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ACCURACY MEASUREMENT OF THE NATIONAL INSTRUMENT STARTER KIT 2.0'S PING))) ULTRASONIC SENSOR

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***Abstract*—**This article is based on the reflection and/or absorption of ultrasound (US) waves in some materials that can be found in indoor environment.

Sound and ultrasound waves are defined as longitudinal pressure waves in the medium in which they are travelling. This medium can be air, water, steel, concrete, granite blocks, human body, etc.

Targets/subjects whose dimensions are larger than the wavelength of the colliding sound waves will reflect these waves; the reflected waves are called "echo". Using the time-of-flight (TOF) technique, we can measure the distance between the US system and the target. But there are some materials which can absorb the US waves and the system will not find any obstacle, but in reality the obstacle is there.

***Keywords*—**Accuracy of distance measurement, robotics, ultrasonic absorption, ultrasonic distance measurement, ultrasonic reflection, ultrasonic sensor.

I. INTRODUCTION

ULTRASONIC (US) is not a human genuine invention, because some animals, like bats and dolphins, use this technique for long time before humans observed it or (re)invented it. Bats and dolphins navigate for a long time with the help of the US "transducer" embedded in their body.

Based upon the US principle of operation, people created artificial transducers, which ones can be used to different purposes, like robot navigation, distance calculation, internal flaw detection, medical and safety applications, etc. US measurements are very much used in different domains.

The US applications can have more names, like, "real time ultrasound" (RTU) in [1], "non-destructive evaluation" (NDE) in [2], or "ultrasonic distance measurer" (UDM) in [3].

US sensors are generally used for anti-collision and rangefinder purposes by measuring the distance to an obstacle [4]; some application ideas where US sensors can be used are: security systems, parking assistant systems, interactive animated exhibits and robotic navigation.

II. SOUND AND ULTRASOUND PRINCIPLES

Sound is a mechanical vibration transmitted by an elastic medium (usually air). The range of frequency of sound that human beings are able to hear is approximately between 20 (Hz) and 20.000 (Hz). This range is by definition "the audible spectrum" and its range can vary by individual. Sound above 20,000 (Hz) is known as "ultrasound", and sound below 20 (Hz) is called "infrasound".

In the air, US speed is approximately 345 (m/s), in water 1500 (m/s) and in a bar of steel 5000 (m/s) [3], but this values depend on the physical parameters of the travelled medium, like humidity, temperature, atmospheric pressure in case of air, temperature, salinity, pressure in case of water, and steel type, carbon containment in percent, etc. in case of steel. Ultrasonic wave propagation velocity in the air is the same as sonic velocity.

US measurement is widely used since it is a noninvasive technique and the equipment is relatively inexpensive and compact [5].

US sensors can be found in a wide range of frequencies ranging from 20.000 (Hz) to a few hundreds of (MHz) [6]; US transducers with frequencies of 2.25, 5, 10, 20, 50 and respectively 100 (MHz) were used in [7].

The ultrasonic pulse can travel in the material reflected, refracted, scattered or transmitted through its (in)homogeneities [8].

The industrial community has used ultrasonic time-of flight (TOF) and phase-shift (PS) methodology to detect distance of objects to plus/minus 0.05 (mm) [9] - this shows how precise can be the measurement using US.

The US system is presented in Fig. 1., and works as follows: a burst signal is transmitted for short duration (is emitted) by the emitter. After that there will be a silent period. This period is actually called "response time" and is the time waiting for reflected waves. The acoustic emitted signal may find an obstacle or not. If an obstacle is found, the acoustic signal will be bounced back from the obstacle. This back-bounced signal is called "echo". The echo is received by the receiving transducer and is

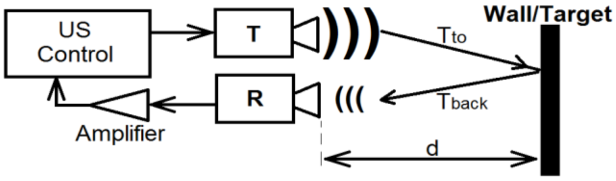

Fig. 1. Schematic principle of US System

converted into electrical signal. Usually this signal is amplified, filtered and can be converted into digital form [8]. Using the elapsed time between transmission and reception, the distance between the US system and obstacle/object can be calculated.

