# **Trunk-Mounted PDR System Based on Inverted** Pendulum Model

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#### Abstract

The Pedestrian dead reckoning (PDR) using IMU mounted on trunk (e.g., back or chest), which is called trunk-mounted PDR, based on the inertial navigation system (INS) has better positioning performance due to the use of INS mechanization. However, the positioning error would accumulate rapidly because of the high noise level of low-cost inertial measurement unit (IMU). Existing trunk-mounted PDR are almost based on the assumption that the lateral and vertical velocity are zero, the same with the IMU is affixed to the vehicle, called nonholonomic constraint (NHC). However, the human body is a non-stationary platform with swaying motion observed in pedestrian movement, which does not align with the NHC. In this paper, the pedestrian movement pattern is modeled as an inverted pendulum model (IPM), that one point is the foot on the ground and the other one is the IMU mounted on the trunk, with the length of the pendulum is the distance from the IMU to the ground. At the same time, a trunk-mounted PDR based on IPM is proposed, which contains velocity measurement based on IPM (IPM-V) and distance increasement measurement based on IPM (IPM-D). Based on IPM-V, lateral speed is calculated using angular rate from gyroscope and length of the pendulum without assuming zero value, while lateral and vertical distances remain at zero within a single step cycle depending on IPM-D. Experimental findings demonstrate that the proposed method offers enhanced positioning accuracy and robustness compared to existing trunk-mounted PDR methods, with an 80% improvement in positioning accuracy.

#### Keywords

Pedestrian navigation, inertial navigation systems (INS), inverted pendulum mode(IPM).

# 1. Introduction

The demands for navigation and positioning have increased rapidly in people's daily lives[1]. While the global navigation satellite system (GNSS) effectively fulfills these requirements in outdoor settings, it faces limitations in indoor environments where satellite signals are obstructed. Various methods such as Bluetooth[2], Wi-Fi[3], UWB[4], and magnetic field matching [5] are commonly employed for indoor navigation. However, these techniques are infrastructure- or database-based, necessitating significant financial investment and human resources prior to the operational functionality of the system. Pedestrian dead reckoning (PDR) is an approach utilizing inertial navigation systems (INS) for indoor positioning and navigation. This autonomous method relies solely on data from the inertia measurement unit (IMU), which includes accelerometers and gyroscopes, to determine position without the need of external information or devices[6]. Consequently, PDR is considered a cost-effective and practical solution to indoor navigation compared to techniques that depend on infrastructure or databases.

Current PDR primarily relies on the integration of inertial navigation systems, specifically the Foot-mounted PDR which utilizes an IMU embedded in shoes. With high frequency of sample, Footmounted PDR has the ability to provide continuous 3-dimension position in real world space. Indeed,

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the errors will accumulate rapidly because of measurement noise when using a built-in Micro-Electro Mechanical System (MEMS) IMU without any other measurement[7]. To address this issue, some methods such as zero-velocity update technology (ZUPT)[8] and heuristic drift elimination (HDE)[9] are proposed. However, the requirement of special shoes to assure the device could operate normally is a notable constraint on Foot-mounted PDR[10].

Some researchers have taken attention to the potential of mounting IMU on trunk(e.g., waist, back, chest) to promote PDR to broader applications. [11] proposes an inverted pendulum based on a waist-mounted IMU to estimates step length; [12] integrates heading from madgwick algorithm, step length from the step model and an efficient map-matching algorithm based on particle filtering using a chest-mounted IMU; [13] estimates step length by Weinberg model and heading by a quaternion-based derivation of the explicit complementary filter based on a head-mounted IMU without rotation when operating. The scenario where a mobile phone is placed in a jacket pocket can be compared to affixing an IMU on the trunk of an individual. In this situation, it is assumed that the mobile phone has zero lateral velocity[14], which is similar to nonholonomic constraint (NHC), then the INS result is used to fuse with other information like magnetic field[15].However, while an individual moving, a distinct sway is evident, suggesting that the hypothesis does not match the real observations.

This paper introduces a trunk-mounted PDR based on only one IMU, using the inverted pendulum model (IPM) derived from pedestrian movement patterns. This system contains measurement of velocity based on IPM (IPM-V) and measurement of distance increasement based on IPM (IPM-D). Based on IPM-V, lateral speed can be computed by the date from the gyroscope. Based on IPM-D, lateral and vertical distance are zero in one step cycle. The proposed system only relies on an IMU consisted by accelerometers and gyroscopes, without additional devices. The experiment results show the proposed method exhibits superior accuracy and robustness compared to existing methods with nearly 80% improvement.

