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Ultrasonic Radar System (URAS) for an efficient detection of indoor spaces using Arduino

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***ABSTRACT—E*xploration of unknown spaces have been increased in order to create advanced guide systems for robots and people affected by disabilities. The most common applications are related to the exploration of unknown and/or dangerous spaces that are not accessible to people by exploiting the advantages offered by ultrasonic technology such that this makes easier identification and mapping. This work aims mainly at designing a new low-cost system(URAS), to blindly map environments by using ultrasonic sensors, then gives the acquired information through an Android-based device.**

***INDEX TERMS*—Arduino, Android, Environmental Mapping, Internet of Things, Ultrasonic Radar System, Virtual Reality.**

I.INTRODUCTION

Internet of Things (IoT) usually refers to a set of technologies (e.g. sensors, tags, mobile devices, and communication technologies) to design and create advanced and complex systems that aim at improving the quality of life [1]-[2]. Through the paradigms and the standardization of IoT [3], it is possible to develop ad-hoc hardware systems where physical components communicate and cooperate, in order to reach a common goal [4]. Recently, new wearable devices, incorporating advanced electronic technologies, have been developed under the framework of IoT, to provide practical functions and features to aid people in their everyday life. In particular, several solutions have been developed by Academia to improve the quality of life of blind and visually impaired people. For instance, Rey *et al.* in [5] propose a wearable device based on both a cheap ultrasonic sensor for the detection of obstacles and a vibrotactile feedbacks to warn the end-userabout the detected obstacles.Several works design novel IoT solutions based on ultrasonic technology, serving several purposes such as: the detection of obstacles; the tracking of human and robot's behavior in an environment; and the mapping of environments. More recently, several applications based on ultrasonic technology have been developed to improve the mapping and localization of a robot module and the software has been choosen with effectiveness.The robot is composed of different sensors and devices and with the different areas of technology and techniques for the exploration of unknown and/or dangerous spaces that cannot be accessed by humans. As a matter of fact, ultrasonic sensors have become a popular measurement tool because of both their simplicity and affordability. A great deal of research efforts have focused on developing systems that can be remotely controlled to explore an environment. For instance, Correra *et al.* in [6] design an autonomous navigation system based on two parts: a navigation system based on the Microsoft Kinect device; an artificial neural network (ANN) deployed on a laptop integrated in the navigation system to recognize different configurations of the environment. Similarly, Bergeon *et al.* in develop a 3D mapping system by creating a robotmodule based on the Kinect device and a 2D laser sensor to increase the accuracy of the system.

The novelties proposed by our (hardware and software) solution are: (*i*) the design and creation of a miniaturized, independent module that can be integrated in any kind of robot module (e.g. the one here introduced) or that can be worn by the user because of its compactness and lightness. In particular, the size of the independent module is 6x9 cm and it weighs 100 grams, battery included; (*ii*) the design and development of an Android-based application that allows user to remotely control the independent module integrated in a robot module receiving the directions inputs through two kinds of remote controllers provided in the Android-based application: a software remote controller composed of four buttons that represent thepossible directions of the robot module; an accelerometer-based controller exploiting the information provided by the embedded accelerometer sensor to fluently move the robot.

II.RELATED WORKS

Bharambe *et al.* in [16] design a device composed of two ultrasonic sensors connected to a microcontroller that has to be grasped by the end-user. Through this device, the end-user

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can detect possible obstacles, then receiving a feedback through the vibrator motors placed on three fingertips. Gupta *et. al* in [17] proposed an advanced guide cane that guides the user in both outdoor and indoor environments thanks to a global positioning system (GPS) and an obstacle detector system based on an ultrasonic sensors. Sunehra*etal.* in [18] design a mobile robot system for remote sensing and monitoring with the ability to avoid obstacles. The system is controlled remotely by an end-user via a base station composed of a laptop and connected to the Internet in order to communicate with the robot module. The robot is composed of different sensors and devices such as a camera's smartphone and an ultrasonic sensor to detect a possible obstacle. Chmelar *et al.* in [19] introduce a platform composed of a RGB camera and ultrasonic and laser sensors combining the measurement provided by such sensors to map the whole environment. The final output is a 3D vector map of the analyzed environment that has to be created via laptop.

