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# Understanding the Performance of Zero Velocity Updates in MEMS-based Pedestrian Navigation

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## Abstract

Zero Velocity Update (ZUPT) is an important update to aid an autonomous inertial pedestrian navigation. The objectives of this paper are to briefly revisit the concept of ZUPT and its importance, testing it on real walking pedestrian and comparing its performance when used with either conventional 'Dead Reckoning approach (DR)' or with 'Kalman Filter approach (KF)' as either one of these approaches is commonly used in literature. Performances were analyzed further with the inclusion of two correction modes (Linearly Weighted Interpolation and Residual Velocity). Experiments were performed using a low cost Inertial Measurement Unit (IMU) from MicroStrain (3DM-GX1). It was shown that the KF approach outperformed DR-only approach, but comparable performance with KF was noticed when DR is combined with correction mode. Finally, a combination of RV correction mode with forward KF solution was shown to improve the position output.

**Keywords:** ZUPT, Kalman Filter, Dead Reckoning, Pedestrian Navigation.

## 1. Introduction

Navigating in area where GNSS signals are compromised is one of the most difficult navigation problems today – if GNSS signal were to be used alone. For instance, users spend quite a huge amount of time for indoor positioning such as for shopping, working and studying, where GNSS signal are either blocked or poorly received for position localization. Therefore, it is common to see the combination of various positioning technology with GNSS-based system. In a situation where GNSS is not available, this 'other' positioning technology are used instead.

Among those is the use of Micro-Electro-Mechanical Sensors (MEMS) as the positioning sensor. The system often comprises accelerometers and gyros and is commonly known as an Inertial Measurement Unit (IMU). The MEMS accelerometer and MEMS gyros sense the acceleration and the attitude rate, and these measurements can then be translated into a meaningful position solution using inertial navigation technology [1]. Due to the low-cost nature of these sensors, it can even be worn by the user – in the context of this paper, pedestrian.

However, the measurements from these sensors are also huge because of the fact that they are low-cost. For pedestrian, a method called Zero Velocity Update (ZUPT) is often adopted to constrain some of these errors [2].

There are essentially two methods of using ZUPT in MEMS-based pedestrian navigation system (which will be discussed further in section II). First is the use of a conventional dead reckoning method, for example in [3, 4], where the relative position is computed by integrating velocity data from normal mechanization equations from inertial navigation technology. This is performed by simply zeroing the velocity during each detected stance phase when user is walking. Second is the use of an estimation filter to estimate the errors in MEMS sensors, where ZUPT is used as velocity measurement updates to the filter [5, 6, 7, 8].

In this paper, a comparison will be made between these two methods, Kalman Filter is used as a representative of an estimation filter for the second method. This comparison is performed to better understand the performance of ZUPT under different methods when only ZUPT is available to update the navigation system. One might argue that using estimation filter such as KF is indeed far more superior than not using any filter, but it is interesting to analyze the outcome of the comparison to better appreciate the use of ZUPT in these two conditions.

## 2. Algorithms

In a MEMS-based pedestrian navigation, the knowledge of when stance phase occurs is very important. A few methods of detection are listed in literatures such as using the magnitude of total acceleration [9], moving acceleration variance [10], magnetometer based [11], neural network based [12] and the magnitude of gyro signals [13]. By comparing these data with a certain threshold, the start and end of the stance phase can be detected. The detection of stance phase is important because this is the only time in an autonomous pedestrian navigation where the data is known beforehand. Velocity of the IMU in its body frame are theoretically zero during this condition and this has allowed the use of ZUPT. Any nonzero measurements during this moment can therefore be assumed to be errors. The velocity measurements can be zeroed and to avoid discontinuities in the measurement function, the errors are propagated backward at least one walking step so that a smooth measurement function can be obtained [14].

In MEMS-based pedestrian navigation, the advantage of putting the IMU on foot is that ZUPT can be applied whenever the stance phase is detected momentarily. This is because IMU is 'strapped' to the foot and as such will be correlated with foot gait events – detecting ZUPT from IMU measurements correspond to detecting the correct gait event (stance phase).