The rest of the paper is organized as follows. Section 2 introduces the principles of trunk-PDR based on IPM including Extended Kalman Filter (EKF) and the IPM derived from pedestrian moving patterns. In Section 0, experimental analyses are carried out to evaluate the proposed approach against conventional methods, focusing on the positioning accuracy. Section 4 summarizes this paper and looks forward to future research.

## 2. Proposed method

### 2.1. Coordinate systems

There are three primary coordinate systems in this paper: the IMU coordinate system (b), the human coordinate system (h), and the local horizontal coordinate system (n). The b-frame represents the IMU coordinate system, with its origin at the center of the IMU and the x-y-z directions indicating forward-right-down. The h-frame represents the human body coordinate system, sharing the same origin as the b-frame, with x-axis pointing towards the pedestrian's front, y-axis pointing to the right, and z-axis forming a right-handed orthogonal system with x-axis and y-axis. The n-frame represents the local horizontal coordinate system, with x-axis pointing towards virtual north, y-axis towards virtual east, and z-axis pointing downward.

### 2.2. System overview

The proposed algorithm workflow is depicted in Figure 1. The IMU provides angular rate and specific force inputs to the INS mechanization module for the computation of the IMU's navigation states, including position, velocity, and attitude (PVA). Concurrently, the IPM module utilizes the gyroscope angular rate with the rotation radius to produce lateral velocity measurements and zero increments in lateral and vertical directions. At the same time, the forward velocity module utilizes specific force data to detect steps and estimate step length. The Extended Kalman Filter (EKF) module then fuses these measurements to improve the system's accuracy and reliability.



**Figure 1**: Architecture of the trunk-mounted PDR system based on IPM **2.3. INS mechanization** 

The traditional INS mechanization is a typical inertial navigation algorithm with very rigorous theoretical logic. As the MEMS-IMU has a high level of noise, some items like earth rotation can be disregarded. therefore, the formulation of simplified INS mechanization for the MEMS-IMU is below [16]:

$$\begin{cases} r_k^n = r_{k-1}^n + v_k^n dt \\ v_k^n = v_{k-1}^n + C_{b,k}^n \left( \Delta v_k^b + \frac{\Delta \theta_k^b \times \Delta v_k^b}{2} \right) - g^n dt \\ C_{b,k}^n = C_{b,k-1}^n \left( I + \Delta \theta_k^b + \frac{\Delta \theta_{k-1}^b \times \Delta \theta_k^b}{12} \right) \end{cases}$$
(1)

Where *k* means the sample time; *dt* is the sample interval;  $r_k^n$  and  $v_k^n$  are the position and velocity in the n-frame at the k-th epoch;  $C_{b,k}^n$  donates the direction matrix from the b-frame to the n-frame at the k-th epoch.  $\Delta v_k^b = (f_k^b - b_{a,k})dt$  and  $\Delta \theta_k^b = (\omega_k^b - b_{g,k})dt$  donate velocity increasement and angle increasement in the b-frame, respectively.  $f_k^b$  is the specific force.  $\omega_k^b$  is the angular rate.  $b_{a,k}$  and  $b_{g,k}$  are the bias of the acceleration and the gyroscope, respectively.  $g^n$  is the location gravity vector in the n-frame, and ×is the cross-product form of the vector.

#### 2.4. Extended Kalman Filter

In this article, the 15-dimensional error state based EKF is chosen to integrate the IMU information and virtual measurement.

$$X = \begin{bmatrix} \delta r^n & \delta v^n & \phi & \delta b_a & \delta b_g \end{bmatrix}^T$$
(2)

Where  $\delta r^n$  is the position error in the n-frame;  $\delta v^n$  is the velocity error in the n-frame;  $\phi$  is the attitude error;  $\delta b_a$  and  $\delta b_g$  are errors of bias of the accelerometer and the gyroscope, respectively, which are modeled as a first-order Markov process.

#### 2.5. Measurement based on IPM

In this paper, the IMU is mounted on the back as an example to analyze the data from the IMU and model the movement when a pedestrian moving. Existing trunk-mounted PDR methods almost depend on the assumption that the lateral velocity is zero. However, as shown in Figure 2, the output of the accelerometer on the y-axis in the h-frame cannot be disregarded because of its notable strength and repetitive characteristics.



