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Research article

Online Wavelet Complementary velocity Estimator

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ABSTRACT

In this paper, we have proposed a new online Wavelet Complementary velocity Estimator (WCE) over position and acceleration data gathered from an electro hydraulic servo shaking table. This is a batch estimator type that is based on the wavelet filter banks which extract the high and low resolution of data. The proposed complementary estimator combines these two resolutions of velocities which acquired from numerical differentiation and integration of the position and acceleration sensors by considering a fixed moving horizon window as input to wavelet filter. Because of using wavelet filters, it can be implemented in a parallel procedure. By this method the numerical velocity is estimated without having high noise of differentiators, integration drifting bias and with less delay which is suitable for active vibration control in high precision Mechatronics systems by Direct Velocity Feedback (DVF) methods. This method allows us to make velocity sensors with less mechanically moving parts which makes it suitable for fast miniature structures. We have compared this method with Kalman and Butterworth filters over stability, delay and benchmarked them by their long time velocity integration for getting back the initial position data.

1. Introduction

High speed in manufacturing of high precision components [1,2] and micro-feeding Mechatronics solutions, is a prime requirement. The main problem of mass production of the precise components is their high price of machinery tools and the time consumption in the production processes. To being precise, it needs high quality in surfacing and dimensioning in the production line. For precise producing goods, todays mechanical structures in analysis and production parts has been reached to the highest levels in decades. But, what mainly effects the precision in the machinery tools, is the vibration induced to the mechanical structures from various sources such as natural frequencies of the working structure in higher speeds and oscillations induced by nonlinear frictions in lower speeds [3]. In heavy duty operations like steel face milling the critical modes for vibration are related to the whole machine tool structure (chatter frequency is between 15 and 100 Hz). The introduction of additional damping in the machine tool structure can increase milling stability. However, a passive absorber is not feasible in many machining processes where the dynamics of the system change according to the working position and an active damper is needed. The famous Direct Velocity Feedback (DVF) are well known in active suspension literature [4–7] from old to new methods such as skyhook [8,9]. The DVF, which utilizes actuators and the acceleration signal from sensor, is an advanced Mechatronics solution which in performance is comparable with smart materials like piezoelectric actuators in damping strategies. This solution is cheaper in cost, but its reliability is strictly challenged by inner algorithms for sensor fusion and controller types. Any good controller has a bandwidth which is limited by its sensory inputs. So using high quality sensor feedback to controller maximizes the whole control system bandwidth. Designing soft sensors to deriving high quality velocity from other sensors in real time due to the technical difficulties is an open challenge in literature [10].

Traditional inertial velocity sensors are based on the movement of a mechanical mass in an electromagnetic field which produces some currents to be sensed. Otherwise piezoelectric velocity sensors are accelerometers with an electronic integrator built in to the unit with a high pass filter for removing the bias created by integrator [11]. So deriving this velocity from online numerical differentiation or integration of a measured data with noises has great importance in signal processing, control engineering [12–14], numerical analy-

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sis, or failure diagnostics [15]. It is used in implementation of control strategies which uses the least cost sensors available (just position or angular). But, these low cost sensors deliver such a noise over useful signal which using numerical differentiators over them gives a high noisy results which is practically unusable in high precision works and must use some kinds of filter where each of these filters have their own benefits and problems.

Different online linear filters such as Butterworth or Chebyshev Types I and II, elliptic and some nonlinear filters such as wavelet [16,17] have been used in the industry for removing this kind of noise from digital differentiators. Another approach is based on the least square on a polynomial structure [18,19]. High gain observers which adjust the model by weighting the observer output deviations from the system to be controlled [20,21] is another implementation. Design of numerical differentiators in the frequency domain is based on the assumption that an ideal $n-th$ order differentiator has a frequency response of magnitude ω^n [22–24]. Extended Kalman Filter is a special strategy for state estimation which can be used for digital differentiation [25–27]. The main problem in differentiator design is to combine differentiation exactness with robustness in respect to possible measurement errors and input noises. But most of these filters have delays because of deleting high frequency contents of the signal and phase shifting in much frequencies. If nothing is known on the signal structure except some differential inequalities, then sliding modes [28,29] for its exactness and robustness are used. This method is good as the noise on the signal is as low as possible, with high noise the differentiator results contains a high chattering which makes it impossible use in real feedback control systems. A simple and old estimation technique for velocity that is often used in the flight control industry is to fusion measurements in the complementary filter [30]. A complete overview on all these filters has been done in Ref. [31].

