VEHICULAR ACOUSTIC DOPPLER VELOCIMETRY BASED ON RECONFIGURABLE ANALOG AND DIGITAL DESIGN
THEORETICAL APPROACH AND REVIEW

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ABSTRACT

Velocities of vehicles in slow movement are difficult to be determined because of noise and technological limitations. The paper introduces a novel method for estimating velocities that can be implemented in vehicles at low speeds. For ADV (Acoustic Doppler Velocimetry) a couple of ultrasonic transducers are used. The paper presents a review about ADV (or Ultrasonic Ground Speed Sensor) and a theoretical approach method that consists of using ultrasonic velocimetry based on Doppler effect. The solution takes advantage of reconfigurability to prepare the analog signal on FPAA (Field Programmable Analog Array) and process the IF (Instantaneous Frequency) by DSP (digital signal processing) on FPGA (Field Programmable Gate Array).

1. INTRODUCTION

The purpose of this article is the feasibility study of a method to estimate with high accuracy of real time velocity of vehicles. This work falls within the framework of a project aiming to create a precise pose determination solution for mobile robots and vehicles. For a complete pose determination solution, a good estimation of the velocity is needed. There are obviously various techniques for measuring the speed, but most of them are either costly or imprecise. Effectively, some parameters (technology, frequency, processing and other parameters) affect the speed estimation. A common situation for mobile robots is when the wheels slip then the estimation of the speed become erroneous. To overcome this issue velocimetry could be a solution; in this paper Acoustic Doppler Velocimeter (ADV) (Also known as Ultrasonic Ground Speed Sensor [1] is considered. This study has the final objective of reaching small ride height (ground clearance) in order to implement the solution on mobile robots. The paper has the following structure: The first sections are dedicated to present velocimetry and reconfigurability. The third section introduces the proposed solution, background and testbed for emulation is presented which is followed by the added values and contributions to the related literature.

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2. VELOCIMETRY

Velocimetry has been priory created to measure the velocity of fluids. There are mainly two types of velocimeters: Transit-Time Ultrasonic Flowmeter and Ultrasonic Doppler Flowmeter. Both have been initiated in mid-1950 when H. P. Kalmus designed in 1954 the first Time-of-Flight flowmeter [2], whereas in [3] mentioned that the history of Acoustic Doppler Velocimetry stretch back to 1956 with Shigeo Satomura, Matsubara and Yoshioka works. In [4] Shigeo Satomura introduced a new method of measuring small vibrations using Ultrasonic Doppler Flowmetry for cardiac applications.

In the literature many implementations are proposed in the form of patents and articles since 1960’s [5]. Kenji Imou et al. published in 2008 their last results about speed estimation for agricultural vehicles [6]. Imou’s system is based on 2 ultrasonic transducers and discrete electronics implementation testes in different ground surfaces types [7]. In general case, ADV consists of an US (ultrasonic) transducer emitting an acoustic wave with frequency of \( f_e \), then another US transducer receives the frequency \( f_e(t) \) shifted by \( f_d(t) \), which is directly proportional to the speed of the vehicle \( v(t) \) as described in equation (2). ADV is built on the notion of Doppler Effect resumed by the following equation:

\[
 f_d(t) = \frac{f_e}{c} v(t) \tag{1}
\]

where \( c \) is the speed of sound in the air. In order to perceive the Doppler effect, an angle \( \alpha \) (different from zero) is needed between the incident acoustic wave and the direction of the vehicle. The velocity will be expressed as:

\[
 v(t) = \frac{c}{2 f_e \cos \alpha} f_d(t) \tag{2}
\]

This technique is applied in the estimation of low speeds (around 10mm/s) [7].

3. RECONFIGURABILITY

Experimentation is a critical step to test the robustness of the solution before its validation. In general, after validation using discrete components comes the step of ASIC (Application-Specific Integrated Circuit) design to save space and unit cost. During experimentation phase, most of times, the system needs to be redesigned taking into consideration the new experimental conditions. This can be constraining in terms of cost, redesign time and test; Reconfigurable systems have been made to face this problem.
There are two categories of reconfigurable systems: FPGA and FPAA. The idea is to use FPGA to reconfigure the processing unit and FPAA to reconfigure the frontend needed for analog signal conditioning [8]. FPAA could be avoided using built-in ADC and digital filtering, but in case of multisensor measurement, the solution is costly in term of hardware resources and execution time is extended. Actual built in FPAA ADCs are limited, Jennifer Hasler is actively working on new architectures including large scale FPAA with improved ADC [9].

