIC SENSOR]

Dimensions, m	distance D m	EM signal unprocessed SNR_{dB}	US signal unprocessed SNR_{dB}	EM signal processed SNR_{dB}	US signal processed SNR_{dB}
(1.75 x 2.00)	1	33	36	58	55
(1.75 x 2.00)	2	30	33	50	54
(1.75 x 2.00)	3	27	25	52	44
(0.50 x 0.50)	1	32	32	46	50
(0.50 x 0.50)	2	26	29	47	47
(0.50 x 0.50)	3	24	23	46	40
(0.25 x 0.25)	1	34	36	52	65
(0.25 x 0.25)	2	22	33	45	56
(0.25 x 0.25)	3	16	25	36	48
(0.12 x 0.12)	1	24	36	43	52
(0.12 x 0.12)	2	12	23	33	40
(0.12 x 0.12)	3	6	15	31	30
(0.06 x 0.06)	1	13	41	37	59
(0.06 x 0.06)	2	2	27	25	45
(0.06 x 0.06)	3	0	18	19	32
(0.03 x 0.03)	1	6	29	31	46
(0.03 x 0.03)	2	1	17	13	35
(0.03 x 0.03)	3	0	11	10	25

In Table I, the fifth and sixth columns show the SNR_{dB} after signal processing; it is possible to observe a significant increase of the SNR_{dB} value for both systems which make them equivalent even for the case of small objects. Only for very small objects, placed far from the source, the two systems are not equivalent, but these are not relevant cases for the mobility of visually impaired people. However, with this kind of processing, the EM system is now able to detect the presence of all the obstacles even in the case of the smaller metal plate.

IV. RESULTS

A. Obstacle Distance Measurement

In this paragraph, we compare the system capability to detect an obstacle and to provide the correct distance D between the obstacle and the sensor. The testing conditions were the same for both systems and for each obstacle; the two measurements were carried out simultaneously to avoid repositioning errors. The obstacles were placed at height H (varying with the elevation angle θ) from the floor and at a distance $D_{\min}$ from the measurement system (Fig. 7), whereas the height X of the measurement system was 1 m. $D_{\min}$, H, and the angles ϕ, θ, and α are defined as shown in Fig. 7. Angle ϕ is introduced to indicate the lateral position of the obstacle with respect to the z-direction on the $z-y$ plane, whereas the opening angle α identifies the rotation of the obstacle with respect to the plane normal to the z-axis (this is the case, for example, of a half-open door); θ is the elevation angle on the plane $x-z$.

In Table II, we report the results obtained for different typical obstacles (presented in paragraph 2); in this case, we report the minimum distance from the obstacle $(D_{\min})$, the obstacle position (in terms of ϕ and θ), and the distance D, as measured by the EM sensor with signal processing $(\mathrm{EM}_{\mathrm{SP}})$, by the digital output of the ultrasonic (US_D), by the analog output (US_A), and by the analog output after filtering $(\mathrm{US}_{\mathrm{AF}})$.

The results reported in Table II show a mean overestimation of the measured distance of the $\mathrm{EM}_{\mathrm{SP}}$ with respect to the minimum distance of almost 3 cm; the same result is obtained with the $\mathrm{US}_{\mathrm{AF}}$. With both systems, all the objects can be detected. The mean difference with the minimum distance is reduced with US_A and the US_D values, but in these cases, it is not possible to detect all the obstacles. The ultrasonic system used in digital mode (US_D) is not able to detect (ND) small objects, such as the plastic chain or the pole placed in a lateral position, because the measured peak is lower than the system threshold. In the case of the wooden door opened at 30°, 45°, and 60°, the EM system $(\mathrm{EM}_{\mathrm{SP}})$ is more reliable with respect to all the ultrasonic systems; in fact, in this case, the received signal is mainly due to the energy scattered by the edge of the door, and this effect is more significant for the EM waves.

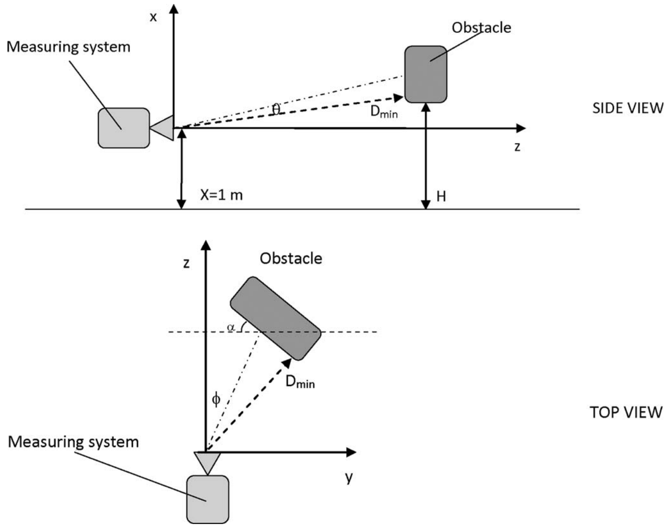


Fig. 7. Obstacle distance test setup.

