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Sensory navigation device for blind people

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***Abstract*—This paper presents a new Electronic Travel Aid prototype which is especially suited to facilitate the navigation of visually impaired users. Device architecture consists of a set of 3D-CMOS laser sensors implemented into a pair of glasses, stereo headphones as well as a FPGA used as processing unit. The device is aimed to be used as a complementary device on navigation both through open known and unknown environments. The FPGA and the 3D-CMOS electronics are in charge of the object detection. Distance measurement is achieved by using chip-integrated technology based on the Multiple Short Time Integration method. The processed information of the object distance is released to the user via acoustic sounds through stereophonic headphones. The user interprets the information as an acoustic image of the surrounding environment.**

***Index Terms*—Audio systems, 3D-CMOS sensors, object detector, navigation device for blind people.**

I. INTRODUCTION

THERE are over 45 million of totally blind people in the world WBU, 2009); 5,9 million are living in Africa, 3.2 million in America and 2 million in Europe. Blind people have significant constraints in their everyday life, mainly with regards to their mobility. Though they are often able to learn specific routes (e.g., how to get to the nearest shop or station), this ability is far from the desirable independence in navigation. Mobility has been defined by Foulke as “the ability to travel safety, comfortably, gracefully and independently through the environment” (Foulke, 1997). This concept, when applied to the blind traveler, implies that he must be able to detect the obstacles which are located in his walking path, to avoid them and to succeed in following his route. All these goals could be achieved by relying on accessory devices which facilitate the navigation, known as Electronic Travel Aids (ETAs). ETAs include electronic intelligent devices whose main objective is to overcome human constraints, perceiving the surrounding environment and presenting it to the blind user through tactile, vibrations, speech or acoustic senses.

Nowadays, there are three main groups of ETAs, according to their working principle: *radar*, *global positioning* and *stereovision*. The most known are the ETAs based on radar principle. These devices emit laser or ultrasonic beams. When a beam strikes the object surface, it is reflected. Then, the distance between the user and the object can be calculated as the time difference between the emitted and received beam.

The Lindsay Russel Pathsound (Russell, 1965), (Mann, 1970), considered as the first ultrasonic ETA, belongs to this first group. The device delivers three types of acoustic sounds for three different distances. The device uses ultrasonic transducers mounted in a box hanging around the user neck. Another ultrasonic ETA is the Mowat Sonar Sensor (Morrissette et al., 1981), it consists of a hand-held device which, by using the sense of touch as well as vibrations, informs the user about the obstacle presence. Sonicguide (or the Binaural Sonic Aid), designed by Kay in 1959 (Kay, 1964), was another revolutionary ETA in the 60’s. The working range of the Sonicguide is up to 55º in azimuth and up to 4m in distance. The ultrasonic wide-beam transmitter is mounted on the glasses between spectacle lenses. A secondary channel is added to the output, so that the acoustical signals with low-frequency tones are separately sent to the left and right ear. This procedure is named binaural technique or stereophony. The distance is strongly dependent of the frequency. Object direction depends on the interaural amplitude differences. Due to the binaural cues, Sonicguide is able to represent the environment with a great precision both in distance and direction.

A second type of ETAs includes devices based on Global Positioning System (named as Global Navigation Aids). These devices aim to guide the blind user through a previously selected route; also, it provides user location such as street number, street crossing, etc. Within this group, the most well-known devices are the Talking Signs and SONA (Sonic Orientation Navigation Aid) (Brabyn, 1982), (Kuk, 2002). Their working range is up to 30m in outdoor environments, both of them having a similar working principle. An interesting device is the Personal Guidance System, developed at the University of California at Santa Barbara (Loomis and Golledge, 2003), (Loomis et al., 2001). Using radio signals provided by satellites, the device is able to provide real information of each Earth point, informing in real time about the user position in the environment.

With the introduction of the webcam, many researchers proposed the application of stereovision to develop new techniques for surrounding environment representation. Nowadays, there are few prototypes in the world using stereovision: among them, the Voice prototype (Meijer, 1992), (Meijer, 2005), the Real-Time Acoustic Prototype (Dunai et al., 2010) and the Eye2021 (Dunai et al., 2011). All these devices intend to represent the surrounding environment through acoustic signals.