The Wavelet Transform (WT) is a powerful tool of signal and image processing and it has been vastly used in many scientific areas, such as signal processing, image compression, computer graphics, and pattern recognition [32–36]. Noise filtering using wavelet has been a very mature technology [37–39]. On contrary the traditional Fourier Transform, the WT is particularly suitable for the applications of non-stationary signals which may instantaneous vary in time [40,41]. But even the wavelet filtering alone on a specific signal, based on its nature tries to remove(or smoothen) the higher resolutions beneath the original signal, so it causes delay in output filtered signal. Many attempts have been done in joining wavelet multi-resolution analysis with kalman filtering to estimate states from high noise data [42–45]. These methods require application of kalman filter over each resolution level, which needs high serially computation resources.

So, finding fast and accurate algorithms which could give the absolute velocity value of the system with low noise, least delay and stable properties, is the main challenge of this paper. This fast and reliable velocity can give us high precision accuracy out of control feedbacks regardless of environmental vibrations.

At this paper, in the next section we define the mathematical definitions needed for presenting the position, velocity and the acceleration with some preliminaries on discrete wavelet, Butterworth for noise canceling and Kalman filter for state estimation have been introduced. In the third section, structure of the proposed complementary estimator is mathematically explained and proved. The fourth section describes the experimental results in compare to kalman filter, the butterworth and a complementary estimator which uses butterworth filters instead of wavelets.

2. Problem definition and preliminaries

By considering an analog position signal as $P_s(t)$ and an analog acceleration signal as $A_s(t)$ we can construct an object motion states as:

$$\begin{bmatrix} P_r' \\ V_r' \\ A_r' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} P_r \\ V_r \\ A_r \end{bmatrix} + w$$
$$\begin{bmatrix} P_s \\ A_s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_r \\ V_r \\ A_r \end{bmatrix} + v \tag{1}$$

Where the states are $X(t) = [P_r(t), V_r(t), A_r(t)]'$ and sensed data are $Y(t) = [P_s(t), A_s(t)]'$. The $w = N(0, Q)$ and $v = N(0, R)$ are the uncertainties with Gaussian Distribution of variances Q and R. The goal of this paper is to estimating $V_r(t)$ with lowest delay as possible. In contrary to lowest delay, we also want to acquire a velocity which is suitable for stabilizing control feedbacks which contains integration procedures inside.

2.1. Multi-resolution analysis and discrete wavelet transform

Multiresolution Analysis (MRA) is a convenient framework for hierarchical representation of functions or signals on different scales. The basic idea of multiresolution analysis is to represent a function $f(x)$ as a limit of successive approximations. Each of these successive approximations is a smoother version of the original function with more and more of the finer "details" added. Wavelets are terminating basis vectors which are used to decompose a signal using a set of coefficients. The process of decomposition uses a sub-band coding scheme that is illustrated in Fig. 1. The Discrete Wavelet Transform (DWT) can be computed using the filter banks $\overline{h(k)}$ and $\overline{g(k)}$ which form a quadrature conjugate mirror filter pair with $h(k)$ and $g(k)$, which are given by Eq. (A.7) from two conjugate functions, the wavelet function $\psi(x)$ and the scaling function $\phi(x)$. The result of the analysis step is a set of intermediate coefficients, which represent the weights of the original signal in terms of the basis functions used, namely the scaling function and the wavelet function. The original sampled signal is filtered with the scaling function and the wavelet function and down sampled by two, resulting in the trend and detail coefficients at level one. The trend coefficients thus obtained are then used as the original signal and filtered with the scaling function and the wavelet to yield the coefficients at level two. This process is repeated depending upon the number of decomposition levels desired. For reverse procedure, the detail and the scale add up, then being up-sampled and passed from reverse scale filter, ready to being added to detail of the lower levels. By these coefficients the $f(x)$ can be decomposed in wavelet and scale spaces as equation (A.6).

The problems of temporal and frequency resolution found in the analysis of signals with the Short time Fourier Transform (STFT), i.e. best resolution in time at the expense of a lower resolution in frequency and vice-versa, can be reduced through the MRA provided by Discrete Wavelet Transform (DWT). The temporal resolutions, Δt,

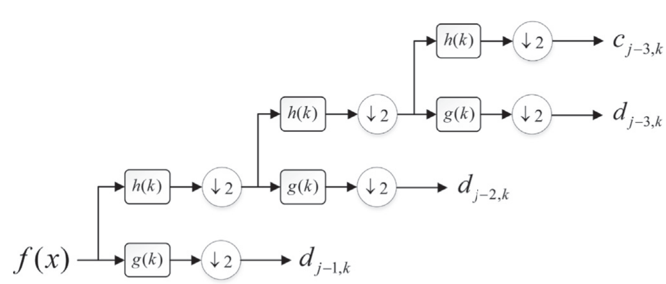

Fig. 1. Illustration of the analysis part of a three-level decomposition scheme using sub-band coding.