Figure 2: The data of accelometer on x-axis and y-axis in the h-fram during individual moving .

Hence, as shown in Figure 3, a pedestrian's gait involves a rhythmic alternation of the left and right feet swinging and resting while moving. To maintain balance, the pedestrian's center of gravity shifts to the right when the left foot swings forward and the right foot is planted on the ground. This process is mirrored when the right foot swings forward and the left foot is grounded. As a result, the IPM is proposed to describe the pattern of an individual's movement. The trajectory of the IMU mounted on the trunk follows a curve, represented by a red point in Figure 3.



Figure 3: The IPM while the pedestrian moving

#### 2.5.1. Measurement of velocity on the basis of IPM(IPM-V)

When the IMU is firmly affixed to the trunk, it will exhibit lateral movement in accordance with the body's motion. The dynamics of the IMU can be modeled as an inverted pendulum. The foot, in contact with the ground, serves as the pivot point, and the IMU traces a curved path. Consequently, the tiny displacement of the curve can be articulated as follows, as illustrated in Figure 4, when viewed from the  $x^h$  direction of Figure 3:

$$ds = d\alpha \cdot l \tag{3}$$

Where ds is the tiny displacement of the IMU;  $d\alpha$  is the tiny angle through which the lever rotates; *l* is the arm of the inverted pendulum, which is nearly the height from IMU to the ground. By deducing the above equation and projecting the vector to the h-frame, the lateral velocity obtained from the IPM can be expressed as:

$$P_{\nu}^{h} = C_{b}^{h} \omega_{nb,x}^{b} l \tag{4}$$

Where  $v_y^h$  is the velocity of y-axis in the h-frame;  $C_b^h$  is the translation matrix form the b-frame to the h-frame, which is confirmed by the mounting angle.  $\omega_{nb,x}^b$  is the angular rate from the b frame to the n frame. Considering that the MEMS IMU cannot measure the earth rotation for its high noise level, hence,  $\omega_{nb}^b \approx \omega_{ib}^b$ . The forward velocity is calculated by step-model, which includes detecting steps and estimating step length[17], and the vertical velocity is zero the in h-frame. According to the introduction to measurement of velocity above, the measurement of velocity is:

$$\tilde{v}^{h} = \begin{bmatrix} \frac{SL}{dt} & C_{b}^{h} \omega_{ib,x}^{b} l & 0 \end{bmatrix} = v^{h} + \varepsilon_{v}$$
(5)

Where  $\tilde{v}^h$  means the measurement of velocity in the h-frame;  $v^h$  is the truth of velocity vector. *SL* is the step length and *dt* is the time of step interval at n-th step. SL divided by dt is the forward velocity.  $\varepsilon_v$  is the noise of measurement of velocity. Given that the velocity update occurs within the h-frame, it is necessary to convert the velocity of the state from the n-frame to the h-frame. Therefore, the velocity from the INS mechanization in the n-frame from can be expressed as:

$$\hat{v}^{h} = C_{b}^{h} \hat{C}_{n}^{b} \hat{v}^{n}$$

$$= C_{b}^{h} C_{n}^{b} (I + \phi \times) (v^{n} + \delta v^{n})$$

$$\approx v^{h} + C_{b}^{h} C_{n}^{b} \delta v^{n} - C_{b}^{h} C_{n}^{b} (v^{n} \times) \phi$$
(6)

Where *I* is the Identity matrix;  $\phi$  is the attitude error; ×is the Skew-symmetric matrix of the vector. Therefore, the measurement of error states can be written as:

$$\delta z_{v} = \hat{v}^{h} - \tilde{v}^{h}$$

$$\approx \left(v^{h} + C_{b}^{h}C_{n}^{b}\delta v^{n} - C_{b}^{h}C_{n}^{b}(v^{n}\times)\phi\right) - (v^{h} + e_{v})$$

$$= C_{b}^{h}C_{n}^{b}\delta v^{n} - C_{b}^{h}C_{n}^{b}(v^{n}\times)\phi - \varepsilon_{v}$$
(7)

Hence, the measurement transition matrix is:

$$H_{k} = \begin{bmatrix} 0_{1\times3} & C_{b,k}^{h} C_{n,k}^{b} & -C_{b,k}^{h} C_{n,k}^{b} \left( v_{k}^{n} \times \right) & 0_{1\times3} & 0_{1\times3} \end{bmatrix}$$

$$IMU \quad y^{h}$$

$$I \quad y^{h$$

Figure 4: Lateral velocity on the basis of IPM.