However, the proposed system is expensive due to the presence of the laser sensor and the RGB camera. Ismail *et al.* in [20] propose a mobile robot to create a map of an unknown environment while simultaneously locating the platform itself in the environment. To reach this goal, they design an algorithm that extracts features from raw sonar data received from the mobile robot. The robot is composed of a set of sonar sensors connected to an Arduino UNO platform and sends the acquired data to a laptop in order to process the data and to recreate the environment. The growing popularity of mobile devices has changed the point of view of researchers, who started exploiting this emerging technology providing innovative solutions. As a matter of fact, to improve the mapping of real environments using compact systems, Limet al. have developed a mobile robot that exploits a smartphone wirelessly connected to an embedded Arduino platform [21].

BI.ULTRASONICSENSORFOR OBJECTDETECTION

The most common ultrasonic sensors exploited in several state-of-art approaches are the HC-SR04 [26] and HC-SR05sensors, which can be used both indoor and outdoor since ultrasonic technology is not sensible to light variations and to low light environments.

This kind of sensors is composed of a transmitter and a receiver enabling the computing of the distance from an object without losing in accuracy, except in presence of objects made of sound-absorbing materials which obviously make the measurements inaccurate. The measurements are performed through a sequence of ultrasonic pulses at the frequency of 40 KHz that can hit objects in the range of 2cm to 400cm [26]-If an object is in the sensor's range, the ultrasonic pulses are reflected by the surface of the object and their echoes are then retrieved by the receiver, as shown in Fig. 1.

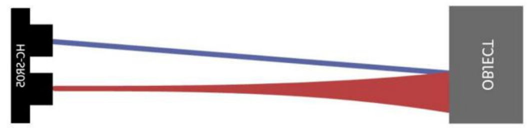

Fig. 1. Example of the HC-SR05 during the detection of an obstacle detection in its working range.

The hardware design of the proposed URAS is based on the Arduino platform and with the system effects and the required base systems of the work.

Exploiting the information about the timing interval between the sending of the pulse and the reception of its echo, it is possible to compute the distance from the obstacle through the connected microcontroller board, such as Arduino [28]. To enable the communication between the ultrasonic sensor and the microcontroller board, it is necessary to connect the digital pins of the sensor to the board,i.e.: (*i*) the *Trig pin* is used to send to the HC-SR05 a pulse of 5 Volt for a duration of at least

(*ii*) the*Echo pin*is used to receive a signal that identifiesthe echoes retrieved by the receiver. Through these pins, the microcontroller manages the sensor and sends the ultrasonic pulses retrieving their echoes.

II.PROPOSED URAS AND DATAVISUALIZATION

The URAS aims at providing a new low-cost, compact solution to blindly map light-free indoor environments and to display the acquired data of the environment to the end-user through different kind of views (i.e. 2D, 3D, and VR).

In particular, we have decided to use an ultrasonic sensor that exploits a 40 KHz sound wave because the advantage of this choice is threefold: first (*i*), this design solution helps in reducing the possibilities of false echoes, since it is very likely that a 40 KHz wave will come from the actual ultrasonic sensors itself rather than from any other source. Then (*ii*), since the attenuation is directly related with the choice of the frequency of the wave, at

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40KHz attenuation is approximately 0.5 dB/ft, while it increases rapidly increasing the frequency, jumping to 2.7 dB/ft at 150 KHz. Finally (*iii*), since we aim at providing a new low-cost, versatile ultrasonic system compatible with the Arduino Nano platform and Android-based mobile devices, we decided for a 40 KHz ultrasonic sensor, that is the most popular choice for prototyping.

