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An approach for velocity and position estimation through acceleration measurements

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ABSTRACT

This paper proposes an approach for velocity and position estimation through acceleration measurements. In this approach, the noises of acceleration signal are removed through a smoothing process based on diffusion equation, a special partial differential equation (PDE). Then a mechanism is designed to remove abnormal deviations in the signal before and after integration. The proposed approach can substantially reduce the errors (drifts) accumulated from the integration of acceleration signal. Its effectiveness and superiority over other popular methods are validated by simulation and experimental results.

1. Introduction

Determining velocity and position of a moving body from its acceleration measurements is one of the important issues for the operations of many kinds of engineering systems, such as unmanned aerial vehicles (UAVs) where accelerometer is usually used for the state feedback [1,2]. It is important in the measurement of ground deformation [3] and structure movement [4]. It is also used for the motion generation in virtual reality [5].

Inertia sensors like gyroscopes and accelerometers, the main sensors found in inertial navigation systems (INS), have been widely used as the sensors to feedback the signals needed for velocity and position measurement in more and more applications [4,6,7]. However, the noises in the signals from those sensors become the main source of the integration drift and the reduction of measurement accuracy. For example, large integration drifts have been observed in the position signal calculated from the acceleration signal from an accelerometer even when it is at rest [8].

One approach to reduce the measurement errors is via using the information of the additional sensors such as global position system (GPS) [9,10] and computer vision [11,12]. Usually, the information from the additional sensors is updated with a time interval considerably longer than that for the acceleration measurement. However, this approach increases the complexity and the cost of the system. The reliability of the system is also compromised when the signals are lost due to the change of environments. For example, GPS signals are not available indoor or unreliable in remote areas and in some weather conditions.

Another popular approach is to use Kalman filter (KF) to process sensor signals [13,14]. Kalman filter is essentially an optimal design which is sensitive to the parameters of the noise model, misalignment and the bandwidth of inertial sensors [15,16]. A better performance can be achieved by using non-linear extended Kalman filter (EKF) which can predict the state of a system under the assumption that its model is locally linear [17]. The Jacobian matrix of the process and its observation are evaluated analytically, but sometimes they are not available or do not have a finite value. For some complex and highly non-linear systems, linearization is not feasible [18,19].

Recently, a nonlinear-multiple-integrator algorithm based on finite time stability and singular perturbation theories has produced good results in suppression of drifts in velocity and position estimation from acceleration measurements [2]. The algorithm is complex and computationally intensive. It contains several parameters which have to be tuned manually to get a satisfactory result. In the worst case when those parameters are not selected properly, the results of the algorithm will even become divergent.

Some researchers have utilized the unique features (e.g. zero mean) of some types of motions to improve the accuracy of velocity and position estimation. For instance, in a study of human walking, the errors of orientation estimation are compensated by utilizing the gyroscope readings and the cyclic pattern of the human walking motion [13]. The same approach has also been

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used for the compensation of the drift in the position estimation in an oscillating motion [14,20]. However, this method requires an accurate prior knowledge of the motion which is usually not possible in practice.

The fact that the reduction of integration interval can improve the accuracy of the dead reckoning method has been explored in [21]. In this approach, the integration process is reset once the stop of motion is detected. However, this is only possible when there is a sufficiently short period between the neighboring stops.

This paper presents an effective and easy-to-use approach to estimate the velocity and the position from the acceleration measurements. It does not need any additional sensors, prior knowledge of motion or system model. It includes a smoothing process to remove the noises from the acceleration signal without causing phase shift, and an algorithm to amend the signals before and after numerical integration to further prevent error accumulation. The proposed approach can be applied for the motions with either zero or none-zero mean velocity and position. Its advantages over other existing methods are validated through simulations and experiments.

The rest of the paper is organized as follows. In Section 2, the problem statement is presented. In Section 3, the steps of the proposed approach are presented. They include a signal smoothing process based on diffusion equation and a mechanism to amend the signals in the process of integration. The effectiveness of the proposed approach is discussed and is compared with other methods. Simulation and experimental results are presented in Section 4 and the conclusion is given in Section 5.

