Low-Cost Ultrasonic Obstacle-Avoidance System using FPGA

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Abstract

There have been numerous accounts of research relating to navigation assistance using vision sensors for those who are visually impaired. The struggle now is to find a solution that is low-powered, easily portable, low-cost, and still effective, which could theoretically be used by visually impaired users in order to improve their quality of life. This paper presents the design and implementation of such a system. The architecture begins with an array of ultrasonic sensors to survey the scene. Following that, distance information is used to provide indications about nearby obstacles to its user. Data processing is done on a FPGA, which acts as the link between the input and output devices. The results show that an effective personal obstacle-avoidance system can be uncomplicated.

I. Introduction

Unfortunately, it is not uncommon for one to witness another individual using a white cane or guide dog to navigate in a building or on the city streets. The reason we see this so often is because the World Health Organization estimates that there are 285 million across the world who struggle with visual impairment [1]. As a society, we have seen amputees receive tremendous support from the scientific community through advanced prosthesis and robotics research. With time and effort, support and solutions available for the visually impaired could become just as popular. The current and major roadblock though is the difficulty of working on and with the optic nerve, which is responsible for the neural paths that generate our vision [2]. Until ophthalmologists can successfully treat certain forms of visually impairment, there is a great call for research and low-cost, portable devices to aid those who are struggling.

II. Previous Work

In recent years, many solutions have been proposed for navigational assistance, all with positive and negative aspects. For instance, the work done by Mahmud et al. [3] presents a solution similar to the one proposed in this paper. However, this design still uses a white cane which can be an obstruction in crowded environments. Yelamarthi et al. [4] had promising results with their Kinect-based haptic feedback gloves. However, while the Kinect can track humans, it is a costlier solution and the gloves can also limit some of the actions a user can perform. Sharma et al. [5] also provide an architecture that is similar to this one, acting as a low-cost and portable solution. Their concept uses both an Arduino Uno and Raspberry Pi though, which adds potentially unnecessary hardware, and doesn't provide haptic feedback. Mustapha et al. [6] present a unique solution to the problem by using force sensing resistor, infrared, and ultrasonic sensors in combination on shoes to gather data, which is then wirelessly sent to a receiving PIC microcontroller over ZigBee communication. Karabchevsky et al. [7] designed an acoustic obstacle detection system for unmanned underwater vehicles, which uses advanced algorithms running on a FPGA to create a low-power solution with high-cost sensors. Hamza et al. [8] utilized an FPGA and two cameras processed by a stereovision algorithm to successfully detect obstacles in real time, but they made no mention of cost or power consumption. Boroumand et al. [9] used a fuzzy algorithm on an FPGA with infrared sensors to successfully guide a robot along a path and avoid obstacles in its way, but they made no mention of power consumption or cost in their design. Nguyen et al. [10] designed an assistive device for the blind that uses an electrotactile display placed on the user's tongue, which is less convenient for users to wear, but still proved to be effective. Lapyko et al. [11] developed a navigation system intended to be used outdoors which relies on GPS, internet, and a smartphone. This system was low cost, but was focused on navigation and not obstacle avoidance. Scheggi et al. [12] developed a system utilizing a cane, vibrotactile bracelets, and glasses equipped with a camera. This system combines navigation and obstacle avoidance but without mention of cost or power consumption. Velazquez [13] outlines a number of wearable devices for the visually impaired that already exist today.

III. Design

At the highest level, all obstacle avoidance systems can be broken down into three sub-systems: input, output, and processing. The input component is responsible for measuring the existence of obstacles, or lack thereof, within the immediate surroundings. The output sub-system is responsible for alerting the user to nearby obstacles and providing some indication of how to avoid them. The processing sub-system receives the input, interprets the data, and translates it into information that the output sub-system can understand. Some obstacle avoidance systems are more complicated than others, but all need these three sub-systems.