In fact, Arduino allows to create ad-hoc hardware modules, based on different sensors connected to the platform, and to manage their behaviors through ad-hoc programs written in Wiring programming language [32], deploying them on the platform. In addition, the integration of a bluetooth component allows Arduino to forward the data to a third-party application which aims to process and/or show that data to the end-user. We choose Android as target mobile platform to develop the mobile application because of its worldwide diffusion and open source nature [33]-[34]. Through the Android SDK, we defined all the methods and mechanisms to develop a mobile application that allows users to: (*i*) manage the communication between the smartphone and the independent module; (*ii*) display the data acquired through the module; (*iii*) and remotely control the position of the URAS. Inthe following sections, we present the main structural choices behind the design and development of the proposed system.In particular, we have decided to use an ultrasonic sensor that exploits a 40 KHz sound wave because the advantage of this choice is threefold for the conformation of the output that has been taken such that the materials taken for the analysis are the full type concentration for the articles provided and their diagram is shown.

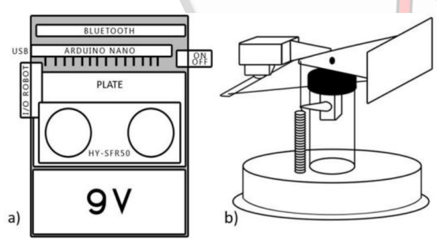

Fig. 2. The schema of the proposed URAS composed of a) an independent module and b) a robot module.

A.Design of the Ultrasonic Radar System

The hardware design of the proposed URAS is based on the Arduino platform in order to exploit its open-source nature, creating a system able to map surrounding environments by exploiting cheap components without any loss in accuracy. We design the hardware of our URAS by defining two modules:

(*i*) an independent module, which is the core of our URAS and provides the hardware components to map an environment (see Fig. 3a); (*ii*) a robot module, which is a physical support for the independent module and composed of two servo-motors remotely controlled by an Android-based smartphone (see Fig. 3b). In particular, we propose here a simple prototype of a robot module to test the behavior of the independent module of the URAS and the mobile application.

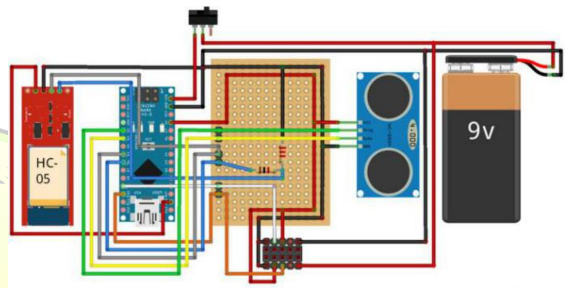

Fig. 3. The circuit diagram of the independent module of the URAS.

As shown in Fig. 4, the independent module is composed of the following hardware components: (*i*) *Arduino Nano version3.0* is the main component of the system, because it allowsmanaging the independent module [30].It can be connected to compatible modules through 14 digital input/output pins and 8 analog inputs and it can be supplied by an external battery allowing to be integrated in a mobile unit.Finally, the compact size of the Arduino Nano (i.e. 40x15 mm) and the possibility to programmatically manage its behavior and that of the connected components makes if they fit for our aim; (*ii*) the HC-05 Bluetooth Module provides the communication between the remote device and controller (i.e. the Android-based application) and the independent module. It is based on CSR Bluetooth chip BC417143 supporting the Bluetooth protocol version 2.0 [35]. The operating frequency is an ISM band of 2.4 GHz exploiting an encrypted Gaussian minimum shift keying (GMSK) modulation to communicate with an authenticated device. Finally, this module supports several baud-rates forcommunication and, for the URAS, we selected the 57600 baud-rate; (*iii*) the HC-SR05 ultrasonic sensor is used to gather the information about the distance from a detected object; (*iv*) the connection board aims at efficiently connecting each hardware component to the Arduino board supplying the required power; (*v*) a toggle switch button is connected to the Arduino Nano platform to switch it on/off; (*vi*) a 9V battery to supply power to the whole system; (*vii*) a plastic case contains all the above

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mentioned components and is modified to provide an integration with the robot module or a mobile device using a holder.Here, in order to test the behavior of the independent module when it is integrated in a robot module, we developed a simple prototype of a static robot module. In Tab. 1, we report the price (in euros) of each hardware component and the final price of the proposed URAS,. Once theURAS is activated, an initial setup of each element is required to start mapping the environment. In particular, it is necessary to make the URAS reachable by the mobile device through the bluetooth communication channel and, if the independent module is connected to the robot, to set the position of the two servomotors at 90 degrees (i.e. the standard position).

