A new Approach for Pedestrian Detection in Vehicles by Ultrasonic Signal Analysis

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Abstract— **This paper introduces a new approach for pedestrian detection by means of a sophisticated analysis of ultrasonic signals. The main objective is to enable driver assistance systems in vehicles to recognize whether an obstacle in front is a pedestrian or a car. In case of a likely collision the sensor allows to activate pedestrian protection systems in an early stage. The sensor evaluates ultrasonic signals backscattered from the obstacle by task specific signal analysis methods. It consists of an ultrasonic transducer, an embedded system for transducer control and signal acquisition as well as a computer for signal analysis and feature extraction. Unlike Radar systems this pedestrian detection approach is also able to detect non-moving persons and even children.**

Keywords— Signal Analysis, Pedestrian Detection, Pedestrian Protection, Ultrasonic Sensors, Automotive Sensors

I. Introduction

The detection of pedestrians is one of the most challenging tasks to be solved by autonomous vehicles driving within urban areas. If a car is likely to collide with a pedestrian systems to protect the person must be activated. Contrariwise, in case of a likely accident with another car or a wall systems to protect the passengers need to be activated. Current sensors used in collision avoidance systems such as radar just detect obstacles rather than differentiating for the radar cross section is not specific enough [1].

Another approach is to deduce the type of an object from the impact energy. A person will deliver less energy than a car during a crash. The disadvantage is that the pedestrian has already been hurt when protection measures are triggered for the collision has happened upon pedestrian detection.

Computer vision using pattern recognition approaches for object differentiation can detect pedestrians [2]. However, comparing various methods resulted in a miss rate of at least 20%. Among others, reasons for low performance are occlusions. The miss rate gets worse for small people such as children [3]. Additionally, images become unrecognizable due to droplets in the case of rain. The detection of persons by means of vision systems at night or befogged is extremely difficult. A system described in [4] calculates speed and size of objects via radar and camera by means of evaluating images sequences. However, lots of scenarios exist such as overlapping objects which can result in unusual sizes or movements. Also, a differentiation is not possible if objects have the dimensions of people or people do not move.

To overcome these disadvantages of existing systems a new pedestrian detection sensor based on ultrasonic signals is proposed. For it consists of an ultrasonic sensor and an embedded systems its costs are much lower compared to other solutions such as computer vision.

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II. Reflection of Ultrasonic Waves on Rough Surfaces

According to the theory of wave propagation the ultrasonic wave is reflected as it illuminates materials whose acoustic impedance differs from air [5]. If the surface is abrasive with respect to the wavelength then the wave is not only reflected but also scattered and backscattered. The reflected and backscattered parts of the wave interfere so that the shape and the abrasiveness of the surface are modeled onto the wave. This process is resulting in a signal which not only differs significantly from the original signal that has been sent during the burst but also carries the information about the properties of the reflection surface.

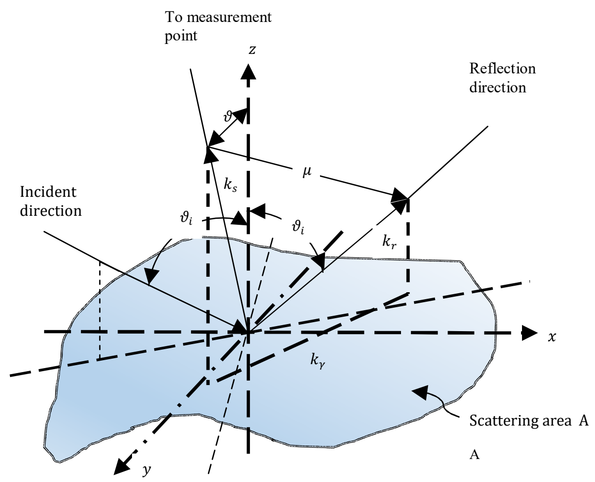

Fig. 1: Ultrasonic wave illuminating a rough surface

A mono-acoustic wave $p(\vec{r})$ at location $\vec{r}$ in a scattering area as shown in "Fig. 1" can be modelled according to the Helmholtz equation [5]

$$(\nabla^2 + k^2)p(\vec{r}) = -L(p(\vec{r})) \qquad (1)$$

where

∇^2 is the Laplacian operator,

k is the wave number (k = ω / c),

c is the speed of sound,

ω is the angular frequency of the acoustic wave and

$L(p(\vec{r}))$ contains the variations in medium compressibility as well as density and therefore the roughness which causes scattering.

The solution of the Helmholtz equation by means of Greens's function is:

$$p(\vec{r}) = \int_V L(p(\vec{r}'))\frac{e^{jk|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}d^3\vec{r}' \quad (2)$$

where V is the scattering volume, i.e. the volume of space where the operator L is nonzero.

