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Discrete Extended Kalman Filter Based Ultrasonic Time-Of-Flight Estimation

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ABSTRACT : In mobile robotics applications, the existence of noise measurement may impact on the performance degradation. The noise measurement of the sensor is produced due to several reasons, such as low specification, external signal disturbances and the complexity of the measured state. Therefore, it should be avoided to achieve the good control performance. One of the solution is by designing a signal filter. In this paper, a new digital signal-processing method for ultrasonic time-of-flight (TOF) estimation is presented. The method applies the discrete extended Kalman filter (DEKF) to the acquired ultrasonic signal in order to accurately estimate the shape factors of echo envelope as well as locate its onset. It is so possible to assure reduced bias and uncertainty also in critical TOF measurements, such as those involving low signal to noise ratio (SNR) as well as severe distortion of echo shape. A number of numerical tests are conducted on simulated signals with the aim of highlighting the good performance of the method when operating in critical conditions.
Keywords— Ultrasonic Sensor, Mobile Robotics, Temperature Compensation, Discrete Extended Kalman Filter.

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I. INTRODUCTION

Ultrasonic based measurements are extensively used both in research and production field, spanning in endless applications: environment sensing of autonomous mobile robots, high definition imaging of biomedical devices, precise location of micro-flaws in materials, accurate estimation of the level of flammable fluids or dangerous rivers, and so on [11]. The reason of this success mainly relies upon the opportunity offered by ultrasonic's of conceiving rather simple methods or building up relatively cheap meters, characterized by satisfactory accuracy, reduced measurement time, and, above all, high level of intrinsic safety.

Ultrasonic sensors are generally used for non-contact presence and proximity measurements in all industrial areas. Ultrasonic measurements are based on determination of Time of Flight (TOF) [2] i.e. the time necessary for an ultrasonic wave to travel from the transmitter to the receiver through the target over which it is reflected back. The distance of the object from the transducer 'D' is estimated from the product of one half of the time measured and the propagation velocity of the ultrasonic wave i.e.

$$D = (C \times T)/2 \qquad (1)$$

Where C is the propagating velocity of the ultrasonic burst and T is the round trip time of flight as shown in **Fig.1** Accuracy of the measurement depends on the knowledge of c and the correct estimation of T. The sound velocity shows an almost linear dependence with temperature which can be easily compensated. Typical value of C at room temperature is 343.5 m/s

$$C = 331.31\sqrt{1+\frac{T}{273.15}} \quad m/s \qquad (2)$$

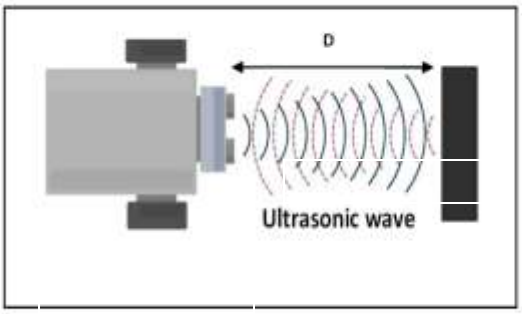

Fig. 1 Illustration of Ultrasonic Ranging

Time of flight can be determined by using Continuous wave technique and Pulse echo technique [3]. The Pulse echo method of ultrasonic sensing is popular because of its reliability and compactness. In pulse echo method there are many techniques for TOF estimation but the most common ones are threshold method and cross-correlation estimation [2]. Threshold method is simple and fast, where the detection occurs when the received signal exceeds the given threshold level. The problem here is that on the average, it estimates a larger TOF compared with the actual one. This happens because of the long rise time of the received signal caused by the current commercially available airborne ultrasonic transducers (narrow bandwidth). This error could be corrected if the shape of the received signal was constant. In practice, this is not the case as the error depends on many factors, for instance, on the signal-to-noise ratio (SNR) [6] and on the defined threshold level. TOF measurements using DSP techniques are preferred due to their reliability and accuracy and they provides accuracy in highly noisy environments.