Nowadays real time 3-D imaging becomes an important factor in many applications such as: pattern recognition, robotics, and pedestrian safety, object tracking, etc. 3-D imaging is essential for distance and shape measurement of the objects. The application of the 3-D imaging in the Electronic Travel Aids for the blind people provides more benefits regarding the distance and direction estimation or object surface and texture identification. Over the last decades, the use of multiple sensors has enables to obtain additional information about the surrounding environment, simultaneously scanning a wide range of that environment. This method, comparing with the existing methods, does not require manual scanning using orientation of the torso, hand or head.

Based on the idea of using multiple sensors, a novel Electronic Travel Aid for blind people is presented in this paper. The device enables the distance measurement by using the 3-D CMOS sensor Time-Of-Flight measurement principle.

The paper is structured as follows: Section II describes the developed system architecture; details of the 3D CMOS sensor circuit and of the distance measurement and sound generation methods are provided there. Section III describes and analyses the results obtained when testing the prototype with real users. Finally, in Section IV, the conclusions of the work are summarized.

II. SYSTEM ARCHITECTURE

The Acoustic Prototype principle is based on human cognition; the electronic device scans the environment while the human brain interprets the collected information.

The Acoustic Prototype is based on smart sunglasses with laser photodiodes as well as a 3D CMOS sensor with a high-speed shutter implemented in a small bag together with the FPGA and earplugs (Fig. 1). The FPGA processes the signals arrived from the 3D CMOS sensor to the Correlated Double Sampling (CDS) memory; it measures the distance between the detected objects and the sensor. Then, it applies this information to the acoustic module, which represents the distances as sounds which are delivered to the user through stereophonic headphones. The idea of using binaural sounds in the Electronic Travel Aids for blind people was introduced by Kay in Sonicguide device in 1959 (Kay, 1974). He added a secondary auditory channel to the previously developed Sonic Torch, in order to obtain a more real interpretation of the real environment.

Besides, the Acoustic Prototype uses acoustic sounds, measuring the corresponding Head-Related Transfer Functions by using a KEMAR manikin. Tachi et al. in 1984 (Tachi et al., 1983) and (Gonzales-Mora et al., 2004) implemented this method in 1995, within the framework of the Espacio Acustico Virtual, a navigation device for blind people.

In order to obtain an enough wide range of the environment information, the Acoustic Prototype uses multiple laser sensors. A similar procedure was used in the NavBelt device (Shoval et al., 1998). This device uses eight ultrasonic sensors, each one covering an area of 15º, so that the whole scanned sector amounts for 120º. In the case of the developed Acoustic Prototype, sixty-four near-infrared laser sensors mounted in a pair of sunglasses are responsible for scanning the environment. The covered sector is 60º; the environment is scanned every 0.94º. The distance measurement method is based on the Time-of-Flight measuring principle for pedestrians (Mengel et al., 2001). The distance is calculated as the time difference between the laser impulses sent and received by the diode. This is carried out by the 3-D CMOS sensor, knowing the laser impulse velocity. This technique enables a fast environment scanning and information processing by the FPGA. Finally, the device delivers, through stereophonic earphones, the acoustic sounds representing the detected objects.

A. *3D CMOS sensor circuit description*

The 3D CMOS sensor chip is based on a 0,5 μm n-well CMOS process. It includes 1×64=64 photo diode pixels, an imaging optics, electronic boards and a power supply.

In Table I and Fig. 2, the main sensor specifications are given.

The pixel pitch is 130 μm in horizontal and 300 μm in vertical direction. The resulting area is then: $1*300\ \mu m*64*130\ \mu m = 2.5\ mm^2$.

