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ScienceDirect

Procedia Computer Science 35 (2014) 93 – 100

Procedia Computer Science

18th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems - KES2014

A surrounding world knowledge acquiring by using a low-cost ultrasound sensors

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Abstract

This article describes a bio-inspired method of identify the type of obstacles which could appear e.g. on the MAV's (Micro Air Vehicles) way. The method is based on measurements made by a low-cost ultrasonic sensor. This kind of sensors are widely used for a distance measurement. The bio-inspired method used by ultrasound sensors uses echo of ultrasound signal to collect the knowledge about the surrounding world. Bats, which use ultrasonic waves to navigate in the dark, were our source of inspiration. In our research we are focusing on the off-the-shelf sensors because of their wide availability. We have shown that we can determine not only the distance but also we can get the basic information about the surrounding space by using the measurement obtained from a simple ultrasonic sensor. Three types of obstacles (smooth surface, rugged or uneven surface, a multifaceted space) and distant space beyond the reach of measurement have been distinguished. All prepared obstacles have been identified properly in our experimental research. Additionally the proposed method can better determine the distance from the nonsmooth surface. A classic method for measuring such obstacles, for which a standard deviation is calculated may not be sufficiently credible due to too large error. In such situation, our analysis allows the use of distance measurement with much more confidence. Our method has been developed in order to support MAV navigation system based on distance measurements made by ultrasonic sensor.

Peer-review under responsibility of KES International.

Keywords: ultrasound sensor, distance measurements, obstacle avoidance system, quadrotors, micro air vehicle, MAV

1. Ultrasound distance measurement

Ultrasound sensors are widely used for a distance measurement. The bio-inspired method used by ultrasound sensors uses echo of ultrasound signal to collect the knowledge about surrounding world. The unrivaled examples of animals which utilize echo location method are dolphins and bats. Dolphins use the underwater ultrasound waves for navigation and communications while bats use ultrasound waves propagating in the air for navigation and ranging during their flight through a completely dark caves. Especially bats are interesting in our research because our quadrotors [1,2] reach similar to bats flight speed - 1 to 6 m/s [3] and also we try to develop autonomous indoor navigation system.

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Peer-review under responsibility of KES International.
doi:10.1016/j.procs.2014.08.088

Although the ultrasound signals utilized by bats differ from our signals, the algorithm of collecting the knowledge about surrounding world is similar. Most bat species utilize the wide-band chirp signal[4,5,6]. The bat emits a broad directional beam of multi FM modulated signals. Next it analyses the echo signals received back through (using) its ears. There are many echoes signals with different time delay and different frequency structure of the received signal. Analysis of echo delivers the information about distance to obstacle but also the information about wide of this obstacle and about surface. Using two ears bat can also recognize the direction of the echo. In our algorithm we try to utilize many consecutive narrow-band ultrasound signals generated by a Commercial Off-The-Shelf (COTS) sensors. Such approach is usefully/functionally similar to multi FM modulated signal. the rest of the algorithm is similar - captured echo signals are analyzed to find the distance and some characteristics of the reflecting surface.

Popularity of ultrasound sensors comes from rather simple mathematical model behind the ultrasound waves nature. The wave propagates with the speed c from the ultrasound transducer toward a reflecting surface and return back to transducer. Therefore it is enough to measure ToF (Time of Flight) - t_{of} - and using simple formula $d = ct_{of}/2$ the distance from reflecting object can be found.

There exist many SOANR (SOund NAvigation and Ranging) methods utilizing different ultrasound waves. Among them pulse-echo techniques[7,8] are widely-known, because of their simplicity. More complex methods involving the modulation of either amplitude or frequency of ultrasound waves also exist[9,10]. Many of these sophisticated methods exist only in laboratories.