It must be remarked that, for partially sighted mobility, ETA systems is more important to ensure the capability to detect all the possible obstacles even with an overestimation of their real distance, rather than guarantee a higher measurement precision with the risk of missing some obstacles.

TABLE II
DISTANCE MEASURED BY THE EM AND ULTRASONIC SYSTEMS FOR DIFFERENT TYPICAL OBSTACLES

Obstacle	**D_{min}, cm**	**ϕ, °**	**θ, °**	**Measured distance, cm**			
				EM_{SP}	**US_D**	**US_A**	**US_{AF}**
Plastic pole (178 cm)	300	0	0	302	ND	300	301
Metal door (175 x 200 cm)	300	0	0	304	303	302	301
Plastic basket (H=28 cm; ϕ=30°)	300	0	0	306	ND	308	307
Plastic plate (50 x 50 cm)	300	0	0	304	298	300	300
Wooden plate (67 x 67 cm)	300	0	0	304	299	300	300
Metal plate (45 x 55 cm)	300	0	0	303	300	301	300
Plastic chain Waist (H=1m)	300	0	0	300	298	298	304
Knee (H=0.4m)	306	0	-10	307	302	302	307
Head (H=1.65m)	307	0	12	308	305	304	310
Plastic pole, (lateral position)	316	18	0	321	ND	316	315
Wooden door (α = 0°)	300	0	0	304	302	304	307
Wooden door (α = 30°)	282	0	0	285	ND	ND	289
Wooden door (α = 45°)	273	0	0	276	ND	ND	283
Wooden door (α = 60°)	266	0	0	270	ND	ND	277
Wooden door (α = 90°)	260	0	0	264	263	264	268

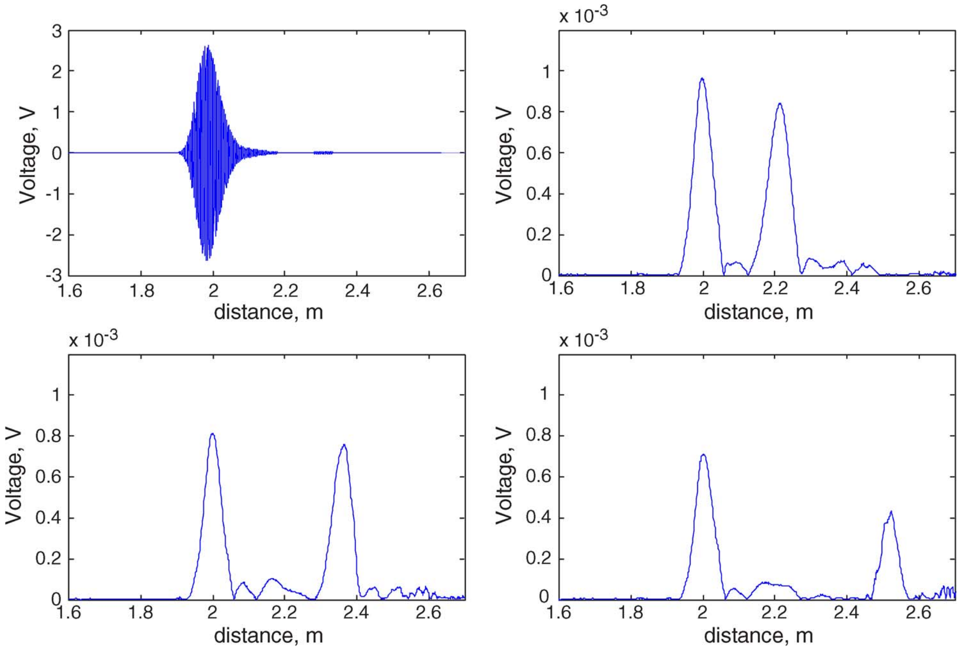


Fig. 8. Reflected signals for a cardboard box with a thickness of 22 cm [(top left) US_{AF} signal and (top right) EM_{SP} signal]. EM_{SP} reflected signal for a cardboard box of (bottom left) 36 cm and of (bottom right) 52 cm.