Each pixel consists of a n-well/p-substrate photo diode PD, an inherent capacitance C_D, a sense capacitor C_{sense0}, a hold capacitor C_{HD}, a reset switch Φ1, a shutter switch Φ3, a buffer SF1_out, a select switch Φ4 and a binning switch Φ2 (Fig. 3). The amplification factor of the buffer is 0.85. The circuit operates by resetting periodically the photo diode capacitance C_D and the sense capacitance C_{sense0} to the voltage U_{ddpix} and the obtained discharge. The obtained integration time of the discharge is controlled by the shutter switch Φ3. Then the capacitor C_{HD} reads out the remaining voltage stored on C_{sense0}. When the select switch Φ4 is connected, then the stored voltage from the C_{sense0} is read out by using the Correlated Double Sampling CDS. At the same time, when the voltage is read out by the C_{HD}, on C_{sense0} the next voltage value is performed. Obviously the chip performs the information almost in real time and continuously reducing to the minimum the dead time.

By using the Correlated Double Sampling and analog averaging, the device reduces power consumption, chip temperature, circuit noises, etc.

The main processing unit of the 3D CMOS sensor is implemented on the FPGA (Field-Programmable Gate Array) board. The FPGA controls the system and makes possible the configuration of the system as well as the control of the 3D CMOS sensor, the camera, the shutter and the memory.

A VHDL, hardware description language for electronic design automation and an embedded configurable soft-core processor NIOS, are used in the FPGA for the development of the CPU (Central Processing Unit). This processor system is equivalent to a microcontroller that combines the CPU, memory and the peripherals into one single chip.

B. Distance measurement method

In order to calculate the distance to the object, it is important to know the distance measurement method used by the 3D-CMOS sensors (Fig. 4). The measurement principle is based on the Time-Of-Flight (TOF) distance measurement using the Multiple Short Time Integration (MDSI), and the analog switched-capacitor amplifier with Correlated Double Sampling (CDS) operation (Elkhalili et al., 2004). The main feature of the MDSI method is that several laser pulses can be averaged on-chip, reducing the required laser power; in this way, the ratio-to-noise and range resolution measurement accuracies are increased. Also, the MDSI allows the accumulation of many laser pulses in order to achieve the best accuracy for all image pixels independently.

The Time-Of-Flight measurement method measures the travel time of the emitted laser pulse of some tens to hundreds of nanoseconds to the environment and the reflected one. Besides, when the short light pulse is emitted by a near-infrared range (NIR) laser diode, the shutter is started, while it is stopped when the reflected light pulse is received by the detector. The light pulses are assumed to be ideal rectangular pulses.

The total travel time of the laser pulse, from the laser module to the environment objects and back to the 3D CMOS sensor, depends on the amount of irradiance measured by the sensor, on the reflectance of the object, on the object distance and on the amount of irradiance corresponding to other light sources from the environment. It is important to eliminate the effect of these other light sources and object reflectance from the range information on the 3D CMOS sensor. To this end, two integration times are defined.

Let T_p be the light propagation time of the laser, let T_1 be the short integration time on the shutter (Fig. 5). In the first measurement, the shutter time T_1 is equal to the light time T_p, because both times are synchronized. The received laser pulse leads to a linear sensor signal U at the propagation time T_0, where T_0 is calculated as:

$$t_{TOF} = T_0 = 2\frac{d}{v} \tag{1}$$

where d is the measured distance and v is the light speed.

At the time T_1, the shutter intensity $U_1 \sim E_{laser} * (T_1 - T_0)$ is stored in the analog memory of the CDS stage, where E_{laser} represents the irradiance measured at the sensor.

To measure the time delay, two measurements are required: the first at the short time shutter T_1 and second at the long light shutter time T_2. When using only T_1, different factors, such as laser power, object reflectance, sensor intrinsic parameters, or background illumination are included; they require a complex calibration procedure. In order to overcome this constraint, a second time T_2, named long light shutter time is used. At T_1, only a portion of the laser pulse and reflected light intensity is detected, whereas T_2 comprises the full-reflected light intensity. In this case, the long light integration time T_2 greatly exceeds the laser pulse T_p, $T_2 \geq 2\ T_p$. In Fig.5 it can be observed that the laser pulse and the reflected laser pulse are located inside the long light shutter time. At time T_2, the shutter intensity $U_2 \sim E_{laser} * T_p$ is obtained.