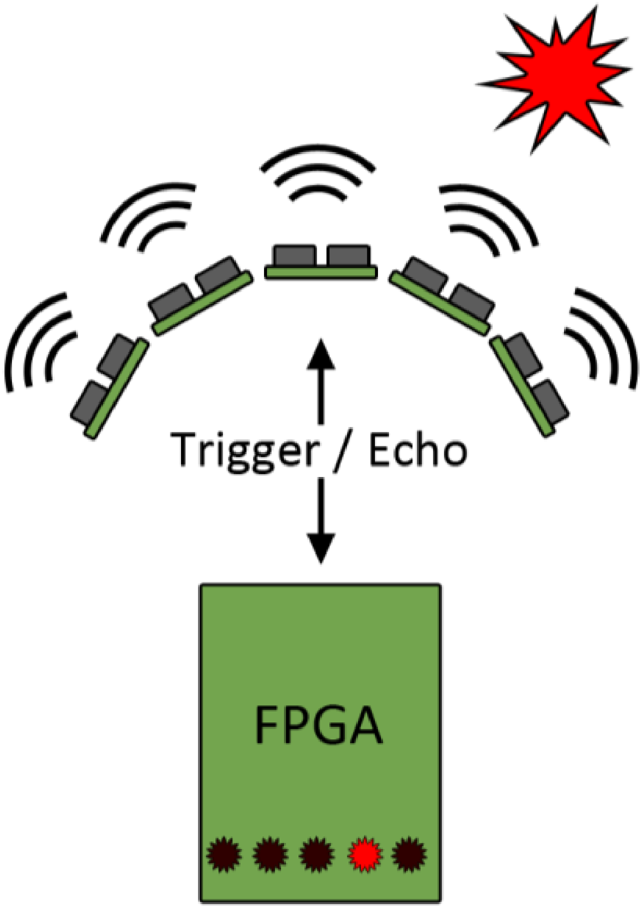

Figure 1. Illustration of system architecture.

A. Input

The input sub-system needs to be able to accurately measure the space around the user and, from those measurements, be able to distinguish between empty space and an obstacle. It should be able to do this passively without requiring special attention from the user and without impeding the user's comfort or mobility. Ideally, the system would be able to take measurements without the user's awareness, allowing the user to pursue normal activity without hindrance.

Ultrasonic range sensors are well suited to this purpose. They have a range of measurement which is well suited for a person's immediate surroundings. They have good accuracy and can take measurements quickly enough to alert a person moving at a walking-pace to an obstacle in their path. They are small enough to wear, operate nearly silently, and are very inexpensive.

B. Processing

The processing sub-system translates the information from the input to a format that can be understood by the output sub-system. This task is often handled by a microprocessor, which is good at handling digital information. For simple processing, however, a field programmable gate array (FPGA) can do the same thing without the overhead of a microprocessor. Compared to a microprocessor for the same task, a FPGA is usually faster, lower power, and is not prone to programming errors like memory leaks and run-time exceptions. A FPGA does usually, however, require more time to design and implement.

C. Output

The output sub-system interfaces directly with the user. It must present information from the processing sub-system in a way that the user can understand and quickly react to. Ideally, it will do so in a way that doesn't overwhelm, confuse, or prevent the user from understanding stimuli that they normally can without the device, such as by playing audio instructions that drown out the voice of another person giving directions. The assumption is that a person using this device has limited vision, so a visual output would not normally make sense. However, those without complete vision loss can respond to some visual stimuli.

IV. Implementation

A. Input

The input sub-system is an array of five ultrasonic sensors. Each ultrasonic sensor is an HC-SR04 [14], which can be cheaply purchased. This exact ranging module provides measuring functionality between 20 and 4000 mm. Accuracy of a stable reading will be within 3 mm. Each sensor has four pins, VCC, Trigger, Echo, and Ground. Together, the trigger and echo pins are responsible giving distance measurements that are read by the sensor. Initially, a high transistor-transistor logic (TTL) pulse must be sent over the trigger pin for at least 10 µs. This signal causes the module to drive out an ultrasound at 40 kHz in the form of an eight cycle burst. Based on the

time taken to hear the signal again after being reflected off an obstacle, the sensor generates a pulse width at the input's TTL level that corresponds to the magnitude of the distance measured.
The ultrasonic sensors operate at 5 V, while the FPGA operates at 3.6 V. The FPGA can provide a sufficient signal to trigger the ultrasonic sensors, however, the returning echo signal is too high voltage for the FPGA. A voltage divider, using a 1 kΩ resistor and a 680 Ω resistor, was used between the ultrasonic sensor and the FPGA to decrease this returning signal voltage.