B. Further Features of the EM System

In this paragraph, we report some tests which were particularly significant in order to highlight further features of the EM system. Analyzing the EM reflected signal, it is possible to obtain some information about the dimensions of the object: This is, for example, the case of an empty box made of penetrable material. Since the wave impinging on the front wall of the object is partially transmitted inside the obstacle and then reflected at the rear wall of the obstacle itself, it is possible to obtain information regarding the thickness of the object.

The ultrasonic is not able to provide any information regarding the thickness of the object because the reflection coefficient for the acoustic waves is almost one for most of the materials, and so, most of the energy is reflected at the front wall. In Fig. 8, we report the scattered signals on a rectangular cartoon box (dimensions: 22 cm × 36 cm × 52 cm). Three measurements were carried out by rotating the box, so that three obstacles of different thicknesses of 22, 36, and 52 cm were simulated. The two figures at the top report the comparison between the US_{AF} and EM_{SP} system responses when the box thickness is 22 cm, whereas the two figures at the bottom are the signals measured by the EM_{SP} system when the box thicknesses are 36 and 52 cm, respectively.

It can be noted that, for the EM_{SP} sensor, two peaks in the reflected signal are always present and that the distance between these peaks corresponds to the thickness of the empty paper box. The first peak is related to the reflection at the front; the second peak is related to the reflection at the second interface present on the wave path (back side). Another difference between the EM and the ultrasonic system performances is

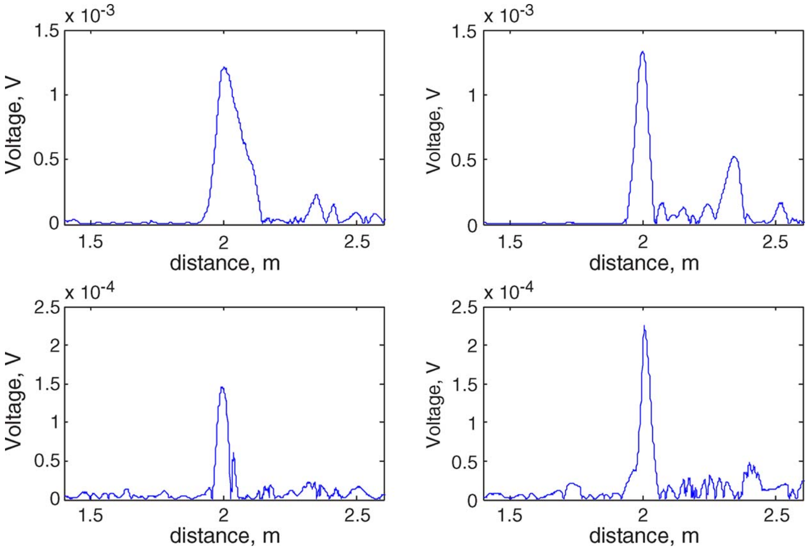


Fig. 9. Signals for horizontally stretched chain. Metal chain with (top left) vertical and (top right) horizontal polarizations; plastic chain with (bottom left) vertical and (bottom right) horizontal polarizations.

due to the nature of the wave: The ultrasonic wave is a scalar physical quantity, whereas the EM wave is a vectorial physical quantity. We investigated if the effect of this peculiarity could create some problems in detecting obstacles with unidimensional geometry (like poles, chains, tubes, etc.), when the EM wave polarization is not aligned with the main dimension of the obstacle and the intensity of the reflected impulse might not be sufficient to be detected. In Fig. 9, we report the reflected signals of two chains made of different materials (metal and plastic), measured with vertical and horizontal polarizations. It can be noticed that, for both the polarizations, the amplitude of the reflected signal does not significantly differ, and both the obstacles are detected. This result demonstrates that the polarization of the wave does not compromise the capability of the EM system to detect unidimensional obstacles.

In Fig. 9, it can also be observed that the characteristics of the material influence the amplitude of the received peaks (metal targets generate the largest reflections). A reduction of the reflected peak of about one order of magnitude has been measured for plastic chain with respect to the metal one, but this does not prevent obstacle detection.

A specific test for the evaluation of the material effect has been carried out on three square (50 cm × 50 cm) targets of metal, dry wood, and plastic, placed at 3 m from the antenna. Peak amplitude reductions of 11 and 25 dB have been measured for plastic and wood targets, respectively, with respect to the metal one. This test provides information for the minimum requirements on the EM system characteristics needed to detect obstacle of such common type of materials. However, it must be outlined that, with the proposed EM system, it is not possible to recognize the characteristics of the obstacle material.