By computing the ratios between the two integrated shutter intensities, U_1 and U_2, the responsivity- and reflectance-free value is obtained:

$$\frac{U_1}{U_2} = \frac{E_{laser} * (T_1 - T_0)}{E_{laser} * T_p} = \frac{(T_1 - T_0)}{T_p} \tag{2}$$

Taking into consideration that the $T_1 = T_p$:

$$\frac{U_1}{U_2} = \frac{(T_p - T_0)}{T_p} \tag{3}$$

So that:

$$T_0 = T_p * \left(1 - \frac{U_1}{U_2}\right) \tag{4}$$

Substituting (4) in (1), the distance *d* of one pixel can be calculated as:

$$d = \frac{v}{2} * T_p * \left(1 - \frac{U_1}{U_2}\right) \tag{5}$$

Note that the parameter given by (5) is calculated for all pixels independently. This means that the Acoustical System calculates the parameter *d* for all 64 pixels. Moreover, the measurement cycle is repeated *n* times, until the system is disconnected. As mentioned before, all the results are stored in the CDS memory circuit in accumulation mode, increasing simultaneously the signal noise ratio and the sensor range resolution by $\sqrt[2]{n}$. To sum up, each measurement is performed when the laser is connected and disconnected, the results are analyzed and the difference is extracted and stored in the CDS memory.

C. *Sound generation method*

Whereas the sensor module provides the linear image of the surrounding environment, the *acoustic module* is in charge of transmitting this information to the blind user, by using virtual acoustic sounds. The function of the acoustic module is to assign an acoustic sound to each one of the 64 photodiode pixels, for different distances. The acoustic sounds will be reproduced through the headphones, according to the position of the detected object, always that the sensor will send distance values to the acoustic module. The sound module contains a bank of acoustic sounds previously generated for a spatial area between 0.5 m and 5 m, for 64 image pixels. A delta sound of 2040 samples at a frequency of 44.1 kHz was used to generate the acoustic information of the environment. In order to define the distances, 16 planes were generated, starting from 0,5 m and increasing exponentially up to 5 m. The refreshing rate of the sounds is 2 fps. 16 MB memories are needed to process the acoustic module. The distance displacement is strongly dependent on the sound intensity and on the pitch. At nearer distances, the sound is stronger than at farther distances. The longer the distance increases, the lower the sound intensity is. Virtual sounds were obtained by convolving an acoustic sound with non-individual Head-Related Transfer Functions (HRTF) previously measured using KEMAR manikin.

The working principle of the acoustic module is similar to ‘read and play’. This means that the acoustic module reads the output data, consisting of coordinates both in distance and in azimuth, from the sensor module and plays the sound at the same coordinates. The time interval between sounds is 8 ms while there are sounds playing. When there are no sounds, the sound module recalls the sensor module after 5 ms.

III. EXPERIMENTAL RESULTS

In this section, the tests carried out with the Acoustic Prototype are described. The experiments, which were developed during two months, involved twenty blind users. The tests were performed in controlled environments under the supervision of instructors and engineers. During the first month, each individual was trained to perceive and localize the sounds listened through the headphones, to learn that these sounds were representing objects of the surrounding environment and to relate them with corresponding obstacles. In other words, they learned that the sound meant “danger” and that they should avoid it. This initial learning period was implemented through different exercises with increasing complexity: from simple object detection to localization of several objects and navigation through these objects avoiding them. Initially, users were complementing the use of the Acoustic Prototype with the white cane. The use of the white cane the users enabled to relate the distance perceived with the white cane with the sounds listened via headphones. The aim of these experiments was to validate the Acoustic Prototype as object detector and mobility device for blind people.

During the indoor laboratory tests, the users walked through a 14 m long path based on eight identical cardboard boxes, placed in zigzag, and a wall at the end (See Fig. 6). The distance between pairs of boxes was 2.5 m (the boxes of each pair were separated 2 m).

A list of parameters including: number of hits, number of corrections and the travel time (also defined by (Armstrong, 1975) were measured. Moreover, each test was performed under three different variants: 1) with only white cane, 2) with only the Acoustic Prototype and 3) combining the white cane and Acoustic Prototype.