A. TOF measurements using DSP Techniques

There are many different DSP algorithms used to deal with the range finding applications where the main task of DSP is the time of flight estimation sometimes refers as Time Delay Estimation (TDE) [7]. TDE is usually characterized in two Sequential steps: First step involves in digitization of transmitted and echo signals and the second step involves in adopting a DSP algorithm to estimate the desired TOF with the acquired samples. Major sources of inaccuracy can be found in additive noise affecting the acquired ultrasonic signal, shape distortion of the received echo, and dependence on temperature of the propagation velocity [4]. In the presence of zero mean additive white Gaussian noise the Cross Correlation Estimation (CCE) or Matched Filter has proven to be optimal [8]. In CCE the transmitted and received signals are cross-correlated. The time at which the correlation result reaches its maximum is an estimation of the TOF and it works well with low SNR signals. When the last assumption is violated, TOF estimates become significantly biased, and the amount of bias can be much greater than the experimental standard deviation. To reduce the effects of distortion parametric models of the echo envelop were introduced but it gained the effects of noise sensitivity and computational burden. The temperature compensation can be obtained by making use of an external sensor and changing the actual propagation velocity according to the current value of the temperature.

An original use of Discrete Extended Kalman Filter (DEKF) is presented in this paper to reduce the aforementioned problems. The novelty of the method mainly relies upon its capability of jointly estimating the whole set of parameters. The main advantage of the new approach is that TOF estimation inherently accounts for distortions the ultrasonic echo eventually undergoes, with a consequent positive effect on bias reduction specifically, after modelling the echo envelope as a stochastic process whose state is identified by the considered parameters, the DEKF provides a robust and reliable solution of the non-linear equation system involved.

In section II we review the theoretical frame work of DEKF algorithm for ultrasonic distance measuring system. Section III describes the simulation results of existing and proposed techniques in MATLAB. Concluding remarks are given in section IV.

II. A THEORITICAL FRAMEWORK

The Discrete Kalman Filter (DKF) is generally adopted to estimate the state of a linear stochastic process. It uses a kind of feedback control based on measurement results of quantities that are linear functions of the state. More specifically, the filter estimates the process state at a given time instant, and then obtains feedback by incorporating a new measurement result into the a-priori (predicted) estimate in order to gain an improved a-posterior (corrected) estimate. In the presence of a non-linear process, the DKF can still be adopted, provided that suitable linearization techniques are applied. Two linearization techniques are available: discrete. linearized Kalman filter (DLKF) and discrete extended Kalman filter (DEKF). DEKF has been used to improve the accuracy of ultrasonic-based location system of robots. The novelty of the method mainly relies upon its capability of jointly estimating the whole set of parameters (A_0, α, T, and τ) that characterize the well-known model of echo envelope, A(t):

$$A(T) = A_o\left(\frac{t-\tau}{T}\right)^{\alpha} \exp\left(\frac{t-\tau}{T}\right) \qquad (3)$$

Where A_o accounts for echo amplitude, α and T are peculiar to the specific ultrasonic transducer, and τ is the desired TOF. Let the state vector x = [A_o, α, T, τ]. Now the system generic equations is simplified as shown in eq.4, since these parameters can be considered constant once the ultrasonic echo has been acquired.

$$\begin{aligned} x_k &= f(x_{k-1}, k-1) + w_{k-1} \\ z_k &= h(x_k, k) + v_k \end{aligned} \qquad (4)$$

Where x_k is the N-dimensional vector of the process state, z_k is the M-dimensional vector of current measurement results. f, h are known functions, w_k and v_k are uncorrelated additive white Gaussian noise sequences. According to DEKF theory the actual state vector can be written as:

$$x_k = x_k^N + \delta_{x_k} \qquad (5)$$

Where x_k^N is a- posteriori estimate of the state vector obtained at the previous step. The perturbation δ_{x_k} perturbation is null for each k of DEKF and the state transition matrix ϕ_k reduces to unitary matrix I.

The basic loop of the recursive procedure to evaluate the discrete-time Kalman estimator of the state vector x_k is as follows:

1. A-priori estimation of the state vector:

$$\hat{x}_k^- = \hat{x}_{k-1}^+$$

Where $\hat{x}_k^-$ is a-priori (predicted) estimate and $\hat{x}_{k-1}^+$ is a-posteriori (corrected) estimate of state vector.