As a result of the spread of ultrasound in the air, there will be considerable attenuation and the degree of attenuation is directly proportional to the level and frequency: at high frequency or high-resolution, it should choose a short distance measuring sensor with high frequency; the measurement of long-distance application uses low-frequency sensors [10].

Modern ultrasound machines are lightweight, extremely portable and battery-operated systems, which are capable of making complex imaging presentations and are available for use in the field [11].

The frequency of ultrasonic wave around 40 (kHz) has the best transmission efficiency [12].

There are surfaces that can simultaneously generate multiple echo responses [6].

Other technologies than Ultra Sound are: vision cameras, time of flight cameras or infrared sensors [6].

The reflecting objects properties can be [3], as shown in Fig. 2.:

1) Surface: An ideal targets surface is hard and smooth. This surface reflects the greatest amount of signal.

2) Distance: The shorter the distance from the ultrasonic sensor to an object, the stronger the returning echo is.

3) Size: A large object has more surface to reflect the signal than a small one.

4) Angle: The portion of the object perpendicular to the sensor returns the echo.

Pro's and con's of using US sensors and US systems:

Pro US: Ultrasound has the features like strong directivity, nondestructive testing, speed, robustness, versatility in use, accuracy, lower cost than other technologies, propagating a long distance in a suitable medium.

The material is unaffected by the propagation phenomenon of the US, allowing the sample to be tested a number of times without becoming deformed [13].

Other US sensor characteristics are: the aerial and in-water transmission speed is slower than light - this makes signal processing easier [4]. US can propagate through steel - light can't do this. US is not affected by the color of an object; it can be used to measure the distance from the sensor to a transparent body - such as a glass object or transparent plastic.

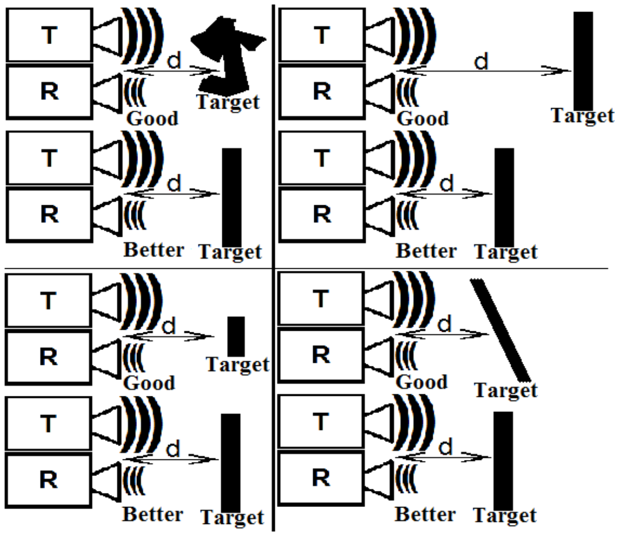

Fig. 2: US reflecting objects properties

Low cost and accuracy as well as speed are important in most of the applications [14]. Ultrasonic sensors are quite fast (fast enough) for the most of the common applications.

US is a good methodology for low labor continuous remote monitoring.

Against US: US can consume more energy than other technologies, it has a lower range and the speed of sound depends on the environmental temperature and humidity [15]. US has low directionality compared to optical sensors [4]. Other shortcomings of US are the inaccuracies, crosstalk, and spurious readings that can appear [16].

Generally high frequencies are desirable for good spatial resolution when US systems are used; but, the highly sound-attenuating composite materials require low frequencies for good penetration. In these cases is used the technique called "Distance Amplitude Correction" or "DAC" and is integrated in every modern Ultrasonic device. It amplifies the signal even in the order of 1 (dB/mm), depending on the material [17].

The application of ultrasound in air is less developed than in other media such as liquids or solids [6].

Some applications need coupling materials to obtain adequate acoustic contact.