2. Problem statement

The position of an object can be calculated directly via double integrating of its acceleration over time. *The Trapezoidal rule* and the *Simpson's rule* are the popular methods for digital implementation of integration [22]. The integration drift normally appears in those methods. There are two main sources of integration drift; one is the data missing due to insufficient sampling rate, and another source is the noises in the signal. As a rule of thumb, the sampling rate shoe be at least twice of the highest frequency of the signal, otherwise the sampling process will result in distortion and loss of information [23]. The noises of the sensor signal have a substantial contribution to the integration drift. For example, assume an acceleration signal in the form of sine wave is described by

$$a(t) = -\sin(t) + e(t), \quad 0 \leqslant t \leqslant 100 \tag{1}$$

where t is time, $a(t)$ is acceleration and $e(t)$ is a non-white noise signal (Fig. 1). Fig. 2 shows the result (velocity) of the first integration of the signal through the *Simpson's rule*. Fig. 3 depicts the error of the first integration (velocity) with time. Figs. 4 and 5 show the position estimation and the errors through double integration.

It is obvious that the drifts generated by the numerical integration have a non-predictable trend. Thus, many existing drift compensation methods based on the assumption that the integration drift has a standard trend in linear or quadratic form generally fail in practice [3].

In the following section, a new approach is proposed to reduce the drift for velocity and position estimation.

3. Proposed approach

In this section, an approach for determining the velocity and the position of an object from noisy acceleration signal is described. As shown in Fig. 6, it consists of several steps including baseline correction, removing noises and filtering coupled with integration process to remove the drift. This process is repeated for double integration.

In the baseline correction step, the gravitational acceleration and any offsets of the sensor are determined first. Gravitational acceleration is readily available. The offset of the sensor can be obtained from the least square fit line from the samples of the readings of the sensor when it is at the rest. They are then removed from the sensor readings to get the acceleration.

In the next step, high frequency noises in the acceleration signal are suppressed prior to integration [25]. The noises are from a number of sources such as fluctuations in sensor sensitivity or instrument hysteresis, and they can be removed by low-pass digital filters [24,25]. An ideal low-pass filter eliminates all frequencies above the cutoff frequency while passing those below unchanged. A low pass filter can cause phase shift and distortion of the original signal. This can be avoided by applying the so called *curve evaluating process* or *smoothing process* [26]. After this smoothing process, the signal can be integrated using the numerical integration method. Finally, the signals are amended before and after integration to minimize the drift. In the following section, each of the above steps is explained in details.

3.1. Removal of noises with the smoothing process

In this step, the noises in the signal are removed through a special partial differential equation named *diffusion equation* which is

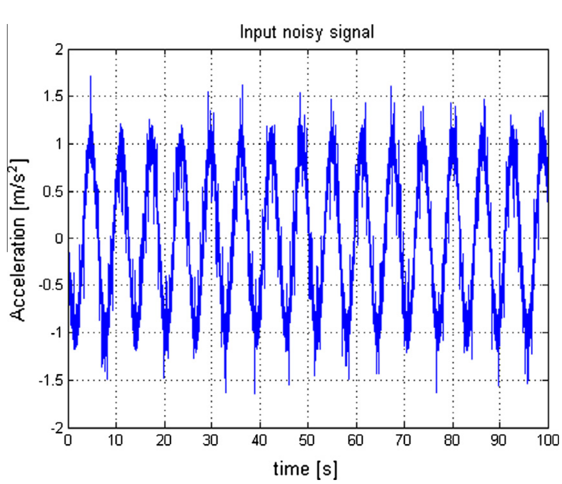

Fig. 1. Acceleration signal with noises.

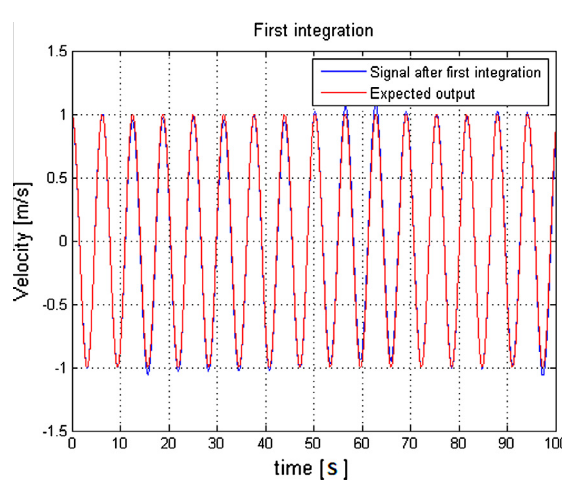

Fig. 2. Velocity derived from the first integration.