2. A-priori estimation of the measurement result through the equation (2)

$$\hat{z}_k^- = A_o\left(\frac{k\theta - \tau}{T}\right)^{\alpha} \exp\left(\frac{k\theta - \tau}{T}\right)$$

Where θ is the sampling period, and A_0, α, T, and τ represent the values of the parameters obtained at the previous step.

3. A-priori estimation of error covariance matrix is given below and is of 4×4 dimension

$$\hat{p}_k^- = \hat{p}_{k-1}^+$$

4. Evaluation of the measurement sensitivity matrix is given below and is of 4×1 dimension

$$H_k = \left.\frac{\partial h(x,k)}{\partial x}\right|_{x=\hat{x}_k^-}$$

5. Calculation of Kalman gain

$$\overline{K}_k = \hat{p}_k^- H_k^T \left(H_k \hat{p}_k^- H_k^T + R_k\right)^{-1}$$

6. A-posteriori estimation of the state vector Conditioned on the current measurement result:

$$\hat{x}_k^+ = \hat{x}_k^- + \overline{K}_k\left(z_k - \hat{z}_k^-\right)$$

7. A-posteriori estimation of the error covariance Matrix:

$$\hat{p}_k^+ = \left(1 - \overline{K}_k H_k\right)\hat{p}_k^-$$

Flow diagram of the recursive procedure that specifies the application of DEKF to ultrasonic echoes shown in **Fig: 2**; N is the number of samples included in the observation interval.

A. Initial condition and recursion finish criterion

The described recursive procedure can be executed once

i. The starting estimates of the state vector and error covariance matrix, referred to respectively as x_0 and P_0.
ii. The experimental variance of measurement noise, R_0.
iii. The recursion finish criterion is available.

With regard to (i), some preliminary considerations are needed. Specifically, the generic element x_i is modelled as random variation, and it can take values in a specific interval $[x_{i1},x_{i2}]$. For each parameter, in fact, a suitable range of values has to be fixed according both to their typical interval. In particular: with regard to A_0, typical values of the amplitude of received echoes should be considered. Concerning α, typical slopes that the rising edge of received echoes exhibits in proximity to the onset should be accounted Referring to T, typical durations of the ultrasonic transmission burst should be enlisted. As for TOF, the related interval is automatically established after the signal Pre processing step of the measurement procedure, details of which are given below. Assuming a rectangular probability density function for each element xi, the starting estimates of the element and its variance are given by:

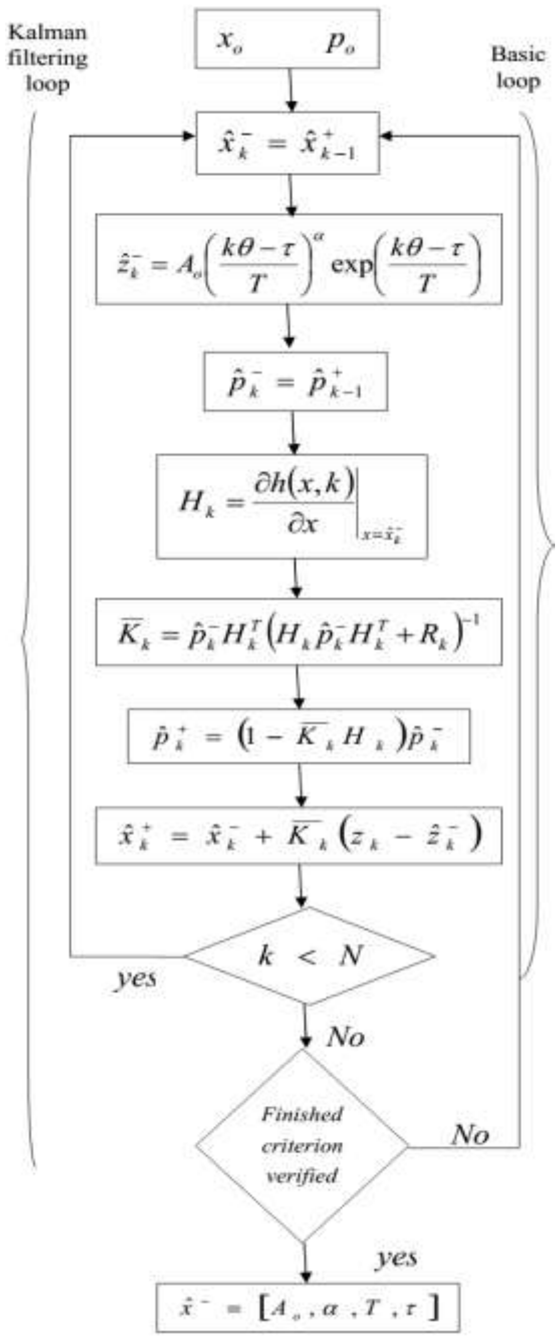

Fig. 2 Flow diagram that specifies the application of DEKF to ultrasonic echoes

$$\hat{x}_{i0} = \frac{1}{2}(x_{i1} + x_{i2})$$
$$\sigma_{i0}^2 = \frac{1}{2}(x_{i2} - x_{i1})^2 \qquad (6)$$

This way, P_0 is a diagonal matrix, the elements of which correspond to the variances of the starting estimates. As for (ii), the variance of the noise floor of the adopted data acquisition system should be measured. Execution of the Kalman filtering loop: A suitable finish criterion is thus needed. At this aim, the value of the modulus of the difference between the state vector estimates provided by two consecutive Kalman filtering loops is compared to a execution of the Kalman filtering loop. A suitable finish criterion is thus needed. At this aim, the value of the modulus of the difference between the state vector estimates provided by two consecutive Kalman filtering loops is compared to a to a proper threshold value (empirical tests suggest the value of 1×10^{-4}). If the difference is lower than the threshold, the recursive procedure stops, and the best estimate of the four parameters of the echo envelope is delivered; otherwise, a new Kalman filtering loop is executed.

III. SIMULATION RESULTS

The simulation is done using TR-40 transducer that acts both as a transmitter and receiver, converting an electrical signal into an acoustical one and vice versa [12]. Signals received from the transducer are filtered by a band pass amplifier whose centre frequency is synchronous with the transducer operating frequency and the block diagram of such a system is shown in **Fig. 3** [10]. The results of the simulations are shown and discussed below.

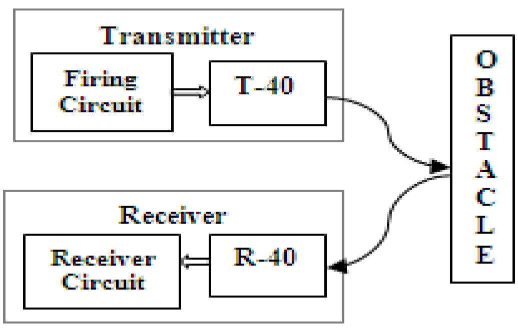

Fig.3 General Structure of the system

A. Results for Threshold detection

Fig.4 shows an example of how TOF estimation is obtained by the threshold technique. The problem here is that on the average, it estimates a larger TOF compared with the actual one. This happens because of the long rise time of the received signal caused by the current commercially available airborne ultrasonic transducers (narrow bandwidth). This error could be corrected if the shape of the received signal was constant. In practice, this is not the case as the error depends on many factors, for instance, on the signal-to-noise ratio (SNR) and on the defined threshold level.

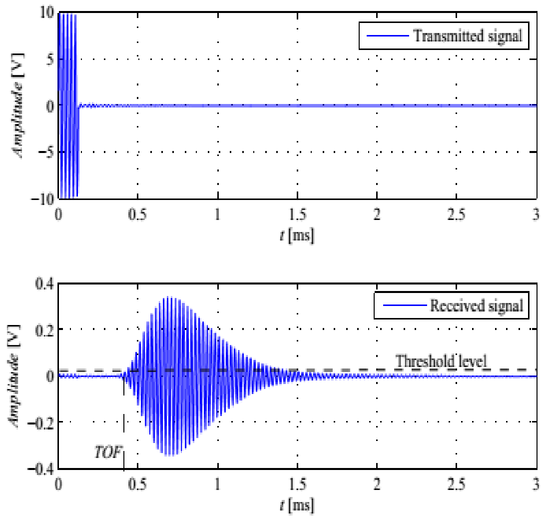

Fig.4 TOF estimation by Threshold method

B. Results for Cross Correlation Estimation

In correlation estimation, for better accuracy the transmitted and echo signals are transduced, digitized and cross correlation is computed in digital form. The time index corresponds to the peak of cross correlation curve is the estimated TOF. The auto correlation of such a transmitted pulse [2] is shown below in **Fig. 5. Fig.6** shows an example of how TOF estimation is obtained by cross correlation estimation. Here, the transmitted and received signals are cross-correlated. The time at which the correlation result reaches its maximum is an estimation of the TOF. Comparatively this technique works well with low SNR signals and it is less affected by low sampling rate problems. It uses all the information contained in the signals.