COTS robotic ultrasound sensors usually utilize piezoelectric transducers and embedded microprocessor, which usually convert ToF measurements to a PWM (Pulse Width Modulation) signal. Master processor orders the start of the measure, than embedded microprocessor generates short ultrasound burst signal at constant frequency about 40 kHz and in parallel it starts the a PWM pulse (i.e. changes the output pin to “one”). After detecting the echo signal embedded processor finishes the the PWM pulse (sets “zero” on the output pin). Besides the simplicity of this method there is a problem with decision which one echo should be picked up. Received echo can be very complex signal to analyze. In fact, it can contain many echoes with different amplitude, shifted in frequency and/or shifted in time. Moreover the way of determine of the ToF of the echo signal remains usually unpublished. Thus it is sometimes hard to discover the real source of the errors in distance measurements.

Also several acoustic conditions can affect the ToF measurement. First of all the speed of sound c in the air highly depends on temperature of the air. The $c(T)$ can approximated by the following equation[11]:

$$c(T) = 331.3 + 0.606 * T \tag{1}$$

where $c(T)$ is a sound speed in the air in m/s and T is temperature measured in °C. Second aspect is the variation of attenuation of sound as a function of both frequency and humidity. Albeit attenuation usually affects maximum target distance, but in some cases it can causes a refraction which changes the way through the waves propagate. Thus the third factor affecting ToF measurements is a multi-path propagation of the sound. In some cases indirect reflection can be treated as a direct echo signal thus sensor returns wrong range information. All of these problems have their reflectivity in accuracy and resolution of measurements.

Our researches are focused not only on the distance measurements but also on the knowledge acquiring. We are working on possibility of determining type of obstacle which is placed in front of the sensor. Some work has been done in this area but usual configuration utilizes many sensors placed around robot body[12,13,14]. In out research we try to pick up as many information as possible from only one ultrasound sensor.

2. Radiation pattern of an ultrasonic sensors

The radiation pattern or beam pattern is sensitivity of transducer as a function of spatial angle. The beam pattern depends on the size and shape of piezoelectric surface which vibrates with ultrasonic frequency. Low-cost sensors utilize circular radiation surface with the diameter equals 2Λ, where Λ is a wavelength of a 40 kHz wave. In this case the main beam angle equals approximately $BW = 30°$ what is relatively a wide beam. The beam pattern can be seen as a cone in the space in front of sensor, where the top of the cone is the sensor and the bottom of the cone is placed on the reflecting surface and forms the circle on it, with the diameter d depending on the distance l. For a given beam pattern and a given distance the diameter can be found by:

$$d = 2l \tan\alpha \tag{2}$$

where α is half of BW. Thus a long distance measurement can easily be affected by more than one target which is placed ±15° from the transducer perpendicular. There are also many side lobes, so even more reflecting targets placed on much bigger angle can be detected as an object in front of sensor. The beam widths for several measured ranges are presented in Table 1. One can observe that the longer measured range is the bigger beam-width is. Therefore the probability of reflection from more than one target increases. For this reason most COTS ultrasound sensors are used in short range application.

Table 1. Beam width and standard deviation as a function of the target range for HC SR04.

Distance cm	20.0	30.0	40.0	50.0	75.0	100.0	200.0	300.0	400.0
Diameter of the beam cm	10.7	16.1	21.4	26.8	40.2	53.6	107.2	160.8	214.4
Standard deviation cm	0.2	0.2	0.2	0.2	0.3	0.5	0.6	0.8	0.9
Relative error %	1.0	0.7	0.5	0.3	0.3	0.5	0.3	0.3	0.2

The Table 1 presents the ultrasound beam width for HC SR04 sensor, calculated with beam pattern $BP = 30°$ taken from sensor datasheet. For the given pattern we calculate the diameter (on the target surface) of the cone created by radiation pattern. Also standard deviation of the measurement was presented. During calculation of standard deviation the experiment with big enough blackboard was provided. The calculations base on statistically significant 7200 measurement done in stable condition for each of the distance presented in the Table 1. Each new echo impulse was generated with frequency 40 Hz (according to sensor datasheet). Standard deviation of the measurement for a short range is about ±2 mm while for the maximum range (4 m) it is less than ±1 cm.

It is worth note, that for quadrotors [1,2], where ultrasound sensors are mounted close to the center of quadrotors, the measured range less than 40 cm means that quadrotor almost touches the target with its propellers. Taking the turbulences caused by object which is so close to quadrotor into account it is clear that such situation is extremely dangerous. Therefore we assumed that minimal safe distance is 50 cm to avoid the influence of the turbulence on MAV stability.