The objective of the project is to use reconfigurable systems to reparametrise the solution of navigation according to the changes of environment conditions in order to reach smaller ground clearance and be embedded on vehicles and mobile robots for real-time processing of the velocity.

4. ACOUSTIC DOPPLER VELOCIMETRY

4.1 Working principle and Background of the proposed solution

An US transducer emits a fixed frequency $f_e$ generated by FPAA to the ground (40 kHz square signal is generated and amplified by the FPAA). The reflected acoustic wave is received by the second ultrasonic sensor before being conditioned by FPAA (Band-Pass Filter and Instrumentation Amplifier). The generic low-cost US transducer has a resonant frequency of 40 kHz. As we are studying low speed cases, we assume that the highest vehicle velocity is 10 m/s. In this case the Doppler shift will be $f_d = 588$ Hz (where $c = 340$ m/s) according to the equation (2) then the band-pass filter will be tuned to $(40 \pm 0.6)$ kHz (see Fig. 1).

![Fig. 1. Overview drawing of the solution and its testbed](image)

4.2 Emulation platform (testbed)

To validate the solution, experimentations should be made with different ground clearances. Because of the transducers have narrow directivity (as shown in fig. 2),
they should be oriented with an angle of $\beta$ in order to maximise the reception of the acoustic waves (as shown in fig. 3).

Fig. 2. Directivity of generic ultrasonic transducers

The angle $\beta$ depends on the maximal $d$ and $h$ distances where $d$ is the distance between the transducers and $h$ is the ground clearance. The proposed testbed structure allows emulating the behaviour of the Doppler effect where the vehicle is in movement. It also provides the possibility of changing the ground clearance and the distance $d$ (making the $\beta$ angle constant); the experiments start with $h_{max} = 400 \text{ mm}$ and the distance $d_{max} = 200 \text{ mm}$ then according to equation (3) $\beta = 76^\circ$.

$$\beta = 90 - \tan^{-1} \left( \frac{d}{2h} \right)$$

(3)

Starting from 400 mm (as shown in fig.3) the accuracy will be calculated until reaching the minimal possible ground clearance $h_{min} = 51 \text{ mm}$ that depends on the minimal distance reached between the transducers; in the proposed structure $d_{min} = 25.5 \text{ mm}$.
Fig. 3. Front view of the proposed structure of the testbed

The testbed allows experimenting different ground clearances by displaying the velocities on PC to compare the results coming from the solution and the odometry.

4.3 Instantaneous Frequency Estimation

As shown in fig.1, after conditioning in FPAA, the signal is converted to digital via XADC (Xilinx Analog to Digital Converter) embedded on ZYNQ target. To calculate the velocity, there is a need for determining \( \tilde{f}(t) \) the frequency received by the US receiver then that requires an IP (Intellectual Property) to processes the real time IF (Instantaneous Frequency) [10]. The IFe (Instantaneous Frequency Estimator) is a DSP IP that uses time-frequency tool called Direct Estimation Method. The received signal is assumed to be sinusoidal since the emitted signal from the first transducer is sinusoidal as well. In this case, the received signal can be written as:

\[
S_r(t) = a(t) \cos(\varphi(t)) \tag{4}
\]

then

\[
S_{rA}(t) = a(t) e^{j\varphi(t)} \tag{5}
\]

where \( S_r(t) \) is the received signal, \( a(t) \) the amplitude, \( \varphi(t) \) the phase and \( S_{rA}(t) \) is the corresponding analytic signal to \( S_r(t) \). The direct method consists of the numerical
derivation of the phase $\varphi(t)$ [11]; then the IF of the received signal could be calculated by:

$$f_r(t) = \frac{1}{4\pi} \arg \left( S_{r_A}(t + 1) S_{r_A}^*(t - 1) \right)$$

(6)

where $S_{r_A}^*(t - 1)$ stand for the conjugate of $S_{r_A}(t - 1)$. For the purpose of implementation, equation 2 has to be rewritten as:

$$v(t) = \frac{c}{2f_e \cos \alpha} (f_r(t) - f_e)$$

(7)

After IF estimation, the result can be injected on equation (7) to process the velocity using Ve (Velocity estimator) IP implemented on the FPGA part of the ZYNQ.

5. SUMMARY AND CONCLUSION

The proposed Acoustic Doppler Velocimetry method is fully reconfigurable instead of discrete components and PC for estimating the velocity of a vehicle. The FPAA has the purpose of reconfiguring the front-end system for emitting and receiving ultrasonic signals, then the aim of the FPGA is to estimate the instantaneous frequency and the velocity of the vehicle. Designing a testbed allows to validate the algorithm and the whole solution for the perspective of embedding on vehicles with small ground clearances.

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