Therefore, it is considered an optimum TOF estimator technique [2]. The accuracy depends mainly on the samplingrate. Many benefits can be gained by proper selection of thesignal to be transmitted and an adequate signal processing technique. The selection of the signal to be transmitted islimited by the bandwidth of current ultrasonic
transducers.

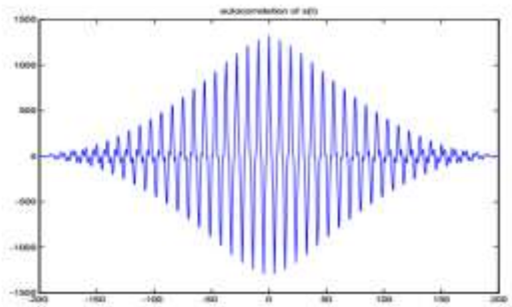

Fig.4 Cross Correlation of Typical Transmitted Pulse

It would be advantageous to apply a signal to the transmitter with both high energy and low bandwidth (for
ex: a quasi-continuous sine wave) which does not havetheambiguity problem. Amplitude modulation (AM) has beenused [6] to achieve this end. Here, the carrier signal,attheresonant frequency of the transducer, is modulatedbydifferent low frequency modulating signals.The phase-shift,for each modulating frequency, between the transmitted and received envelopes is measured. The maximum range and resolution depends on the number and value of themodulating frequencies. One limitation is that the signalsaretransmitted sequentially, increasing the net timetoobtainadistance measurement. Also, calibration foreachmodulatingfrequency, at a specific distance, mustbeperformedtocompensate the randomness of initialphase-shiftsamongthenumber of modulating frequencies.

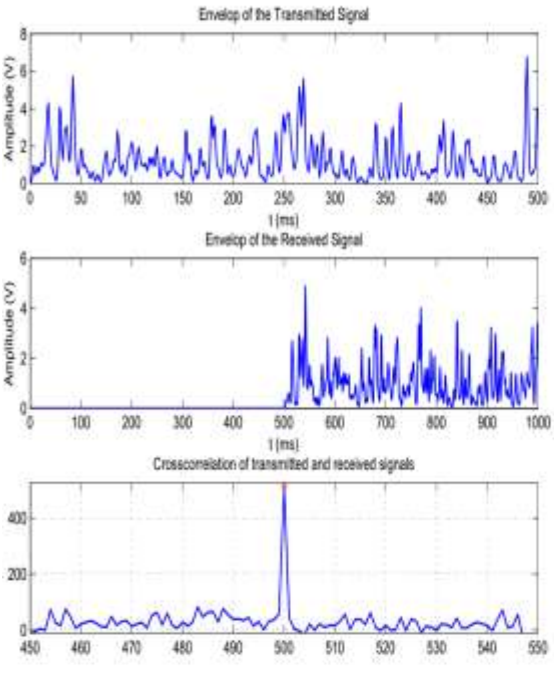

Fig.6 TOF estimation by Cross Correlation estimation

C. **Results for DEKF**

The fundamental steps of the DEKF-based measurement procedure are described below

C.1.Digitization

The ultrasonic signal is at first digitized by means of a data acquisition system, the characteristics of which, in terms of sample rate and memory depth, have to be chosen appropriately. Specifically, the adopted sample rate, f_c, has to satisfy the Nyquist lower bound, and, along with the memory depth, has to grant an appropriate observation interval according to the desired TOF measurement range.