2.1. Rugged or bumpy reflective surface

For the smooth surface which reflects ultrasound beam the relative error in distance measure is less than 0.5%, but for the rugged or bumpy surface one can observe bigger relative error. It is normal situation if one takes into account the beam pattern. The beam which attends such surface can encircle many furrows and each of them can reflect ultrasound wave. Thus, it is very hard to point out which one of these furrows was measured by the sensor. In such situation sensor chooses random echo signal and one can notice random distance values or it would be better to say bigger relative error in measurements. It is probably because a microprocessor embedded on the sensor calculates the energy of each echo signal and chooses not the first one impinging the sensor but rather that one with the biggest energy. So if these energies are nearly equal than one observes bigger relative error.

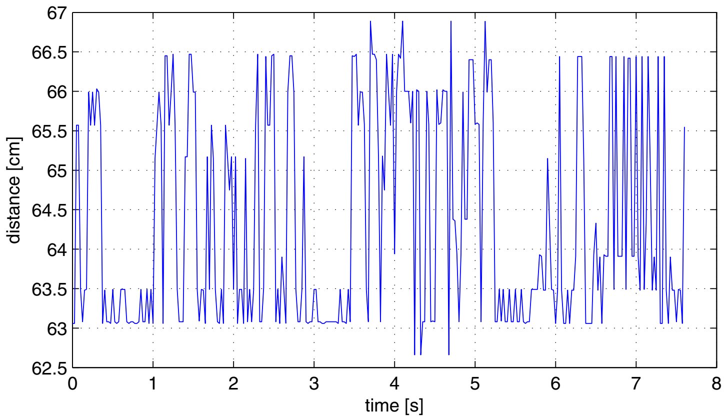

Fig. 1. The results of measurements of the distance to a rugged surface, with the maximum furrow about 30[mm].

In Figure 1 the results of measurement of rugged surface are presented. The furrows on the surface have maximum amplitude about 30 mm. In this case the mean value is 64.3 cm with standard deviation about 1.3 cm. But it is non-precise information for MAV navigation system, because in fact some furrows occur in distance less than 63 cm while other in distance more than 66 cm. Therefore it would be better for MAV navigation system to get the knowledge that the closest object is in distance 62.7 cm and reflecting target has the rugged surface.

2.2. Two or more targets in a far distance

If the reflective surface is rather smooth and MAV is positioned in a relatively far distance an ultrasound sensor measures the distance with some level of uncertainty - according to the Table 1. Thus in case of a situation presented in Figure 2 measurements should be easy to interpret. As an opposite the situation presented in Figure 3 is not so easy to handle because a sensor would randomly pick up one of three (or even more) echoes. It is because of the beam pattern. For long distance more targets can be covered by the ultrasound beam and all of them can produce the echo signal. In this case median nor other filtering algorithm would lost and can produce completely wrong results.

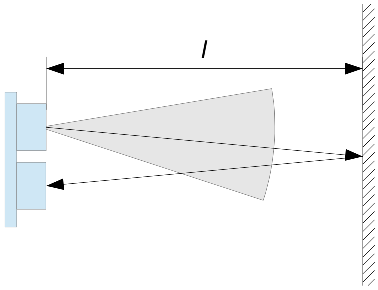

Fig. 2. Ultrasound distance measurement in case of only one reflecting surface.

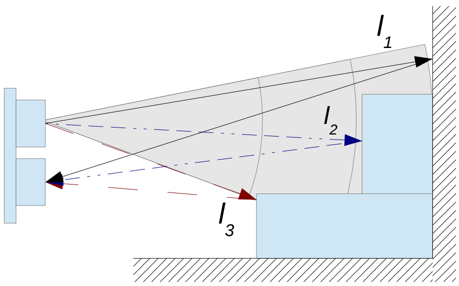

Fig. 3. Ultrasound distance measurement in case of three reflecting targets. Because of sensor radiation pattern the beam can cover many object and all of them reflect ultrasound call.