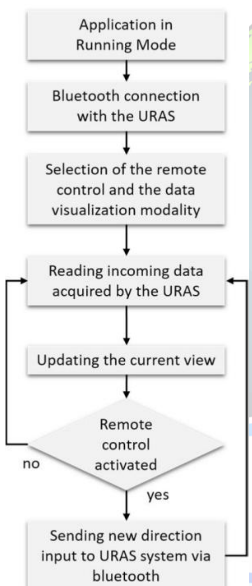

Fig. 4. Simplified flow-chart of the: (a) mapping process performed by theURAS, (b) data acquisition process performed by the mobile application

to the mobile device via Bluetooth. Then, the platform exploits the bluetooth sensor to send the computed data to the Android-based application.If the independent module is connected to the robot, then the algorithm checks if the remote control is enabled and assesses the presence of new direction vectors to update the current position of the robot. To do so, the independent module checks if the received direction vectors are corrupted due to the communication channel condition, avoiding unintentional movements or misbehaviors of the robot module. In particular, the system computes the absolute value of the difference between the new and current angles of the micro-servo and compares the results with an empirical, pre-defined threshold, which is here fixed to 100 degrees.

TABLE I

CODINGCOMMANDSOFTHESOFTWAREREMOTE CONTROLLER

B. Software Design and Ultrasonic Data Visualization by Android and OpenGL

To remotely manage the behavior of the system and visualize the acquired data in real-time, we designed and developed an ad-hoc mobile application for Android-based devices.

The architecture of our application relies on the principles of the well-known design pattern Layers [38]-[39]. Following the guideline of this pattern, we define four layers, each one managing a specific application behavior.

The four layers are: (*i*) the *graphics model* layer, which is used to model and manage the graphic elements that represent the distance information acquired through the URAS. Such package is composed of two sub-layers. The *basic rendering* sub-layer provides methods for the rendering of the elements in bi-dimensional (2D) or tri-dimensional (3D) visualizations, while the *virtual reality rendering* sub-layer defines the functions to manage the VR, defining a binocular stereo vision through the Application Programming Interfaces (APIs) of the Google Cardboard [40]. In addition, the definition of such layers is based on the OpenGL ES library [41]; (*ii*) the *I/Ocommunication* layer supplies the methods to manage thecommunication between the mobile device and the independent module through a communication channel based on the bluetooth protocol; (*iii*) the

business logic layer is the core of the application and allows to initialize the communication withthe URAS and to generate the direction vector to update the position of the robot module. In addition, this layer manages the distance information obtained through the URAS and the creation of the object to be drawn; (*iv*) the *UI* layer allows the end-user to remotely control the robot module and to display the data acquired by URAS in real-time choosing among the 2D, 3D, and VR views.

In the 3D and VR views, the camera's point of view is set at the center of a sphere that has a radius equal to the maximum range of the ultrasonic sensor (i.e. 400 cm), as shown in Fig. 8. The 3D view is characterized by rectangle shapes, differing in color,

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which represent the detected objects and the current distance between them and the HC-SR05 sensor.

Through this data view, the end-user can dynamically change his/her point of view, exploring the mapped environment by using the accelerometer sensor or the software remote controller. If the VR view is selected, the end-user has to wear the Google Cardboard, a cheap cardboard box that allows to exploit the binocular stereo vision [43] and to control the hardware units through the accelerometer.Even though this view adopts the same point of view and objects designed for the 3D view, it requires a different definition of the virtual environment that has to be based on the Google Cardboard APIs [42] in order to properly manage the data visualization and the changing in the camera point of view. Through this view, the end-user can remotely explore the surrounding environment in an immersive way. In addition, thanks to the lightness of the independent module, the end-user can wear it by attaching it to the back of the mobile device.In this way, the end-user has a greater freedom of movement than the proposed static robot module and he/she can explore the whole virtual environment by changing the point of view of the camera via the accelerometer sensor.