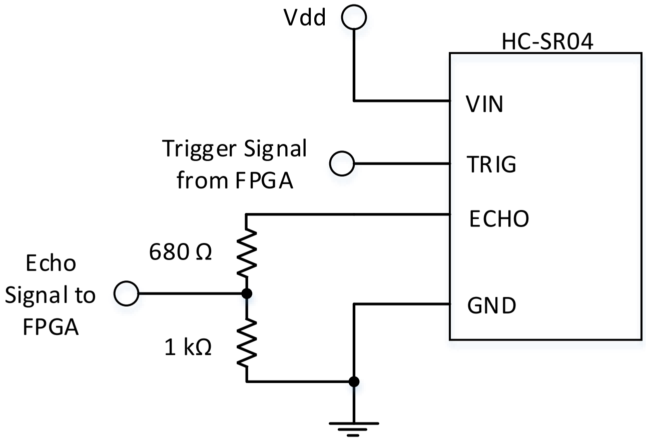

Figure 2. Schematic of connection between FPGA and ultrasonic sensor.

B. Processing

The processing sub-system is implemented with a Xilinx Artix-7 FPGA (XC7A3DT-ICPG236C) [15]. The VHDL code written to program the FPGA was comprised to two primary components: a trigger generator and an echo meter.

The trigger generator was responsible for creating the 10 µs pulse required to trigger the ultrasonic sensors to start a measurement. The trigger generator worked by counting clock cycles. The first 10 µs worth of clock cycles would force the trigger signal to be high. After 10 µs, the trigger signal would be forced low for approximately 80 ms before resetting the clock cycle counter. This cycle repeats indefinitely. The result is a pulse being sent approximately every 80ms. All five ultrasonic sensors were wired to the same trigger generator for simultaneous measurement.

The echo meter component was designed to translate the response of the ultrasonic sensors into a numeric range value. It worked by waiting for the signal on the echo pin from the ultrasonic sensor to rise from low to high. Once high, the component counted clock cycles until the signal dropped low again. The duration of the echo is proportional to the distance measured. Every 5800 clock cycles at a frequency of 100 MHz corresponds to 1 cm measured. In this way, the total distance measured could be quantified.

C. Output

Once the numeric measurement is obtained on the FPGA, an array of LEDs on the FPGA board are used to indicate the nearest obstacle. If any of the ultrasonic sensors reported a distance measurement less than 50 cm, an LED corresponding to the sensor with the smallest reading was illuminated. If no sensor reported a measurement of less than 50 cm, then none of the LEDs were illuminated.

This system of using onboard LEDs was not intended to be used in a final product. It was used because of time constraints and the need for testing. Ideally, a more sophisticated wearable solution would be implemented, but this system could easily be expanded to provide more advanced feedback for the user. One such system could be an array of small vibrotactile actuators worn around the user's waist that vibrate to indicate the direction of a nearby obstacle.

V. Results and Conclusion

First, the accuracy of the individual ultrasonic sensor was tested. The sensor was mounted at a known distance from a variety of materials. One thousand measurements were quickly taken and recorded for each material at each known distance. The average distance measured by the sensor was recorded and compared to the known distance. Also calculated was the probability of detection. This was found by taking the number of measurements out of one thousand that successfully detected the material. Overall, the sensor reliability and accuracy was very good. The results can be seen in Table I.

Table I. Sensor Accuracy.

Material	**Distance (cm)**	**Probability of Detection**	**Average if Detected (cm)**
Aluminum	*100*	1.000	99.2
	200	1.000	198.6
	300	0.997	294.9
Plastic	*100*	1.000	100.3
	200	1.000	197.1
	300	1.000	296.5
Styrofoam	*100*	1.000	96.9
	200	1.000	197.6
	300	0.838	296.3
Paper	*100*	1.000	98.1
	200	1.000	201.3
	300	0.587	294.9

In order to test the implemented system, the array of ultrasonic sensors was placed on a wheeled cart with the FPGA. Large foam-core boards were placed throughout the room to serve as obstacles, and the user was instructed to navigate from one side of the room to the other by looking only at the LEDs on the FPGA board. The user's path was marked on the floor and the time taken to complete the course was recorded. Figures 1, 2, and 3 show the actual paths taken compared to the ideal path. Tables II and III show the quantified accuracy of the paths and the time taken to complete the courses.