### *2.1 Dead reckoning approach – Conventional ZUPT*

In [15], it was shown how land-based mobile mapping system solution is bridged using medium grade IMU during GPS outages with the help of ZUPT. Whenever the system stopped, ZUPT was applied. The velocity measurements were kept at zero during this interval and because of this, the error growth of the IMU was bounded during in-between stop conditions. The position is estimated only for the 'nonzero' data during system movements.

## 2.2 Dead reckoning approach - ZUPT with Correction

The correction mode [16] used with ZUPT was based on the assumption that during one step of walking pedestrian before coming the stance phase, which lasts around 1s, the IMU errors will grow linearly. The knowledge of conventional ZUPT as described before was used in backward mode to linearly spread the error during ZUPT across the whole one step walking data just before the stance phase occurs. The algorithm used was based on Linearly Weighted Interpolation (LWI) assumption using the mean of data acquired during stance phase as the weightage, and the steps are as below:

1. Let  $V_n = \{V_{n_i}\}_{i=1,2,\dots,n}$  be a linear velocity in a global frame in the North direction, which is to be corrected. Similar steps applied to the velocity in East direction.
2. During each complete walking gait for one foot (from heel strike to toe off or from swing phase to stance phase), this correction mode is applied:
  - a) Let  $t_{start}$  be the start time of the movement (swing phase),  $t_{end}$  be the end time of the movement and corresponds to the start time of a stance phase, and  $t_{final}$  be the end time of the stance phase.
  - b) The mean velocity value is calculated during stance phase:

$$\mu = \frac{\sum_{i=i_{end}}^{i_{final}} V_{n_i}}{(i_{final} - i_{end})} \quad (1)$$

- c) The velocity value during movement is corrected as below ( $V_{n_i}^c$ ):

$$V_{n_i}^c = V_{n_i} - \mu \quad ]_{i=i_{end} \dots i_{final}} \quad (2)$$

$$V_{n_i}^c = (V_{n_i} - m) \left( \frac{t_i - t_{start}}{t_{end} - t_{start}} \right) \quad ]_{i=i_{start} \dots i_{end}} \quad (3)$$

Another correction mode that was investigated in this paper is the use of Residual Velocity (RV) approach by [17] in the correction mode. This approach was based on the assumption that immediately when stance phase is detected, the velocity value should be zero. However due to various errors, it is not. The difference between the remaining velocity value and the ideal value (0 m/s) is called Residual Velocity. The distribution of correction coefficient in this approach is based on RV value, instead of ‘mean during stance phase’ as in the previous approach.

### 2.3 Kalman Filter approach – Conventional ZUPT

The Kalman Filter (KF) operates on prediction and update mode. The GNSS measurement updates are normally used in outdoors where GNSS signal is available. In a case where GNSS signal is unavailable, other measurement updates can be used. In this paper, the knowledge of velocity errors during ZUPT is used as the measurement updates to KF to better estimate the position solution and the MEMS sensor errors. The state vectors used are:

$$x = (\delta p \quad \delta v^n \quad \delta \omega \quad \delta g^b \quad \delta a^b) \quad (4)$$

where  $\delta p$  is the vector of latitude, longitude and height errors;  $\delta \omega$  is the vector of misalignments about the navigation frame axes;  $\delta g^b$  is the vector of gyro bias errors and  $\delta a^b$  is the vector of accelerometer bias errors. During ZUPT epoch, the difference between velocity measurements and ZUPT measurements are entered to KF for estimation of errors. Effectively all type of observations or measurements that are known to be zero during stance phase can potentially be used in the measurement update equation, depending on how a system is designed and what kind of state space is being used. Note that the correlation between velocity error and attitude error are not discussed further in this paper. The measurement update used in this paper, which uses velocity update, is shown below (M = other states):

$$\begin{bmatrix} v_{INS}^e - v_0^e \\ v_{INS}^n - v_0^n \\ v_{INS}^u - v_0^u \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & \dots & 0 \end{bmatrix} \begin{bmatrix} dr^e \\ dv^n \\ M \end{bmatrix} + \begin{bmatrix} dv^e \\ dv^n \\ dv^u \end{bmatrix} \quad (5)$$

### 3. Tests and Results

Indoor pedestrian navigation test using a low-cost shoe mounted IMU was undertaken at our collaborative partner Geospatial Research Center New Zealand (GRCNZ). As mentioned before, the IMU used was the low-cost type which has the measurement limit of 300 deg/s for angular rotation and 5g for acceleration. Typical rotation of foot for walking pedestrian is between 600 deg/s to 900 deg/s [18]. The initial position was determined from GNSS receiver in this test; but other external sensors could also be used for initial positioning. The initial orientation of IMU was calculated during short stationary condition (1 or 2 seconds) from accelerometer measurements. The roll and pitch was calculated by differencing with local gravity vector whilst heading was determined from one-off magnetometer reading. Normal strapdown navigation equation such as in [1] was used to resolve and update the position and attitude of the IMU.