As already stated, the proposed recursive procedure is expected to work on the envelope of the ultrasonic echo of interest. After digitization, pre-processing operationsare,thus,needed. In particular, the portion of the digitized signal, accounting for the ultrasonic transmission burst, is firstly cut; in the application example the removed portion covers 2ms. The envelope of the remaining signal is, then, given by the modulus of its analytical version, attained through an ordinary Hilbert transform. If the transmitted ultrasonic burst undergoes multiple reflections, more than one echo is present in the obtained envelope [6]. As a consequence, the echo of interest (generally, the main one) is, finally, isolated through the location of the maximum of the envelope and the selection of the portion, including this maximum, whose values are not buried in the noise floor. Before applying the proposed recursive procedure, the variation interval, [x_{i1}, x_{i2}], of the TOF has to be assigned in order to fix the starting estimates of the TOF itself and its variance, according to what stated above. The upper bound, x_{i2}, is given by the time instant characterizing the first value of the echo of interest obtained at the end of the previous step; in the considered example it is equal to 3.068 msec. The lower bound, x_{i1}, is then gained by subtracting from x_{i1} a suitable number of sampling intervals; the experimental tests have shown that 50 sampling intervals are appropriate to the purpose. After fixing the initial estimates of the state vector and error covariance matrix, the

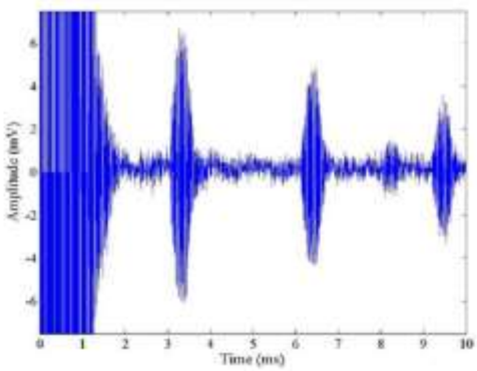

Fig.7 Original Ultrasonic signal digitized at 250 KS/S with multiple Echoes

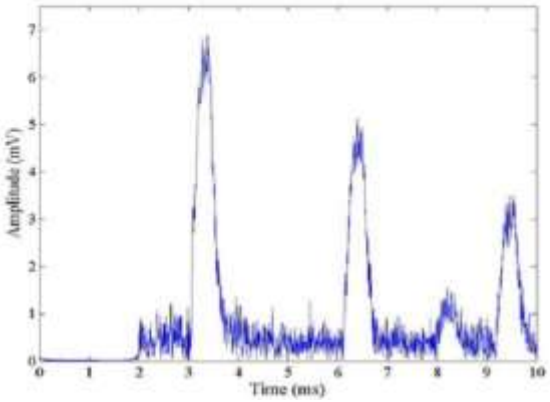

Fig.8 Envelope of the echoes provided by Hilbert Transform

Recursive procedure can run, thus giving, at the end, the wanted values of the TOF and shape parameters of the echo of interest.

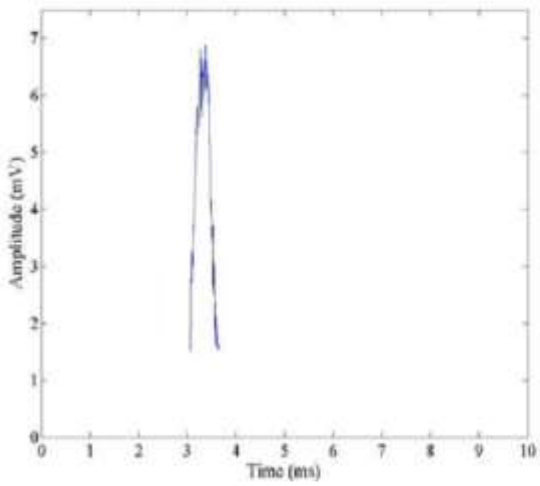

Fig.9 Location and isolation results of echo of interest

IV. CONCLUSION

In this paper, we have presented a digital signal processingtechnique based on DEKF algorithm, for compensating ultrasonic sensor distortion effects of cross correlation estimation. Test results shows that KF algorithm is able to reduce measurement noise generated by the sensor system. The analysis of the variance done generates noise variance value measurement that is proportional to noise variance process specified. However, it is inversely proportional to the time response generated. The smaller the measurement of noise variance value, the resulting response time is slower. Thus, it is required an optimization parameter of selection matrix of noise covariance process and noise measurements in order to produce filtering process and best time performance.

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