In particular, this controller generates the direction vector defined in (4) and allows the independent module to update its position of 10 degrees for each received direction. It can be assessed that this kind of controller limits the accuracy of the mapping and it can be used only with the 2D and 3D views, since it requires a direct input from the end-user who has to press the direction buttons displayed on the screen. To improve the efficiency of the application, we consider the multithreadingprogramming approach that allows the end-user to provide the direction inputs putting them in the queue of the bluetooth socket while the application is receiving the acquired data via bluetooth. Then, the direction inputs are sent to the independent module, updating its own position if the robot module is connected. Finally, the discussed operations are executed until the end-user stops the mapping and the visualization process, and then closes the communication with the independent module.In addition, this layer manages the distance information obtained through the URAS and the creation of the object to be drawn.n the center, at the top, the distance from the last detected object is reported. displaying the same objects that, thanks to the Google Cardboard and the principle of the binocular stereo vision, result in a unique virtual environment.

III. EXPERIMENTAL RESULTS

In this section, we report an overview of the developed mobile application and the experimental results carried out toevaluate the performance of the URAS located in a room and in presence of several objects made by different materials and having different shapes and sizes

A.Application overview

Figs. 1-6 show an overview of the mobile application used to visualize the acquired data and to remotely control the URAS. The main page of the application, namely *MainActivity*, allows the end user to perform several operations, such as the setting of the bluetooth connection and the selection of a data visualization view. By clicking on the bluetooth icon, the end-user is redirected to the *DeviceListActivity* page where he/she can configure the connection between the device and the independent module, from a list of bluetooth devices. Once the independent module is selected, the application automatically sets the MAC address of the device and requires the end-user to insert the password.

Otherwise, if the end-user already knows the MAC address of the independent module, he/she can manually set it through the *SettingsActivity* page, shortening the time required to pair the two devices. In the *MainActivity* page, the user can choose the remote control mode of the URAS by clicking on the device’s buttons, switching from the controller based on the accelerometer sensor to the software remote controller. Finally, to visualize the data acquired by the independent module, the user can click on one of the three vertical buttons which represent the 2D, 3D and VR views, respectively. Through these buttons, the end-user is redirected to a different application page to visualize the mapping process in real-time. When the end-user selects the 2D view, the application displays a radar map composed of 40 concentric circles and triangular shapes that represent the current distance from detected objects. In addition, each gray circle represents a distance of 10 cm from objects, while the white ones represent a distance of 1 m from the detected objects.

Finally, in the upper left corner the distance from the last detected object is reported. If the 3D view is selected, the application displays a 3D environment composed of rectangle shapes where the color of a rectangle represents the distancefrom the hardware system. In particular, if the object is near the module, the rectangle is white. Otherwise, it becomes red as the distance from the detected object increases. The whole virtual environment is composed by a sphere which allows to map an environment completely and to explore its virtual representation .

B.Types of Graphics

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We evaluated the performance of our URAS using several objects made with different materials, having different sizes and located at a different distance in the room.

The tests were conducted in a controlled environment and aimed at evaluating the accuracy of the measurements performed through the URAS by computing the mean, the variance and the standard deviation of the estimated distance. In the first battery of tests, we set a distance of 40 cm between the URAS and the considered objects reporting the mean distance, the variance and the standard deviation measured by the sensor and obtained through 100 trials, where each trial is composed of three consecutive measurements.

In the center, at the top, the distance from the last detected object is reported. displaying the same objects that, thanks to the Google Cardboard and the principle of the binocular stereo vision, result in a unique virtual environment

In the center, at the top, the distance from the last detected object is reported. It is important to underline that the VR view splits the device's screen in two parts, displaying the same objects that, thanks to the Google Cardboard and the principle of the binocular stereo vision, result in a unique virtual environment

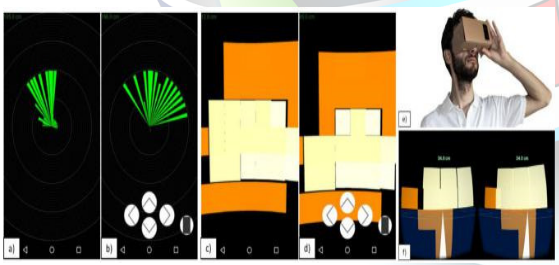

Fig. 6. The 2D view (i.e. the radar map) to display the distance from the detected object (a) using the device sensors, (b) using the software control; the 3D viewcomposed of rectangular shapes that assess the presence of many objects in the considered environment (c) using the device sensors, (d) using the software control.; (e) the end-user wearing the Google Cardboard and (f) the VR view .