The walking test was performed for about 6 minutes and as follows: starting in an office on the first floor, walking to the start case, walking up (two flights) of stairs to the second floor, walking a loop around the second floor, walking up again until the fourth floor, walking into the lift of the fourth floor, descending in the lift to the first floor and walking back exactly the same start point in the first floor.

Data was post processed using POINT (Position and Orientation Integration) software as described in [19]. For stance phase detection, one of the method as described in section II was used. The magnitude of total acceleration was compared with certain threshold and whenever value falls below this threshold, stance phase is declared. Wrong ZUPT detections were removed by checking the occurrence of ZUPT a few steps before and after to confirm the accuracy of ZUPT detection period. 6 possible approaches were analyzed: DR only, DR with LWI correction, DR with RV correction, forward KF, forward KF with LWI correction and forward KF with RV correction. All data were compared with smoothed KF solution as a reference because smoothed KF solution is known to be the best possible solution for autonomous inertial navigation.

The output of three difference methods (from 6 approaches) as discussed in section II is plotted in Fig.1. It shows the Down velocity of these approaches and the figure is self-explainable. The other two velocity plots (North and East) show similarity. DR with correction mode (LWI) shows similarity with KF forward solutions where they outperformed DR only approach (DR with RV correction shows similar output). DR only approach has huge drift in velocity after only a short period of time; that will be translated later into position error. Inversely, the other two approaches are ‘immune’ to some of the drift errors because of the use of ZUPT.

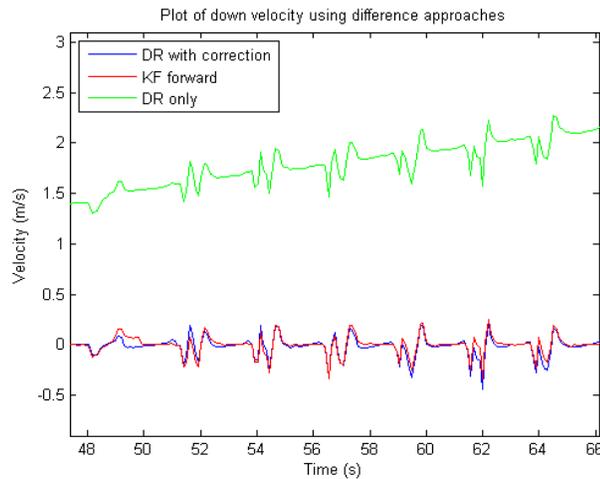


Fig. 1. Plot of down velocity using DR with correction, DR only and KF forward

Further analysis to Fig.1 revealed that although both corrected DR and Forward KF shows similarity, there are still differences in its solution as plotted in Fig.2. Fig.2 shows the Down-velocity difference between KF forward solutions with the LWI-corrected DR solutions and the standard deviation was found to be 0.04 m/s. In layman terms, it means that the difference in position between corrected DR and KF forward solution is about 4 cm in 1 second of movement.

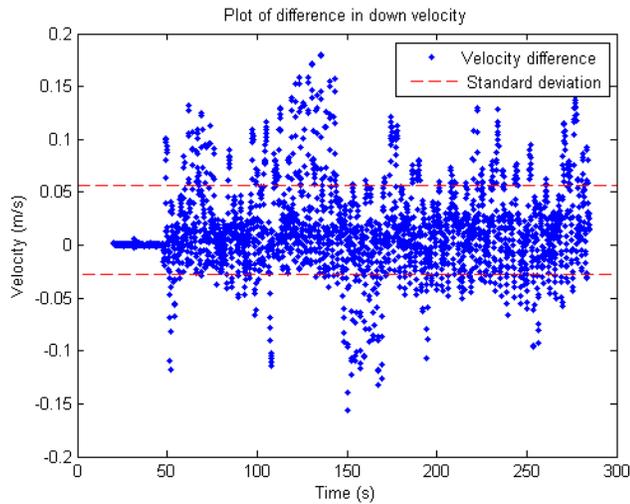


Fig. 2. Plot of Down-velocity differences between corrected DR and KF forward solution.