Assuming $\vec{r} \gg \vec{r}'$ and introducing the scattering vector

$$\vec{K} = k(\vec{\imath} - \vec{o}) \quad (3)$$

with

$\vec{\imath}$ is the unit vector of incident direction and

$\vec{o}$ is the unit vector of observer (measurement) direction.

we can neglect $\vec{r}'$ in the denominator and approximate the nominator as:

$$p(\vec{K}, r) = \int_V L(p(\vec{r}'))\frac{e^{jkr}e^{\vec{K}\vec{r}'}}{4\pi r}d^3\vec{r}' \quad (4)$$

$$p(\vec{K}, r) = \frac{e^{jkr}}{4\pi r}\int_V L(p(\vec{r}'))\, e^{\vec{K}\vec{r}'}d^3\vec{r}' \quad (5)$$

with

r = $|\vec{r}|$

In case of pulse as incident wave consisting of multiple frequencies equation (5) represents a Fourier Transformation in $\vec{K}$ - space:

$$p(\vec{K}, r) = \frac{e^{jkr}}{4\pi r}\, F_{\vec{K}}\{L(p(\vec{r}'))\} \quad (6)$$

For the pressure $p(\vec{K}, r)$ in $\vec{K}$ - space at distance r from scatter volume is linked with the term $L(p(\vec{r}))$ by the Fourier Transformation, it represents the roughness of the scatter volume, i.e. the roughness of the surface.

If the scattering volume is a statistically isotropic medium we can replace $\vec{K}$ by K:

$$p(K, r) = \frac{e^{jkr}}{4\pi r}\, F_K\{L(p(r'))\} \quad (7)$$

In case of the backscattered signal, we get

$$K = 2k. \quad (8)$$

Hence, we can write (7) as

$$p(2k, r) = \frac{e^{jkr}}{4\pi r}\, F_k\{L(p(r'))\} \quad (9)$$

Replacing the wave number by the frequency f of the received ultrasonic signal, we get

$$p(4\pi f/c, r) = \frac{e^{jkr}}{4\pi r}\, F_K\{L(p(r'))\} \quad (10)$$

The practical conclusion of (10) is that the roughness of the surface is modulated onto the reflected and backscattered ultrasonic wave.

Supposed we have a surface consisting of multiple point scatterers spaced in a distance Δr, then the roughness can be modelled as the sum Dirac impulses:

$$L(p(r')) = \sum_{n=-\infty}^{\infty}\delta(r - n\Delta r') \quad (11)$$

Fourier Transformation yields

$$F_k\{L(p(r'))\} = \sum_{n=-\infty}^{\infty}\delta(k - m\, 2\pi/\Delta r) \quad (12)$$

For Dirac impulse is uneven 0 only for

$$k - m\frac{2\pi}{\Delta r} = 0 \quad (13)$$

or

$$4\pi f/c - m\frac{2\pi}{\Delta r} = 0 \quad (14)$$

we get maxima in the frequency spectrum of the backscattered signal at frequencies

$$f = \frac{m\, c}{2\Delta r} \quad (15)$$

The number m = 1, 2, ... denotes the index of a maximum. A surface consisting of point scatterers modifies the frequency spectrum of an incident acoustic wave such that maxima are generated. However, in case of arbitrary scatterer distribution clear extrema will not be present in all cases. However, we can expect the surface characteristics having an impact on the frequency spectra.

The conclusion of (10) is that the roughness of the surface is modulated onto the backscattered ultrasonic wave. Hence, using pulsed waves the location of objects can be calculated by time of flight as well as the object type by analyzing the frequency spectrum of the received signal.

III. Pedestrian Detection Sensor

A first feasibility study resulted in a working model [6] confirming basically that an analysis of the backscattered signal basically has the potential to distinguish pedestrians from cars and other obstacles.

In the current phase of research we aim at a deeper analysis of discriminatory features and at the integration of components in order to develop a sensor for pedestrian detection. It consisting of the 3 parts:

1.) Ultrasonic Sensor SRF02 with a mean frequency of 40 kHz and a power output of 150 mW (manufacturer's data) for sensing.

2.) Embedded System Red Pitaya with a sampling frequency of 1.95 MS/s and a resolution of 14 bit for controlling the SRF02 and for analog digital conversion of the received signal.

3.) Laptop with data analysis software programmed in LabVIEW.

For a measurement the Red Pitaya system ("Fig. 2") sends control data via I2C interface to the sonar sensor SRF02, ("Fig. 3") in order to trigger the emission of an ultrasonic pulse. An analog digital conversion input of the Red Pitaya is connected to the signal the sensor receives and digitizes it.