3. The proposed algorithm of knowledge acquiring

During analysis of echo signals incoming from different obstacles one can intuitively see that there exists an information about surface which reflects the ultrasounds. This information is hidden in kind of similarity between consecutive measurements of the time delay of echo signals. Therefore, based on this discover, we propose algorithm of knowledge acquiring. It means that we propose algorithm which is capable of determining the type of obstacle (TOB). Three types of obstacles and the case with no obstacle have been distinguished as well:

- smooth surface,
- rugged or uneven surface,

- multifaceted space or cavity for example, a hole or an edge,
- distant space beyond the reach of measurement.

Recognizing of these obstacles have been done in two steps. In the first step the measurements have been compared to each other i.e the similarity index have been calculated based on the previous measurements. In the second step the type of obstacle have been determined based on the fuzzy logic inference. The average value of similarity indicators calculated for 20 or 200 measurement samples have became the input variables of fuzzy inference algorithm.

For a given set of measurements $\mathbf{x}(k) = [x(0), x(1), \dots, x(K)]$ we calculate as many as possible similarity indexes according to the following formula:

$$S_N(n) = \frac{1}{N} \sum_{i=n-N}^{n-1} \frac{Ax(n)}{Ax(n) + (x(i) - x(n))^2}, \quad \text{where } \; n = [N, \dots, K]. \tag{3}$$

The $S_N(n) \in < 0, 1 >$ is an intermeasure similarity index, where 1 means full of similarities, 0 no similarity at all. The N is a number of measurements taken into account, thus for different values of N one can calculate short or long term similarity index. A is a priory known accuracy of the measurements $x(k)$.

To achieve better performance of proposed method we calculate the average similarity index as follows:

$$E_N = \frac{1}{K - N} \sum_{n=N}^{K} S_N(n) \tag{4}$$

Based on the the short term E_{20} and long term E_{200} average similarity index the knowledge acquiring algorithm is proposed. First the E_{20} and E_{200} are transformed to fuzzy variables values as follows:

- ESM - small,
- EMM - medium,
- EBG - big.

Also, the four fuzzy variables was defined for TOB:

- TSS - smooth,
- TRG - rugged,
- TML - multifaceted,
- TDS - distant.

For the average similarity values ESM, EMM, EBG and for TOB values TSS, TRG, TML, TDS trapezoidal or triangular membership functions with parameters (a, b, c, d) are defined as follows:

$$\mu_i(x; a, b, c, d) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a < b \wedge a < x < b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & c < d \wedge c < x < d \\ 0 & x \ge d \end{cases} \tag{5}$$

where $i \in [ESM, EMM, EBG]$ or $i \in [TSS, TRG, TML, TDS]$. Note that depending on parameters (a, b, c, d) the trapezoidal or triangular membership function can be obtained. The membership function parameters are shown in Table 2.

The set of fuzzy rules allowing us to determining the type of obstacle (TOB) is as follows:

- smooth surface:
  IF E_{20} == EBG **AND** E_{200} == EBG **THEN** TOB=TSS
- rugged or uneven surface:
  IF (E_{20} == ESM **AND** E_{200} == EMM) **OR** (E_{20} == ESM **AND** E_{200} == EBG) **OR** (E_{20} == EMM **AND** E_{200} == EBG) **THEN** TOB=TRF

Table 2. The parameters of the membership function.

	E_{20}			E_{200}			TOB			
μ_i	ESM	EMM	EBG	ESM	EMM	EBG	TDS	TML	TRG	TSS
a	0.00	0.38	0.85	0.00	0.35	0.60	0.00	0.00	0.33	0.66
b	0.00	0.50	1.00	0.00	0.45	0.80	0.00	0.33	0.66	1.00
c	0.38	0.85	1.00	0.35	0.60	1.00	0.00	0.33	0.66	1.00
d	0.50	1.00	1.00	0.45	0.80	1.00	0.33	0.66	1.00	1.00

- multifaceted surface or cavity (i.e. a hole or an edge):
  IF (E_{20} == EMM **OR** EBG) **AND** E_{200} == ESM **OR** EMM) **THEN** TOB=TML
- a distant space in front of the sensor or surface/object beyond the range of the sensor:
  IF E_{20} == ESM **AND** E_{200} == ESM **THEN** TOB=TDS

For better understanding the above rules can be summarized in a table form (look at the Table 3). The upper row represents fuzzy values of E_{20}, the left column represents fuzzy values of E_{200}, while the middle of the table represents inferred type of obstacle. In order to determine the solution based on the inference the method of a middle of maximum (MoM) was used.