III. TIME OF FLIGHT (TOF)

The distance travelled by a sound wave is directly proportional to the time-of-flight (TOF).

The time between the sending of an ultrasonic signal by the transmitter (T) and receiving the signal by the receiver (R) of a T/R pair represents the time for sound to travel from the T/R pair to the target and, after it, back again to the T/R pair.

The sound wave travels from the transmitter to the target and then is reflected back an equal distance to the receiver, so the distance between T/R unit and target can be computed as the speed of sound's time-of-flight (TOF) divided by 2 [9].

After receiving the reflected pulses, Δt is calculated and the distance of the object can be found, using (1):

$$\Delta t = tR - tT \quad (1)$$

where tR is the received time of US wave and tT is the transmission time.

The distance d between the US sensor and target is proportional to the time Δt (TOF). The distance is calculated, using (2):

$$d = (c \times \Delta t) / 2 \quad (2)$$

where c is the sound velocity [18].

IV. Domains Of Use Of US Sensors

The list of application fields where US sensors and US waves can be used is quite varied, like in the list that will follow. In this list will be presented just some examples, but in reality the number of them is much higher.

The use of US can be divided in different categories, like:

Ultrasonic sensor research: in [14] is presented the accuracy of the measured distance; it is dependent on the separation between the ultrasonic transmitter and receiver.

Automotive/safety: in [19] an advanced accident avoidance system for automobiles is presented, where the main objective of this project is to realize a collision avoiding system for automobiles and to provide security in bad weather.

Agriculture: in [20] is presented an ultrasonic system for weed detection in cereal crops, having separation between weed infested and non-infested areas up to 92.8% success.

Metallurgy and mechanical testing: in [21] is presented and thoroughly studied the micro-structural and mechanical behavior of the nitrogen alloyed type 316L austenitic stainless.

Medical: in [22] ultrasonic measurement of normal spleen size in infants and children in paediatria is described and is established a correlation of spleen size with age, height and weight.

Industry: in [23] are presented two approaches to ultrasonic measurements of temperature in aqueous solutions.

Material research: in [24] US is used for measurement of corrosion depth in exposed concrete to acidic environment.

Geographical: in [25] measurements of velocities and absorption of acoustic waves in minerals at elevated pressures and temperatures were realized to understand seismic information.

Food industry/veterinary: in [9] is presented pre-parturition restlessness in crated sows using ultrasonic measurement.

Mixed projects: in [15] is presented a localization system for Wireless Sensor Networks (WSN) based on ultrasonic (US) Time-of-Flight (ToF) measurements.

Robotics (movement) control: in [16] is presented a new method of obstacle avoidance for service robots in indoor environments.

V. Ultrasonic Sensor Description

The N.I. Starter Kit 2.0 uses an US sensor, which one's datasheet can be found in [26].

This sensor is called "PING))) Ultrasonic Distance Sensor", part number: #28015, made by Parallax.

This ultrasonic distance sensor provides precise, non-contact distance measurements from about 0.02 to 3 (m). It is very easy to connect to microcontrollers, requiring only one I/O pin.

The PING))) Ultrasonic Distance Sensor's features:

1) Range: 0.02 - 3 (m);
2) Burst indicator LED shows sensor activity;
3) Bidirectional TTL pulse interface on a single I/O pin can communicate with 5 (V) TTL or 3.3 (V) CMOS microcontrollers;
4) Input trigger: positive TTL pulse, 2×10^{-6} (s) min, 5×10^{-6} (s) typ;
5) Echo pulse: positive TTL pulse, 115×10^{-6} (s) minimum to $18{,}5\times10^{-3}$ (s) maximum.

The PING))) Ultrasonic Distance Sensor's key specifications:

1) Supply voltage: +5 (V);
2) Communication: Positive TTL pulse;
3) Package: 3-pin SIP, 0.1" spacing (ground, power, signal);
4) Operating temperature: 0 - 70 (°C);
5) Size: 22 (mm) x 46 (mm) x 16 (mm);
6) Weight: 9 (grams).