It was found that with the Acoustic Prototype, the users were able to perceive the height -by moving their heads up and down- as well as the width of the objects. Furthermore, some subjects were even able to perceive the object surface shape - square or round. The minimum width detected was around 4 cm (a crystal door frame). However, this level of perception was reached, after a long training period, by subjects with good hearing abilities and when both the objects and the subjects were static. In comparison with the ultrasonic navigation devices (Clark-Carter et al., 1986), (Shoval et al., 1998), in which the optimal range is up to 3 m, the Acoustic Prototype showed an accurate detection range from 0.5 m to 5 m in distance. With the Acoustic Prototype, blind users detect and perceive all obstacles and are able to navigate safety. It must be mentioned that travel speed depends on the environment complexity and user perception ability, e.g., in the laboratory tests in which the blind users tested the device, the best results were achieved for the 14 m path; 0.11 m/s. In our case, the path was not like in (Shoval et al., 1998), where the walls were used as objects, so that the blind user could permanently obtain the required information from these walls both at his left and right side. In such situation the blind user was guided by the sounds of both walls and walked through the middle, where the sound was attenuated. In the laboratory tests with the Acoustic Prototype, the users must perceive the position of the first obstacle, to avoid it, to find then the second obstacle, to avoid it again and so on… Therefore, the task considered here was more sophisticated and required longer time. Due to this fact, it was relatively easy to go down the wrong way. After several hours, some participants were able to navigate through this path without any errors at a speed lower than 0, 2 m/s.

Other tests were developed outside the laboratory, in the blind school square in a line of 29 m length (Mobility test A) and in street in a distance of 145 m length (Mobility test B). In outdoor environment, common obstacles such as threes, walls, cars, light poles, etc., were present. Table II shows the results obtained from twenty blind participants for the three analyzed environments.

Analysis and comparison between these data reveals that the navigation with the white cane is faster than that with the Acoustic Prototype. This result is obtained because of the training period, since every participant had years of practice with the white cane, whereas the maximum experience with the Acoustic Prototype was only two months. Also, it was observed that the navigation performances with Acoustic Prototype were improving with the time. This fact demonstrates that with the Acoustic Prototype, participants feel safety and navigate without problems after long period of training. This proves again the importance of the training period. On the other hand, the idea underlying the development of the Acoustic Prototype is to be a complementary navigation device and not to substitute the white cane.

From another point of view, the Acoustic Prototype has its own constraints due to the use of a line sensor. This limits the up and down object detection. As mentioned before, the participants should move their head up and down in order to find small obstacles as well as high objects such as threes or poles. Also, long training periods are required as well as hearing abilities to detect stairs and pot holes. In this situation the white cane becomes better. However, while the white cane detects near ground level obstacles, the Acoustic Prototype enables the detection of near and far upper ground obstacles, so the navigation performances of the blind people significantly increase. The device helps blind users to prevent far obstacles as well as to estimate, according to the sound intensity, the speeds of the objects and their direction. Also, it helps them to avoid all the obstacles in advance. Another advantage is the wide azimuth range (60º). By having such large range, blind subjects can determine the position and the width of the objects, helping them in their orientation.

IV. CONCLUSION

This work presents a new object detection device for blind people named Acoustic Prototype. The device is based on a 4×64 3D-CMOS sensor relying on the time-of-flight measurement principle and integrated in a pair of sunglasses. This technology is sustained by 1×64 image pixels and a 3D-CMOS sensor developed for fast real-time distance measurement. A Multiple Double Short Time Integration (MDSI) is used to eliminate background illumination and to correct reflectance variation in the environment. Due to the short acoustic stereophonic sounds, the information of the environment acquisition system (4×64 pixel 3D-CMOS sensor), is transmitted in real time to the user through stereophonic headphones.

The experiments show that the information obtained by the Acoustic Prototype enable blind users to travel safety and increase their perception range in distance and azimuth. It helps blind users to perceive far and mobile obstacles and to avoid them.