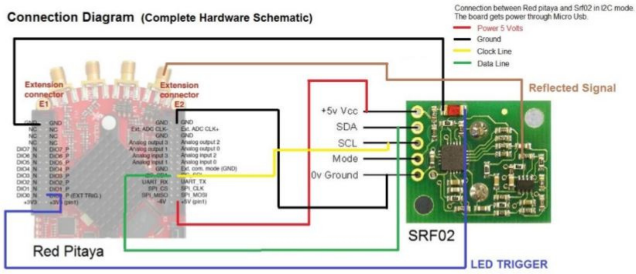

Fig. 2: Interface between Embedded System and Sensor

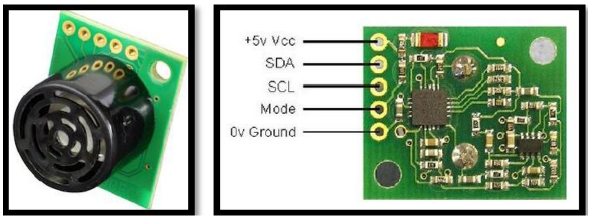

Fig. 3: Sonar Sensor SRF02

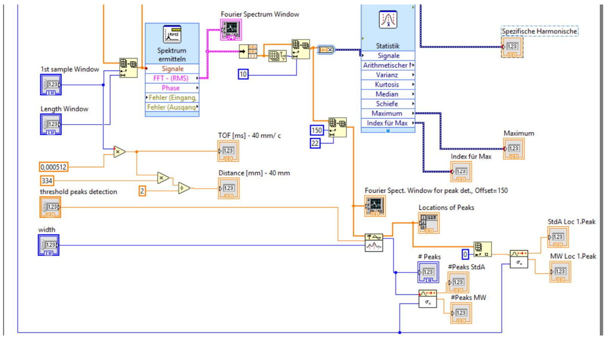

Fig. 4: Excerpt of Feature Extraction Program

Next, the sampled signal is sent via WLAN to a laptop for signal analysis.

The software ("Fig. 4") is written as a state machine consisting of the states Initialization, Data Acquisition, Echo Detection and Distance Calculation as well as Feature Extraction from the original signal.

Features are taken from the Fourier domain as well as from the time domain. The latter is based on the fact that frequency spectra and shape of signals depend on each other. The FFT – window has a width of 8192 samples using a Hanning filter. We do not extract features that are energy dependent such as the acoustic backscatter cross section for energy can depend on the angle of incidence. For instance, an echo received from a human illuminated by an angle of incidence of 0° (related to the perpendicular line to the surface) could have a higher backscatter cross section than that of a human illuminated by 90°.

In order to avoid errors by echo detection algorithm windowing the sample area of the echo is done manually up to now. Simultaneously we develop robust echo detection approaches.

The object distance is calculated from time of flight related to begin of the echo signal using speed of sound at 20° which is 343 m/sec.

The multivariate probability distribution of the features depends on the distance of the objects to the sensor, because the area that is illuminated by the ultrasonic beam grows with the distance to the sensor. Therefore the distance range of the sensor has to be divided into sections.

IV. Using Ultrasonic Signals for Pedestrian Detection

We assume that the structure of surfaces of pedestrians, cars, walls, poles, trees, and other obstacles are different and this is modulated on the backscattered signal independent. In first experiments to proof this assumption we collected ultrasonic data from 20 measurements of a human and 20 of a car part (rear bumper) at a distance of 40 cm. Angle of incidence has been change randomly between -25° and +25°.

As the surface characteristics contribute to the received signal and the contributions are frequency dependent it is obvious that the measured signals contain information about the surface structure. Compared to the test wave sent by the transmitter changes in the frequency spectrum of the received ultrasonic signal can be observed.

Samples of our measurements are shown in "Fig. 5" and "Fig. 6", respectively. Whereas the rear bumper of the car has a relatively smooth spectrum with an almost Gaussian shape and a maximum shifted to the left, pedestrians generate a spectrum with lots of peaks unlike a Gaussian distribution.