Table 3. Inferring type of obstacle bases on the fuzzy rules.

$E_{200} \backslash E_{20}$	ESM	EMM	EBG
ESM	TSS	TML	TML
EMM	TRF	TML	TML
EBG	TRF	TRF	TDS

In spite of simplicity of proposed rules the knowledge about the object in front of ultrasound sensor can be acquiring. Thus ultrasound sensors can be used for both measuring the distance and for determining the TOB. The shortest measured distance should be taken as a distance to the closest object for the security reason, while TOB knowledge can be useful in autonomous navigation tasks or in simultaneous localization and mapping (SLAM) algorithms.

4. Experiment with real ultrasound measurement

In the previous section (Section 3) the proposition of the knowledge acquiring algorithm was presented. Based on the set of measurement the short and long therm average similarity estimators can easily be calculated (4). Using these estimators and set of fuzzy rules (Table 3) the knowledge about a type of obstacle in front of a sensor can be inferred. The results produced by proposed algorithm are presented bellow.

Table 4. TOB classification for a big smooth surface.

	smooth surface								
D [cm]	20	30	40	50	75	100	200	300	400
A [cm]	0.2	0.2	0.2	0.3	0.3	0.5	0.6	0.8	0.9
E_{20}	0.9842	0.9893	0.9940	0.9975	0.9949	0.9912	0.9942	0.9957	0.9956
E_{200}	0.9829	0.9846	0.9928	0.9960	0.9944	0.9910	0.9942	0.9956	0.9952
MoM	1	1	1	1	1	1	1	1	1
TOB	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS

In Table 4 the big blackboard was standing in front of the sensor. The distance D has been changed from 20 to 400 cm. The value of a priori known accuracy A was set according to datasheet of the sensor. As can be seen both similarity estimators E_{20} and E_{200} are close to 1. The fuzzy inferring algorithm returns MoM equal 1, which let us classify TOB as a smooth surface TSS.

In Table 5 different objects were standing in front of the sensor. The first column - called *150/200* - presents results for two blackboards standing in the distance 150 and 200 cm respectively. The frame of a closer board was placed in perpendicular to sensor, thus the sensor can notice echoes from both blackboards. The proposed algorithm classifies such situation as TML, which means “multifaceted surface”. At the same time our algorithm measures the distance

Table 5. TOB classification for a different type of object.

	150/200	*RBS*	*SqWall*	*OS*	*ChrsF*	*ChrsC*
A [cm]	0.5	0.3	0.3	1	0.7	0.5
E_{20}	0.6117	0.8844	0.6680	0.3693	0.4874	0.5507
E_{200}	0.5138	0.8699	0.4677	0.3624	0.4063	0.4816
MoM	0.33	0.66	0.33	0.02	0.33	0.33
TOB	TML	TRF	TML	TDS	TML	TML
D_c [cm]	149	63	209	7.6	165	90

to the closest object D_c = 149 cm properly. Similar situation is presented in column *SqWall*. The sensor was placed in front of square of two walls and there was a wardrobe next to the wall, so the sensor has "seen" three echoes (look at the Figure 4). The closest object - the edge of the wardrobe - was placed 210 cm from the sensor and the angle between sensor perpendicular and this edge was about 45°. So it is clear that even object placed on a big angle can reflect ultrasound signal if this object is close enough to sensor in compare to other object placed in front of the sensor. In this case the proposed algorithm classifies the object as multifaceted (TML) properly.