Otherwise, it becomes red as the distance from the detected object increases.

TABLE II

MEASUREMENT ACCURACY TESTS OF THE URAS IN PRESENCE OFA CARDBOARD BOX PLACED AT DIFFERENT ANGLES.

Angle	Estimated Distance Mean	Estimated Distance Variance	Estimated Distance Standard Deviation
30°	42,55	7,4246	2,7248
45°	41,36	0,5761	0,759
60°	43,65	0,4520	0,6723
90°	40,36	0.2529	0.50292

TABLE III

MEASUREMENT ACCURACY TESTS OF THE URAS IN PRESENCE OFA CARDBOARD BOX LOCATED AT SEVERAL DISTANCES

Real Distance (cm)	Estimated Distance Mean	Estimated Distance Variance	Estimated Distance Standard Deviation
40	39,64	0,2304	0,482418
80	78,98	0,7596	0,875941
120	120,92	1,3136	1,151898
160	161,4141	1,7219	1,318823
200	200,3333	1,5011	1,231366
240	208,1414	0,9075	0,957427
280	206,7475	1,2675	1,131505
320	206,46	0,7084	0,845905
360	206,62	1,0956	1,051982

400	206,79	1,2459	1,121822

The results presented in Table II highlight that the ultrasonic sensor is not able to properly estimate the distance from the cardboard box. In particular, when the cardboard box is rotated at 30 degrees, the sensor makes several mistakes in computing the distance, as underlined not only by the mean distance but also by the values of variance and standard deviations.

Table III confirm, again, the expectation and the ability of the URAS to correctly compute the distance from the considered objects in a range of 200 cm. If this value is exceeded, the system is obviously not more able to properly estimate the distance, providing a value around 206 cm.

IV. CONCLUSION

It is possible to assess that an extensive work has been done in the creation of novel solutions based on ultrasonic technologies for the exploration and mapping of new environments. However, most of these works require additional and expensive sensors, such as a RGB camera or a laptop, and the core of the system is typically embedded in a mobile robot module or in some objects, such as gloves or hats, making it impossible to directly reuse it in other solutions. In addition, none of these solutions provide a compact, cheap andversatile system that can be worn by an end-user or integrated in a robot module. Finally, some of the considered systems provide a visualization of the acquired data based on the image acquired by the camera embedded in the system or through 3D rendering, requiring additional computational resources provided, for instance, by a laptop. Conversely, we overcome all these drawbacks through the definition of the URAS, a novel system for a light-free mapping of indoor environments.

In this work, we proposed a novel low-cost, compact ultrasonic radar system for a light-free mapping of indoor environments. In particular, the proposed hardware and software design of the system allowed us to create a small hardware device that can be worn by a user or be integrated in a ready-to-use robot module and to manage the I/O communication via an Android-based device.

Our solution is composed of four main elements: (*i*) the independent module, which is the core of the system and is designed in order to be cheap, compact and light. As a matter of fact, the size of this module is 6x9 cm, its weight is 100 grams; (*ii*) a prototype of a robot module, used to test the behavior of the system when it is controlled remotely; (*iii*) an Android-based application, which allows users to display and explore the mapped environment through different types of visualizations (i.e. 2D, 3D and VR) and to control the system remotely; (*iv*) the Google Cardboard, which allows users to use the VR view. In particular, through the VR view and the Google Cardboard, the end-user can explore the virtual environment, obtaining accurate information about the location and distance of each detected object.

The URAS was designed and developed to create a modular structure that allows to extend the behavior of the system adding new sensors to the hardware and new features to the mobile application. In addition, the whole system is based on cheap hardware components, enabling the creation of a versatile IoT device that can be easily replicated with less than 53€. Finally, through different sets of measurement-accuracy tests, we have proved that the URAS ensures a correct mapping of environments by using the simple but efficient approach described in section .A. Finally, the proposed solution allows the user to explore the environment mapped through the independent module in real-time, easily obtaining useful information.

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