However, several modifications and improvements are required:

1. Improvement of the vertical range: Currently, in the Acoustic Prototype only one line of 64 pixels of the 3D-CMOS sensor scans the horizontal plane environment at the user eye level. This limits the vertical (up and down) field of view.
2. Improvement of the acoustic sounds: The sounds are generated for an elevation of 0º. If adding vertical scanning sensors, the implementation of sounds for these special elevations is required. In this case is important to study and analyze psychoacoustic localization for virtual environments in elevation, distance and azimuth.
3. Implementation of voice-based guide: Blind users usually require receiving environmental information via voice. Thus, the Acoustic Prototype requires implementation of new vocal instructions as well as modification of the interaction interface.

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Fig. 1. Acoustic Prototype

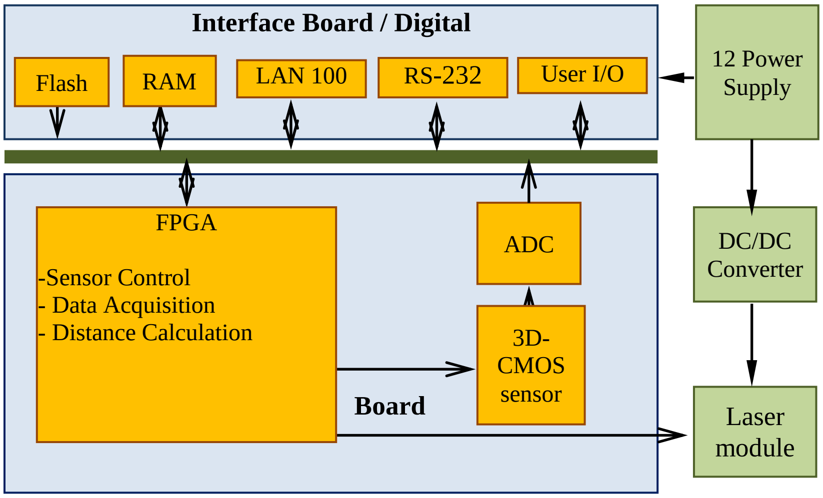

Fig. 2. 3D CMOS sensor hardware

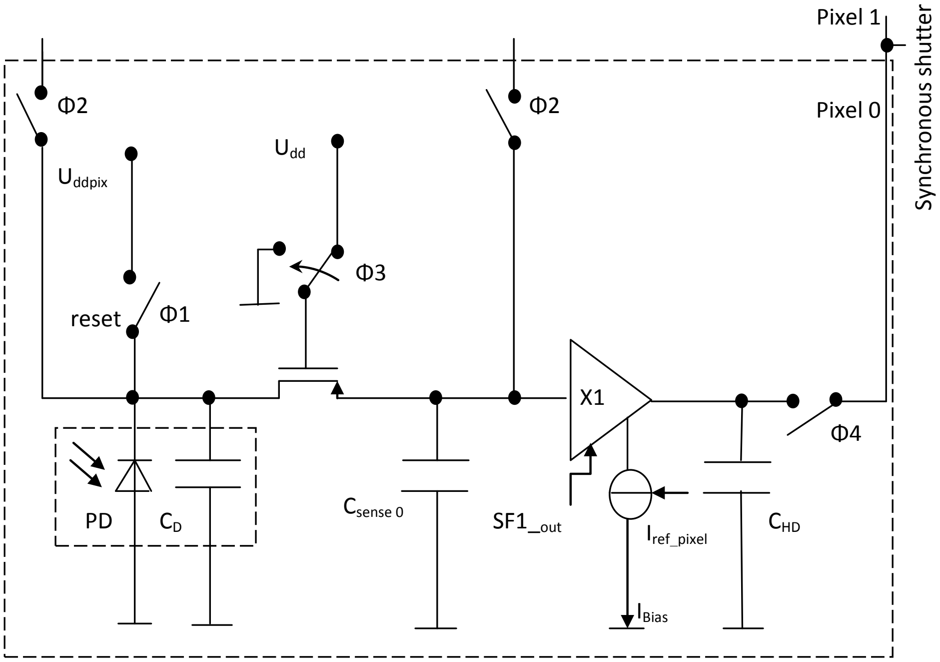

Fig. 3. Pixel circuit

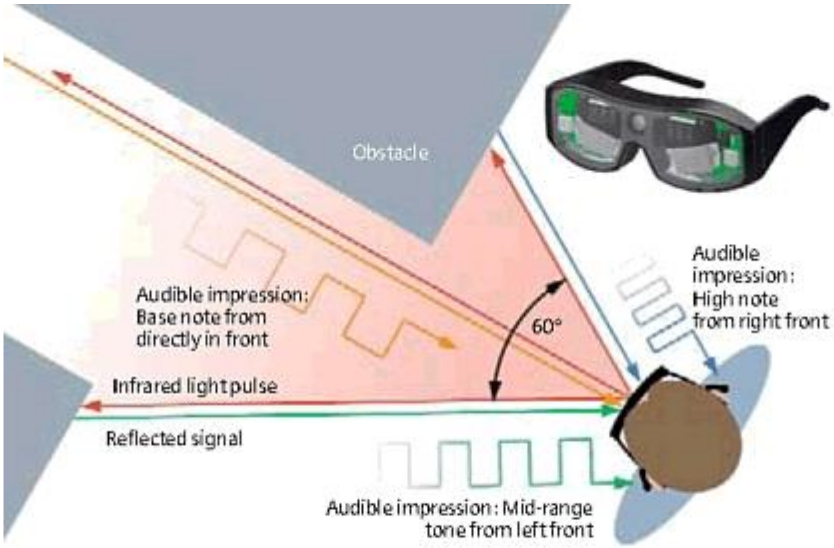

Fig. 4. 3D measurement principle of the distance from the 3D CMOS sensor to the environment obstacles