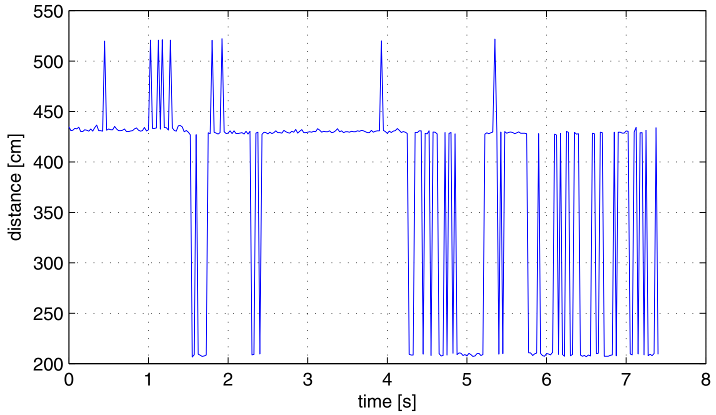

Fig. 4. The raw measurements of the distance to a square of two walls with a wardrobe next to the square.

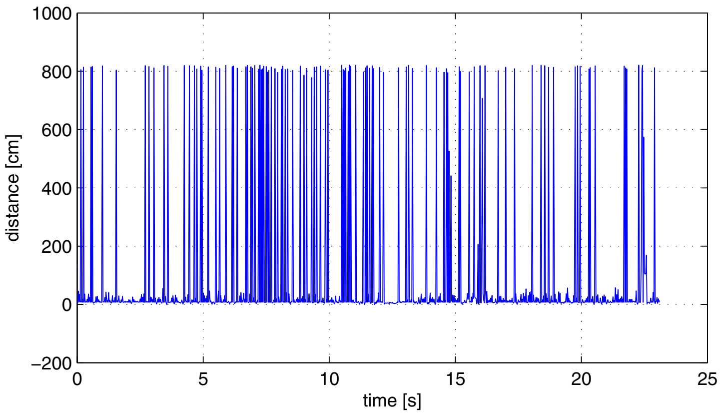

Fig. 5. The raw measurements of the range in case of no obstacles in front of the sensor.

Our algorithm has determined the object type TML also in case when the sensor was directed on the legs of the chairs. There ware many chairs in front of sensor and regardless of a distance the proposed algorithm has classified properly this situation - look at the column *ChrsF* and *ChrsC*. It is important to note that a rugged object TRF - in our case it was a chopped wood laying randomly on a floor - can be easily differentiated from TML as it is shown in the Table 5 in column *RBS*.

The interesting case was observed when we measured an "open space" - it means that in front of the sensor there were no objects - look at the column *OS*. In Figure 5 the result of measurements in case of such situation is presented. As can be seen the sensor randomly has measured values close to 7 mm or close to 8 m. The 8 m values are resulted from the maximum time of waiting for the echo signal, therefore in case of lack of echo the sensor finishes the output signal in arbitrary time. The values about 7 mm are resulted probably from the fact that sensor receives, very low in amplitude, echo signal from the back of the sensor, where microprocessor hardware was placed. It should be noted that TDS is easily distinguished from other situations.

5. Conclusions

The new knowledge acquiring algorithm is presented in this paper. It is shown that using COTS ultrasound sensor it is possible to determine the distance to the closest object laying in front of the sensor and simultaneously to determine the type of the surface which reflects the ultrasound wave. The knowledge collected in these ways can be useful to develop an autonomous navigation system of quadrotor which is similar to bats navigation system. Of course bats can acquire more knowledge about their environment mainly due to the different type of ultrasound wave. A bat generates wide band chirp signal[4,5,6]. Moreover each generated call is unique therefore a bat can pick up its own call in many other calls generated by other bats. Also because of uniqueness of each call a bat can generate next call without waiting for echo and still it is able to pick up an echo and to guess which one call causes this particular echo thus it can determine the distance. In opposite a COTS sensor generates simple bunch of square shaped impulses and every bunch is identical. Thus, it is not possible to differentiate between consecutive bunches and the sensor has to wait relatively long time for echo before it generates next call. Also it would cause several problems in cases of many sensor working in the same space. Our future work will focus on developing ultrasound sensor which utilize signals similar to signals generated by bats i.e. chirp signal with coded modulation, which should let us differentiate consecutive calls as well as other sensor working in the same space.

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