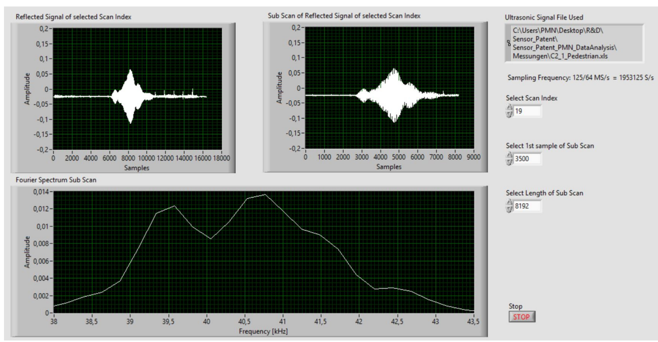

Fig. 5: Frequency spectrum of a pedestrian

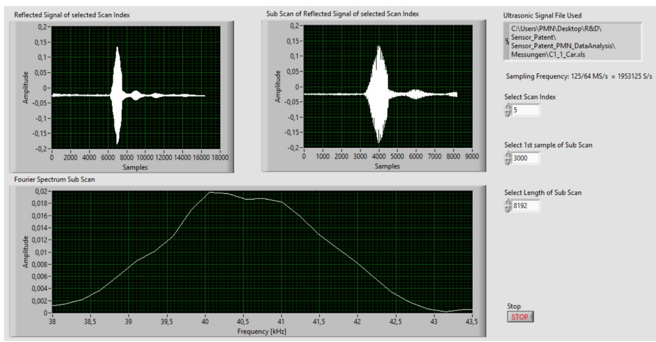

Fig. 6: Frequency spectrum of a rear bumper

TABLE I. MEAN AND VARIANCE OF THREE FEATURES

Feature		Car	Pedestrian
SINAD [dB]	mean	-0.24	0.01
	variance	0.0004	0.18
Location of first peak	mean	8.8	5.65
	variance	0.0004	3.57
Number of peaks	mean	1.4	3.1
	variance	0.24	0.69

For a first analysis we used the features SINAD, location of first peak and number of peaks as listed in Table I. SINAD results from the signal in time domain and is calculated in dB by the ratio of signal energy over signal energy minus fundamental frequency energy. The feature number of peaks is the sum of all peaks in the frequency range from 38 kHz to 43.5 kHz of the Fourier spectrum. The location of the first peak relates to the tick marks in this frequency range. Tick mark 0 is at 38 kHz, tick mark 1 at 38.2533 kHz, tick mark 2 at 38.5066 kHz and so on. The tick spacing is 0.255 kHz for the sampling frequency is 1.95 Mhz and the Fourier window has a length of 8192 samples. Hence, a frequency of 40 kHz is located at tick mark 8.

The discrimination strength of the features have been measured by the discrimination quality of features

$$Q(x,y) = \frac{(\mu_x - \mu_y)^2}{{s_x}^2 + {s_y}^2} \tag{16}$$

where μ_x and μ_y denote the mean values of a feature from object x and y, respectively. ${s_x}^2$ and ${s_y}^2$ denote the variances. Based on the data of table 1 we get discrimination qualities as follows:

Feature SINAD: $Q = 1.9$

Feature Location of 1st peak: $Q = 2.78$

Feature Number of peaks: $Q = 3.1$

All discrimination qualities are larger than 1 which suggests all three features being suitable for object differentiation. Especially the features location of first peak and number of peaks can contribute significantly to distinguish between pedestrians and car parts.

The spectra of car parts in average have 1.4 peaks and the first peak at location 8.8 which corresponds to a frequency of 40.24 kHz. The low number of peaks and a peak frequency close to the fundamental frequency of 40 kHz suggests that the surface of the scanned car parts are smooth which matches the properties of the parts used.

The spectra of pedestrians show 3.1 peaks in average and a first peak at 39.44 kHz which is well below the fundamental frequency. Our interpretation is that the rough surface of humans and their cloths cause scatter resulting in spectra peaks due to interferences.

V. FUTURE WORK

A thorough analysis and interpretation of spectra shapes still has to be done. By means of a corrected spectrum, i.e. by dividing the spectrum of the backscattered signal by the spectrum of the emitted spectrum, we expect to derive how the location of the peaks correlate with the roughness of object's surfaces more exactly. Additionally, future work will focus on the development of a robust echo detection algorithm, of additional features, and of sophisticated classifiers combined with machine learning approaches. In the next step we will integrate all components into a unit that can be mounted at cars.

VI. CONCLUSION

The analysis of the signals backscattered from humans and car parts show clear differences in the frequency spectra. These differences can be related to the surface of the objects. These results suggest that a differentiation between humans and hard objects by sophisticated processing of ultrasonic signals is possible.

Given that many modern cars are equipped with ultrasonic sensors the method described in this paper could provide cars with an affordable pedestrian detection and protection system. This is a huge advantage for smaller cars because alternatives such as vision systems, RADAR and LIDAR are expensive. As for more expensive cars, a fusion with computer vision systems and other sensors could improve detection rates.

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