All of this specification data come from PING))) Ultrasonic Distance Sensor's manual.

The key features of this US sensor are:

1) provides precise, non-contact distance measurements within a 0.02 - 3 (m) range;
2) US measurements work in any lighting condition, making this a good choice to supplement infrared object detectors;
3) simple pulse in / pulse out communication requires just one I/O pin;
4) 3-pin header makes it easy to connect to a development board, directly or with an extension cable, hence no soldering required.

VI. Measurement Description

In this paper ultrasonic sensor measurement test is presented on different materials, using the NI Starter Kit 2.0's ultrasonic sensor, presented in Fig. 3. The used materials are: cardboard sheet, sheet glass, wood, sponge, sheet of plastic, expanded polystyrene, porous gum, metal sheet and fur.

These materials were placed at different distances from the US emitter-receiver pair, having 0° angle (perpendicular) of the incidental US wave, as shown in Fig. 4.a.; in the second measuring round the US wave's incidental angle was 45°, as shown in Fig. 4.b.

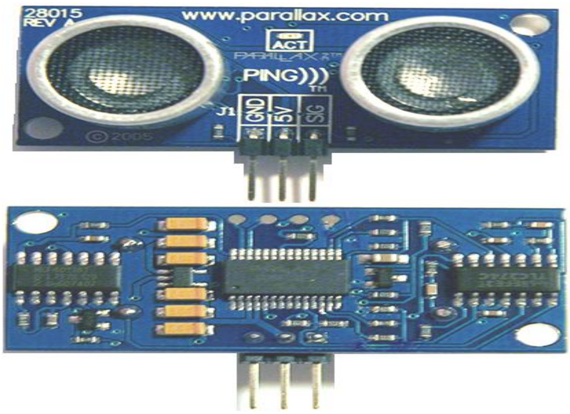

Fig. 3. PING))) Ultrasonic sensor front and back

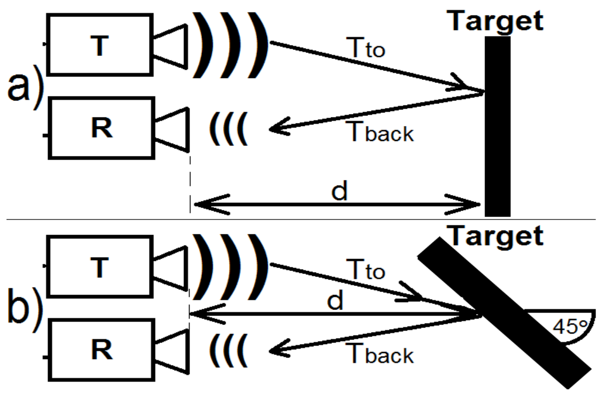

Fig. 4. a.: 0° angle of the incidental US wave
Fig. 4. b.: 45° angle of the incidental US wave

The tested materials were positioned at 0.035, 0.05, 0.1, 0.2, 0.35, 0.5, 0.75 and 1 (m) placed from the NI Starter Kit 2.0's US sensor.

The measurement was realized using N.I.'s LabVIEW program [27]. We are using the LabVIEW Robotics program, version 2012.

This application will realize continuous reading of the distance sensor mounted on the robot, using the "Read PING))) sensor" block and the results will be displayed on the front panel, using the "WaveForm Chart" block. The measured distance is between 0.02 and 1 (m).

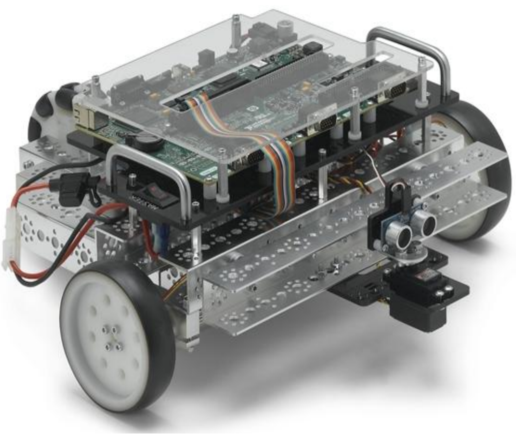

Fig. 5. The N.I. Starter Kit 2.0 robot (in front the PING))) US sensor) [28]