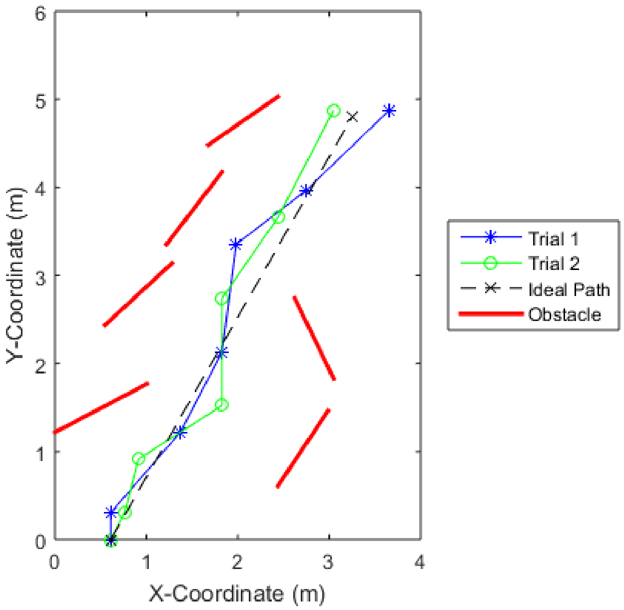

Figure 3. Map of paths and obstacles for test number 1.

The first course was the most simple to navigate, and both attempts resulted in paths that were similar to the ideal path. The relatively straight nature of the course made it easy to keep moving in the proper direction.

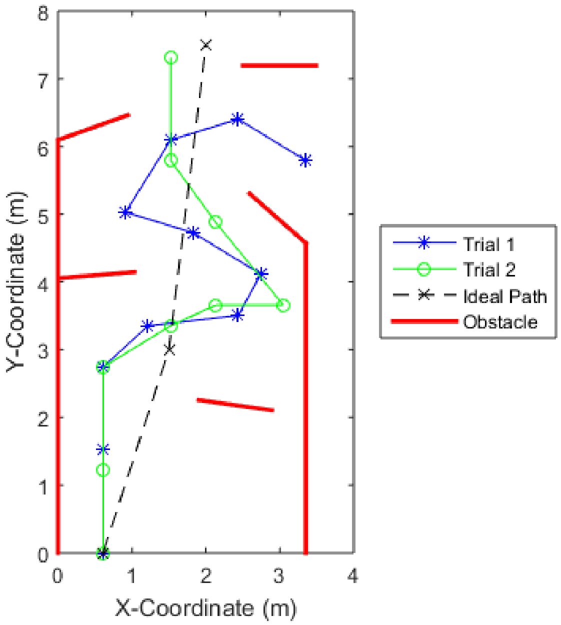

Figure 4. Map of paths and obstacles for test number 2.

The second course was a little more complicated than the first. While a direct path remained through the middle of the obstacles, the obstacle avoidance system did not accurately stay on the path. The indication of nearby obstacles caused the user to follow an indirect path through the course. Trial 1 did not end in the same place as Trial 2.

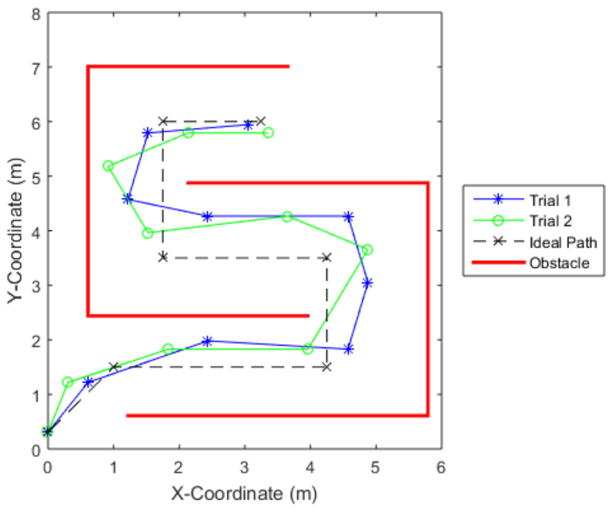

Figure 5. Map of paths and obstacles for test number 3.

The third course was made more complicated without a direct path through the obstacles. The result, however, was that the user's actual path could not deviate much from the ideal path, so the accuracy remained relatively good. When given limited options, the obstacle avoidance system made the way clear to the user.

Table II. User Path Accuracy.

Test #	Additional Distance Traveled Compared to Ideal Path (%)	
	Trial 1	Trial 2
1	9.80	4.95
2	41.96	25.18
3	4.53	7.06

Table III. User Travel Time.

Test #	Time Taken to Reach End Destination	
	Trial 1	Trial 2
1	48.47	54.57
2	1:43.57	1:25.89
3	1:30.46	1:53.07

Overall, the system worked as intended. It accurately detected nearby obstacles and informed the user of their positions relative to the device. Improvements can still be made to the output sub-system with regard to the method of delivering obstacle location information to the user.

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