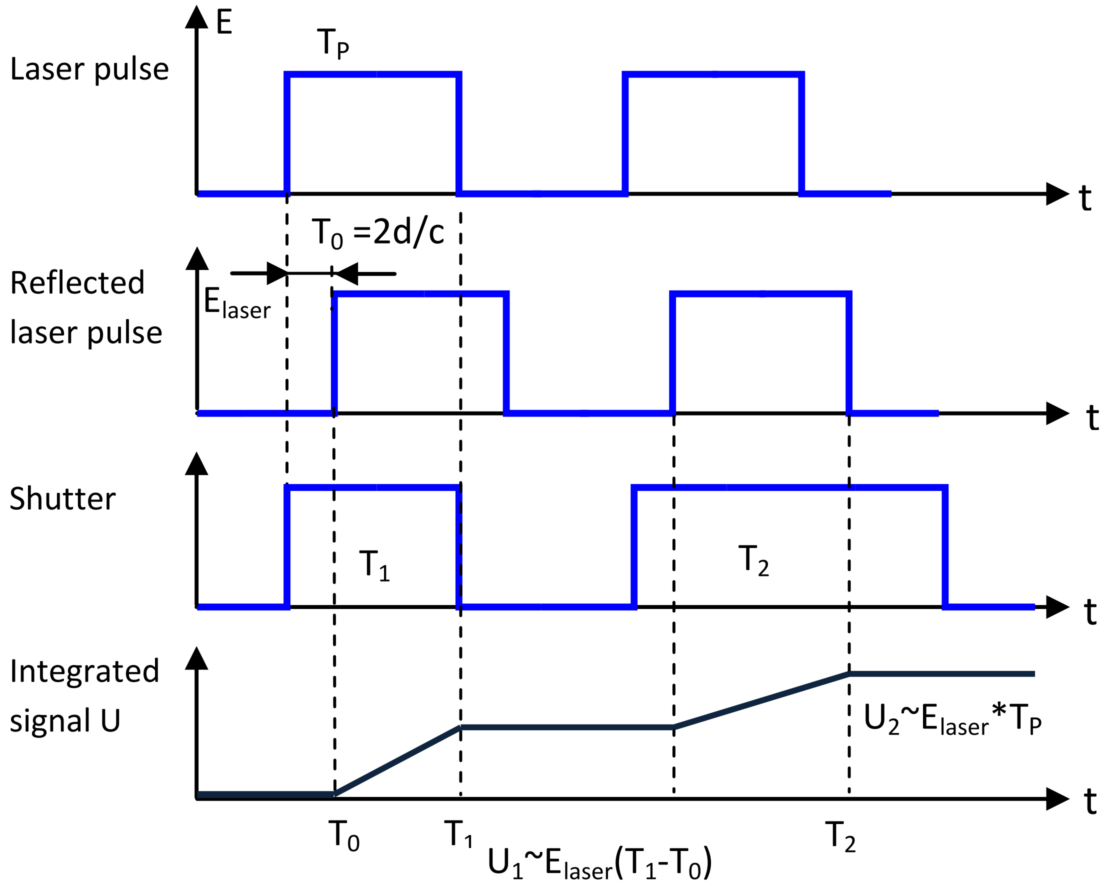

Fig. 5. Timing diagram of the Time-Of-Flight distance measurement principle.

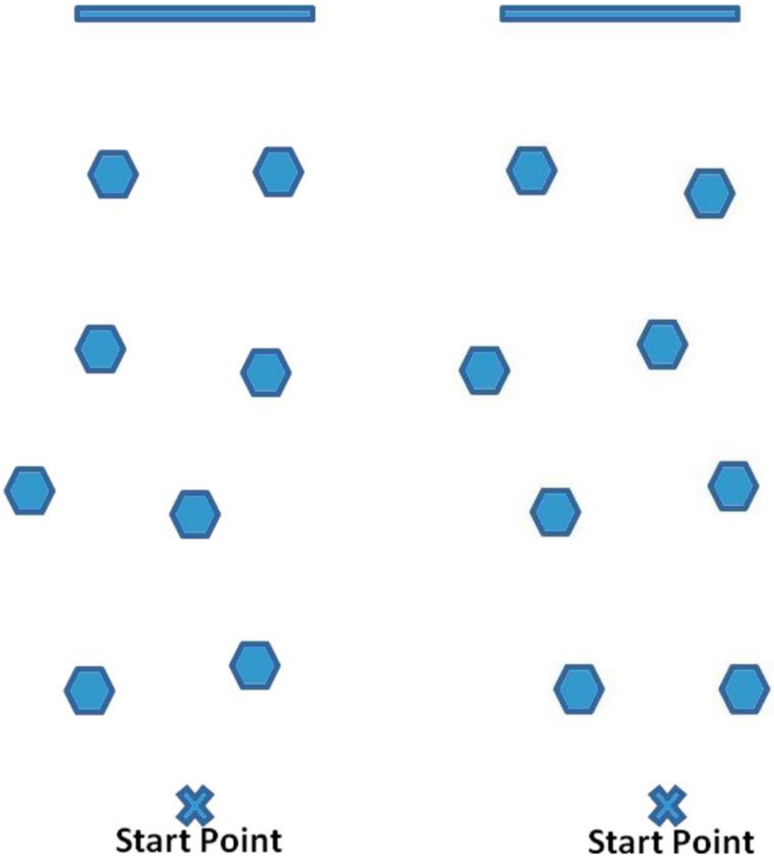

Fig. 6. Experimental laboratory paths

TABLE I
3D CMOS SENSOR PROPERTIES

Parameter	Value
Shutter time	>30*n*s
Noise	< 4W/m^2
Field of view	64º
Image sensor used	64×4 3D CMOS sensor used for pedestrians, ***only 64×1 photodiode line is used on the system***
Distance measurement range	0,5 m to 5 m
Measurement accuracy	< 1% for 100% target in distance
Pixel clock	5 MHz
Supply voltage required	12 V
Sensor technology	0,5µm Standard CMOS
Pixel geometry	130×300µm^2
Laser wavelength	850-910 nm

TABLE II

COMPARISON BETWEEN NAVIGATION PERFORMANCES WITH THE WHITE CANE AND THE ACOUSTIC PROTOTYPE IN THREE DIFFERENT ENVIRONMENTS

Parameter	Laboratory test	Mobility test A	Mobility test B
Distance (m)	14	29	145
Velocity with white cane (m/s)	0.69	0.4	0.54
Velocity with Acoustic Prototype (m/s)	0.052	0.058	0.22
Number of Heats	2.45	2.35	4.7
Number of corrections	1	1.25	3.05