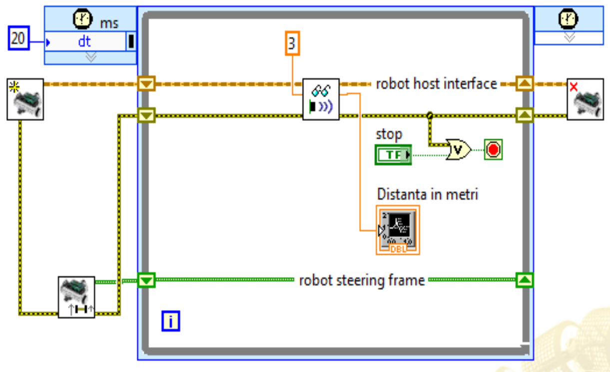

Fig. 6. The LabVIEW Robotics program realized for measuring the distance between the US sensor and the different target materials used in this article

The US sensor reading program will use the specific block for this sensor, namely the "Read PING))) sensor" block.

The distance is determined by measuring the return time of the wave transmitted by the sensor, as described its theory in the chapters before. The used block automatically converts the dates and forwards data directly in meters.

The waveform data is displayed using "WaveForm Chart" block, which generates continuously a graphic on the front panel of the program with the data obtained from the distance sensor.

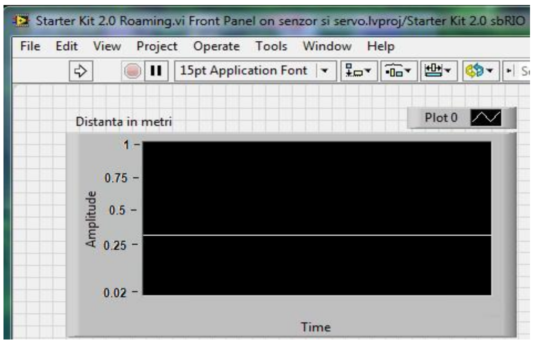

Fig. 7. Screen capture during distance measurement

As can be seen in TABLE I, in case of the sponge, fur and gum, the measured distance by the US sensor are not correct at little distances (between 0.035 - 0.35 (m) distance from the US sensor). These measured distances are bigger - in some situations almost double than the real distance, like in the case of sponge, where the real distance was 0.035 (m) and the measured distance was 0.070 (m), or in case of fur: the real distance was 0.035 (m), the measured distance was 0.066 (m). This measurement error does not appear in the case of other materials.

This problem is not present (or is not relevant) as the distance between these materials and US sensor grows - in case of sponge, fur and gum. The US sensor measures correctly the existing distances - only with little errors - for all the materials from 0.5 meter distance. By "little errors" we understand errors at +/- 10%.

In the case when the incidental ultrasonic wave is 45°, as shown in Fig. 4.b. and the measured distance is shown in TABLE II, the situation and the measured values are much changed, compared to the 0° incidental ultrasonic wave.

In TABLE II we can see that in a lot of places is written "-" instead of a measured value. This is because the distance measurement values were unclear - they were unstable. One reason can be that some materials were reflecting in 45° the incidental ultrasonic waves, and they were measuring in reality other distances than the distance between the tested materials and the PING))) ultrasonic sensor, like in Fig. 8. is drawn.

Other reasons can be that some materials from those used in this test - more specifically sponge and fur - are absorbing the US waves.

In the time of test some observations were made: the metal is a very good ultrasound reflector (it is like a mirror for the light); in the distance measuring errors were frequent (non stable distance values); the glass is like a mirror for the ultrasound, but it had little errors (relatively stable distance values); the cardboard is a worse reflector than metal or glass (probably absorbs a part of the signal's amplitude), but, even so, this property remains observable; the plastic sheet was a good reflector, better than cardboard, but worse than metal or glass sheet; the wood had reflecting properties too; the porous gum had big oscillations at measuring the distance; the expanded polystyrene was somehow mediocre - not the best reflector, but not the worst. These results were somehow predictable. The interesting part was with the sponge, because it absorbed all the ultrasonic wave.