## 2.5.2. Measurement of distance increments on the basis of IPM (IPM-D)

Simultaneously, the movement of the IMU and feet is depicted in Figure 5 (seeing Figure 3 from the  $z^h$  direction). The illustration shows that when both feet are in contact with the ground, the IMU is positioned centrally between the feet. Consequently, during a single step cycle, the lateral and vertical distances of the IMU are zero, based on the IPM. As Figure 5 shows, the right foot moves forward from k-1 to k, and in this step, the lateral distance of the IMU is zero. This establishes a motion constraint where there is no change in the y-axis and z-axis coordinates in the h-frame.

In a single step cycle, assuming that the velocity is linear over a short period, the distance of measurement and the INS mechanization can be expressed as [18]:

$$\Delta \tilde{s}^{h} = \sum \Delta \tilde{s}_{k}^{h}$$

$$= \sum_{i=k-N+1}^{k} \frac{1}{2} \left( \tilde{v}_{i-1}^{h} + \tilde{v}_{i}^{h} \right) dt$$

$$= [\Delta s \quad 0 \quad 0]^{T} + \varepsilon_{s}$$
(9)

$$\Delta \hat{s}_{k}^{h} = \int_{t_{k-1}}^{t_{k}} \hat{v}^{h}(t) dt \approx \hat{v}_{k-1/2}^{h} dt = \frac{1}{2} \left( \hat{v}_{k-1}^{h} + \hat{v}_{k}^{h} \right) dt \tag{10}$$

$$\Delta \hat{s}^{h} = \sum \Delta \hat{s}^{h}_{k} = \sum_{i=k-N+1}^{k} \frac{1}{2} \left( \hat{v}^{h}_{i-1} + \hat{v}^{h}_{i} \right) dt$$
(11)

Where:  $\tilde{v}_k^h$  and  $\hat{v}_k^h$  denote the velocity determined by the step-model and INS in the k-th in the h-frame, respectively. *i* means the sample time in a single step cycle. Then,

$$\delta z_{s} = \Delta \hat{s}^{h} - \Delta \tilde{s}^{h} = \sum_{i=k-N+1}^{k} \left( \Delta \hat{s}_{k}^{h} - \Delta \tilde{s}_{k}^{h} \right) - \varepsilon_{s}$$

$$= \frac{1}{2} \sum_{i=k-N+1}^{k} \left[ \delta v_{i-1} + \delta v_{i} \right] dt - \varepsilon_{s}$$

$$= \frac{1}{2} \sum_{i=k-N+1}^{k} \left[ H_{i-1} \delta x_{i-1} + H_{i} \delta x_{i} \right] dt - \varepsilon_{s}$$

$$\delta x_{k-N} = \Phi_{k/k-N}^{-1} \delta x_{k}$$
(12)

Where,  $\Phi_{k/k-N}$  is the state transition matrix from  $t_{k-N}$  to  $t_k$ , and N is the sample times in a single step cycle. Finally, in a single step cycle, the measurement transition matrix is:

$$H_{s} = \frac{1}{2} H_{k-N} \Phi_{k/k-N}^{-1} dt + \sum_{i=k-N+1}^{k} H_{i} \Phi_{k/i}^{-1} dt - \frac{1}{2} H_{k} dt$$
(14)



Figure 5: Schema of IPM overlooked

# 3. Experiment and results

#### 3.1. Test description

Figure 6 illustrates the positional relationship of the sensors worn by the tester, including the back and heel. The experimental area comprises the standard office indoor environment and the outdoor environment. The MTw IMU device from Xsens is used to collect data with 100Hz and its specification is shown in Table 1. Five methods are used to handle the data form the IMU. They are:

1)IPM-V: This method uses the IPM-V to constrain the accumulated error from INS mechanization; 2)IPM-D: This method uses the IPM-D to constrain the accumulated error from INS

mechanization;

3)IPM-VD: This method uses the IPM-V and IPM-D both;

4)NHC-PDR: This method is state-of-the-art with the assumption that lateral velocity is zero all the time[19];

5)Foot-PDR: This method uses the IMU mounted on the foot with basic zero-velocity update (ZUPT) and zero-integrated heading rate (ZIHR), without additional observation such as environment information.