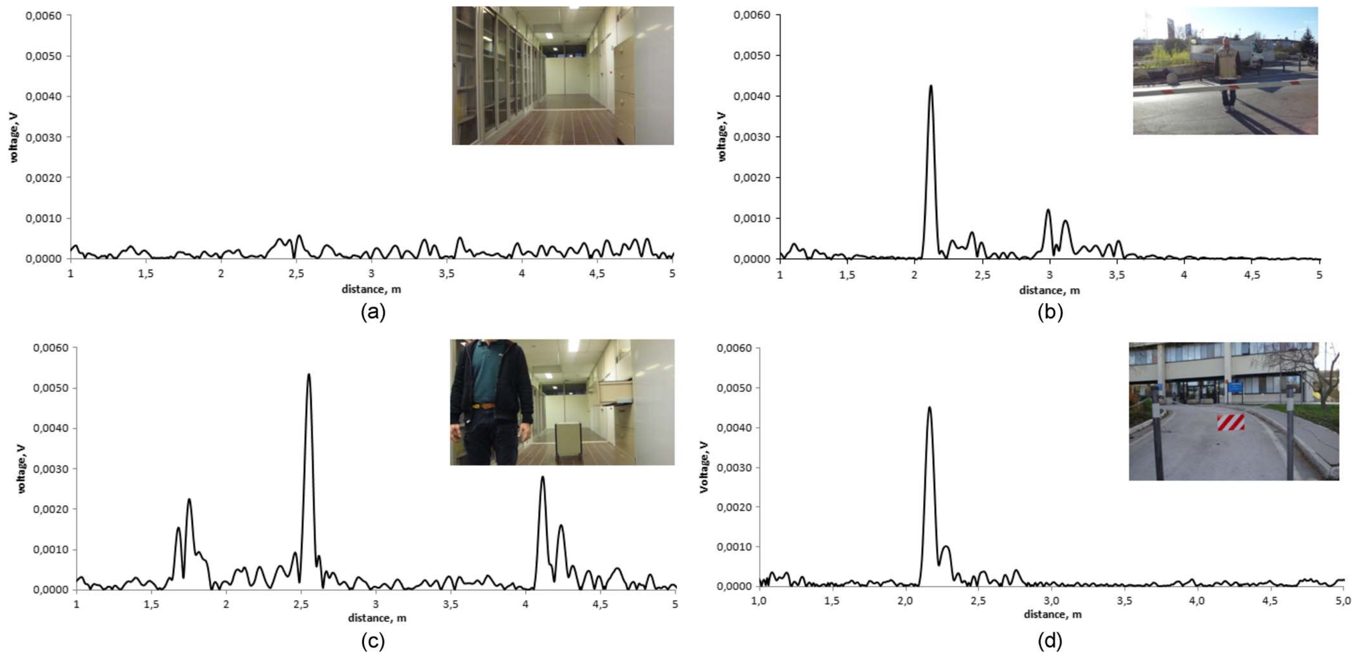
C. Tests in Cluttered Environments

The EM system has also been tested in real cluttered environments where the presence of many scattering targets which are not along the walking path could mask the detection of obstacles. The tested scenarios have been chosen recalling Fig. 1(b)–(d) and are the following:

1) indoor environment: a corridor of the faculty building without obstacles and with three obstacles placed along the walking path: one person (not centered and immobile), a container with an open drawer, and a cart [Fig. 10(a) and (b)];
2) outdoor environment 1: the entrance of the faculty car park where the obstacle is represented by a horizontal moving bar [Fig. 10(c)];
3) outdoor environment 2: a metal chain separating the pedestrian area in the faculty car park [Fig. 10(d)].

All the measured signals are shown in Fig. 10. In particular, in Fig. 10(a), the signal in the absence of obstacles along the corridor, but with the presence of a cluttered environment containing cabinets and lateral walls, is reported. In Fig. 10(b), the signal obtained when three different obstacles are present is shown. It is possible to observe, for the created scenarios, how all the obstacles and their position are clearly identified by the peaks.

On the same figure, we report the signals measured in two cluttered scenarios tested into a car park. In this case, the cluttering effect is due to the presence of irregular terrain, steps, vegetation, etc. The scenario in Fig. 10(c) can be referred to a trunk-level obstacle [as the one shown in Fig. 1(d)] which cannot be detected by the user's cane but is, instead, correctly measured with the proposed system. Finally, in Fig. 10(d), we have verified the system performance when an obstacle similar to the one shown in Fig. 1(b) is encountered; also, in this case, the obstacle is clearly identified. For all the scenarios, the SNR_{dB}, as defined in (2), was calculated for the processed signals, and it ranged from 21 to 23 dB for indoor scenario and from 10 to 21 dB for outdoor scenario. It is important to note that, for all the scenarios, the same free-space antenna response, as for the case of the laboratory tests, was used for the EM signal processing. This demonstrates the robustness of the proposed method, because a specific system calibration for a cluttered environment is not necessary.