TABLE I
MEASURED RESULTS AT 0° ANGLE OF THE INCIDENTAL ULTRASONIC WAVE

Distance measured (mm)	35×10^{-3} (m)	50×10^{-3} (m)	100×10^{-3} (m)	200×10^{-3} (m)	350×10^{-3} (m)	500×10^{-3} (m)	750×10^{-3} (m)	1000×10^{-3} (m)
Cardboard	37	55	104	198	348	496	741	990
Sheet glass	39	52	107	204	341	505	739	990
Wood	37	59	109	203	356	507	735	986
Sponge	70	98	162	260	370	530	850	1020
Plastic	38	59	111	205	355	500	745	985
Polystyrene	37	49	102	198	348	493	743	1003
Gum	41	60	108	200	353	498	755	990
Metal	37	59	110	200	353	492	748	990
Fur	66	83	130	230	377	540	790	1020

TABLE II
Measured Results At 45° Angle Of The Incidental Ultrasonic Wave

Distance measured (mm)	35×10^{-3} (m)	50×10^{-3} (m)	100×10^{-3} (m)	200×10^{-3} (m)	350×10^{-3} (m)	500×10^{-3} (m)	750×10^{-3} (m)	1000×10^{-3} (m)
Cardboard	41	330	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant
Sheet glass	59	160	450	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant
Wood	40	61	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant
Sponge	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant
Plastic	Every measurement's value was between 180 - 250 mm							
Polystyrene	55	60	110	198	340	492	790	1030
Gum	65	102	115	250	300	460	845	860
Metal	40	30	320	Irrelevant	Irrelevant	Irrelevant	Irrelevant	Irrelevant
Fur	Irrelevant	Irrelevant	Irrelevant	230	377	Irrelevant	Irrelevant	Irrelevant

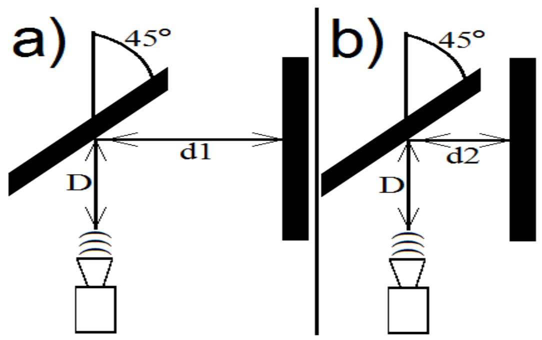

Fig. 8.a. and 8.b.: Ultrasonic distance measurement differences appear when the person who holds the materials stays closer or farther from the target

VII. CONCLUSIONS

This paper examines ultrasonic sensor and distance measurement using different materials at different distances, using the N.I. Starter Kit 2.0's US distance sensor. The real, measured values show that the US sensor is good and usable for indoor robotics sensorial input.

We assumed the temperature is 20 (°C), so the velocity of ultrasound in the air is 343 (m/s). The travel distance is very short so the travel time is little affected by temperature.

Autonomous mobile robots require many kinds and large numbers of sensors to measure the distance, velocity, and scale of objects for environment recognition.

As it can be seen in the tables resulting the measurements, US distance measuring was not always as slight like in Fig. 7. We had some materials where distance measuring was quite hard to realize.

The N.I. Starter Kit 2.0 robot with the presented US sensor will be used in the field of B.C.I. (Brain - Computer Interface), where it will be controlled by the user's brain activity (the user's will). As we can observe, in this case study, there will be needed to introduce some "emergency stop" functions/commands given by the user's brain, because simply leaving the robot to move around, using only the US sensor's measurements will not be enough safe - the unattended robot will hit something for sure in the time of long use.

An observation of ours is that US waves can be used in security applications, instead of laser / ultraviolet / infrared light. US waves can be used as a "sound barrier" - that means US can be used for counting persons or objects or for surveillance.

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