The step detection and step length estimation methods in IPM-V, IPM-D, IPM-VD and NHC-PDR are the same. FOOT-PDR uses the data from IMU mounted on the foot; IPM-V, IPM-D, IPM-VD and

NHC-PDR use the data from the IMU mounted on the back. Since FOOT-PDR is relative positioning methods, use the angle between the tenth step and reference line to correct the test trajectory. This procedure enables the conformity of the trajectory of the five methods.

# Table 1

The specification of the MTw IMU

Sensor Types	Accelerometer	Gyroscope
Range (of scales)	$\pm 160 \text{m/s}^2$	±1200deg/s
Linearity	0.2%	0.1%
Stability	-	20deg/hour
Noise	$0.003 m/s^2/Hz^{1/2}$	$0.05 deg/s/Hz^{1/2}$

Figure 6: The positional relationship between Trunk-mounted IMU and Foot-mounted IMU.

## 3.2. Indoor test

The indoor trajectory is 54.4 m in length with two 90-degree turns. This test contains 10 tests for each method. The end position error for each method, along with its average and variance, is presented in Table 2 and Figure 7 to assess the accuracy of the position estimation in meters. In Table 2, the best and second-best results among the five methods in each trial are highlighted in red and blue, respectively. According to Table 2, IPM-VD and IPM-V achieve the best and second-best results, outperforming NHC-PDR and FOOT-PDR.



**Figure 7**: The results of indoor test: (a) The estimated trajectories of indoor test in 10 tests; (b) End point position error of the indoor test trajectories in 10 tests

**Table 2**The End Point Position Error ot Five Methods in 10 Tests

test	1	2	3	4	5	6	7	8	9	10	Mean	Variance
IPM-V	0.590	2.834	1.038	1.438	0.808	1.796	1.026	1.517	1.378	2.947	1.537	0.571
IPM-D	2.635	0.549	3.353	3.866	1.413	4.133	1.242	3.194	0.800	3.067	2.425	1.548
IPM-VD	0.957	2.606	0.769	1.037	0.140	1.257	0.058	1.418	0.989	1.511	1.074	0.471
NHC-PDR	3.823	3.764	3.919	4.792	3.174	0.885	0.673	2.013	1.883	1.409	2.634	1.864
FOOT-PDR	2.177	2.639	4.532	3.430	5.961	3.180	5.811	5.831	3.833	2.985	4.038	1.798

## 3.3. Outdoor test

The outdoor test area is shown in Figure 8, which is a rectangle of 400m in length. Five trajectories derived from five methods and ground truth obtained from GNSS are depicted in Figure 8. In Table 3, the closing errors and positioning errors of the second turning of the five trajectories. The best and second-best results among the five methods in each trial are also highlighted in red and blue, respectively. The closing error of IPM-VD is 3.231m, which is 79% and 82% better than NHC-PDR and FOOT-PDR, respectively. Considering that the results of the INS mechanization would neutralize each other in opposing directions, the position error of the second turn, which is the farthest point from the starting point on the entire test track, is used to evaluate the performance of the five methods. The positioning error of the second turning of IPM-VD is 2.540m, which is 77% and 87% better than NHC-PDR, respectively.

The reason is that NHC-PDR assuming that lateral velocity is zero, does not align with an individual's movement pattern, while FOOT-PDR lacks the capability to determine direction. The proposed approach imposes restrictions on lateral and vertical velocity or distance, thereby improving the accuracy of direction estimation.



Figure 8: The estimated trajectories of outdoor test

## Table 3

The Position Error of Five Methods in Outdoor Test

test	IPM-V	IPM-D	IPM-VD	NHC-PDR	FOOT-PDR
closing error/m	8.907	7.704	3.231	15.146	17.733
positioning error of the second turning/m	3.711	7.456	2.540	11.2639	19.1625

# 4. Conclusion

This paper presents trunk-mounted PDR based on IPM to use only an IMU to fulfill pedestrian positioning. The proposed method constraints the accumulated errors in the INS mechanization with IPM derived from pedestrian movement patterns, which matches the real observations with the lateral velocity caused by tiny slosh and the lateral and vertical distance are zero in one step cycle in

h-frame, which called IPM-V and IPM-D. The results of the experiments suggest that the proposed methods demonstrate superior position accuracy compared to current methods, showing an approximate 80% improvement in positioning accuracy in the outdoor test. Trunk-PDR based on IPM provides a simple way to install and has huge potential to promote to smartphone-based pedestrian navigation when the smartphone is put in a jacket pocket. In the future, Trunk-INS is expected to integrate with additional techniques employed in foot-INS systems to enhance positional accuracy.

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