Table I show the comparison between the 6 approaches with the reference – assuming the KF smoothed solution as a reference. Table I shows the difference of position standard deviation values (STD) with the reference. The standard deviation of each approach was calculated and differenced with the standard deviation of the reference – the smallest value indicates the best value as it is the closest to the reference value. This is to show how far off each value with the reference value.

The obvious difference that can be compared is the use of DR with different types of correction mode. RV correction shows better performance than using LWI correction. Another approach shown is the combination of KF forward output with both correction modes (LWI and RV). This is performed to show that in a case of long GNSS outage; where there is no external position update to be used for KF smoothing, correction mode can become an alternative choice. This is because correction mode only uses data up to the current step and doesn't require position update. From both tables, it was shown that the 6th approach – forward KF with RV correction – shows an improved position solution from other approaches.

TABLE I  
COMPARISON OF POSITION STANDARD DEVIATION BETWEEN APPROACHES

Approaches	Latitude STD (m)	Longitude STD (m)	2D error (m)
1. DR	3790.46	1437.05	3148
2. DR + LWI Correction	3.00	1.17	25.84
3. DR + RV Correction	0.55	1.24	6.16
4. Forward KF	0.36	1.27	2.04
5. Forward KF + LWI	0.40	1.38	1.89
6. Forward KF + RV	<b>0.30</b>	<b>1.06</b>	<b>1.8141</b>

From Table I; for latitude, it improved from 0.33 m using Forward KF to 0.30 m (~10% improvement), and for longitude, it improved from 1.27 m using Forward KF to 1.06 m (~16% improvement). Also the absolute return position error in the x-y plane was computed as:

$$2D \text{ position error} = \sqrt{(X^2) + (Y^2)} \quad (6)$$

where X and Y represent the 2D final position error in meter (after converting from Lat and Long) assuming that the reference position starts and ends at (0,0). It can be seen that the sixth approach gives better 2D position errors as compared with all other approaches. Fig. 3 shows the position plot of Forward KF, Forward KF with RV correction and the smoothed KF solution as a reference. Note that for the purpose of this paper, all results are based on the assumption that there is no external position update at the end of the trajectory.

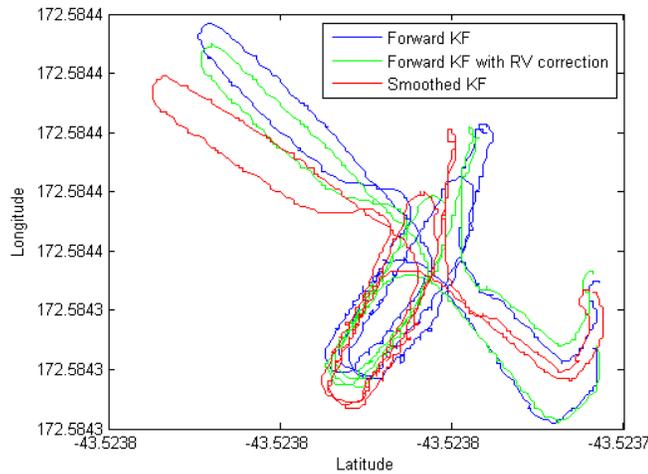


Fig. 3. Plot of down latitude and longitude for Forward KF, Forward KF with RV correction and Smoothed KF solution.

#### 4. Conclusion

Data gathered during experimental test was used to appreciate the performance of different approaches for MEMS-based pedestrian navigation with the assumption that there is no position update available at the end of the trajectory for all approaches – particularly useful for an autonomous navigation in a very long GNSS outage. Although the data were recorded in a short span of time, it is suffice to say that when ZUPT is used alone, the standard KF approach outperformed DR approach, even when conventional DR is assisted with a correction mode.

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