(a) (b) (c) (d)

Fig. 10. Signals measured in cluttered scenario. (a) Indoor corridor without obstacles and (c) the same corridor with three obstacles. (b) Outdoor scenario with a parking gate bar and (d) metal chain for separation of the pedestrian area.

D. *Highlights for the EM System Improvement*

Even if the EM system is a prototype based on laboratory instrumentation, whose characteristics were chosen in order to ensure the equivalence with the ultrasonic one, the results show that the EM system has a good capability of detecting the obstacle and its distance. Moreover, the aforementioned results can provide some suggestions to better the EM system.

The first parameter that can be modified is the working frequency. All experiments were carried out considering pulses with a spectral content within the range of 1–6 GHz chosen in order to assure the equivalence between the two systems, as previously explained. On the other hand, from Table I, it is well evident that, for the EM system, the SNR decreases with the reduction of the obstacle dimensions. This is due to the wavelength of the signal that becomes larger than the obstacle dimension. These results suggest to increase the working frequency range in order to enhance the SNR_{dB}. Moreover, the use of higher frequencies leads to a strong possible miniaturization of the whole device, which entails lightweight and easy-to-wear systems, with evident comfort for the user. Flexibility can also be improved allowing, for example, the device or the antenna to be integrated into the more traditional cane.

A further degree of freedom is represented by the antenna design. In fact, all the results reported were obtained using an antenna with a relatively broad beam. Also, this choice is suggested by the equivalence with the ultrasonic system. However, the beam of the antenna can be designed with increasing directivity, to achieve a twofold advantage: an improved SNR_{dB} and a better definition in obstacle detection.

The different physical nature of the EM pulses with respect to the ultrasonic ones provides further opportunities to improve the system performances. With the propagation velocity of the EM waves being many orders of magnitude greater than sound velocity, this allows a great number of EM pulses to be launched, thereby increasing the information content retrievable from the echoes of the surrounding scenario. Moreover, the EM pulse easily penetrates dielectric object, and this characteristic can be exploited by designing a wearable sensor that does not interact with clothes, making an evident improvement in acceptability and usability with respect to existing systems.

V. CONCLUSION

In this paper, an experimental study concerning the capability of an EM system to detect obstacles in a short-range scenario has been carried out. The aim was to investigate its potential as an auxiliary tool to improve the mobility of the blind or visually impaired people, and therefore, this study aimed to fill a gap because, to the authors' knowledge, this specific subject has not yet been reported in the literature, and most work is addressed to a preliminary investigation of new prospects in terms of electronic aids for disabled people.

The approach followed in this study was to make a comparison between the performances of the EM system under investigation and those of an ultrasonic system which is, at present, the golden standard for ETAs. Bearing in mind the physical differences between the two systems, great care was taken to make the two experimental setups equivalent. The task of the systems was to detect an obstacle and measure its distance from the transmitter position, adopted as a reference point. The choice of the obstacles was driven by considerations coming from the everyday life of partially sighted people, from their potential danger, from their shapes and materials.

Some important features have been experimentally assessed: the precision in the determination of the obstacle distance and the ability in detecting some specific obstacles such as the semiopen door and the plastic pole are superior with respect to the ultrasonic sensing. The ability of EM system in detecting obstacles has been demonstrated in cluttered environment (indoor and outdoor) without any significant degradation of the system performances. Moreover, with respect to the ultrasonic sensing, the proposed system can be used under the garments, minimizing its visibility and consequently reducing the common effect of stigma related to the use of ETA.

Finally, it is worth observing that the EM technology and the design tools are mature and could allow a system to be built up at costs comparable with existing or developing systems.

Further advantages of such a system could be derived from the integration with other wireless telecommunication systems and from the miniaturization, with evident benefits for user acceptability.

It is important to note that any further development of an EM obstacle sensing system, as well as any other ETA specifically designed for visually impaired people, cannot reach its scope without the attention on three important aspects: a correct signal processing to improve system reliability and robustness, an advanced multisensory strategy to optimize system use [36], and an optimized user-to-system interface, which are, in the opinion of the authors, possible only with the feedback of the users [11], [25], [29].

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