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Foot Mounted Inertial Navigation System using Estimated Velocity During the Contact Phase

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***Abstract*—In this paper, we propose foot mounted inertial navigation system using estimated velocity during the contact phase. Generally, pedestrian dead-reckoning (PDR) system with foot mounted inertial sensors often uses zero-velocity update (ZUPT) for reducing the influence of the bias and white noises in the gyroscope and accelerometer signals. extended Kalman filter (EKF) for a ZUPT-aided INS can estimate the errors of inertial navigation system (INS) by using the assumption that there is no movement of the foot on the ground during the stance phase. However, when pedestrian walks irregularly, ZUPT is not suitable because the velocity is not small enough to assume the zero velocity during the stance phase. Therefore, ZUPT cannot estimate the accurate error states of the filter because the zero velocity is not reliable during the stance phase at the irregular walk. In order to improve the PDR system performance, the proposed algorithm uses the estimated velocity measurement by using the constraint between the surface and the foot during the contact phase.**

Keywords—Pedestrian dead reckoning, zero velocity update, contact phase, estimated velocity

I. INTRODUCTION

PDR system only uses its own sensor without infrastructure for estimating pedestrian's position. The PDR system generally uses the assumption that pedestrian changes position by movement of their step. PDR system has a difference in the algorithm according to the mounting position of the sensor [1-6]. Among them, foot-mounted INS [3-7] is used for the accurate position estimation because foot-mounted ZUPT aided EKF can estimate the errors of INS by using the assumption that there is no movement of the foot on the ground during the stance phase.

Generally, foot mounted PDR system often use ZUPT aided EKF for reducing the influence of the bias and white noises in the gyroscope and accelerometer signals. ZUPT aided EKF can estimate the errors of INS by using the assumption that there is no movement of the foot on the ground during the stance phase. However, movement occurs during the stance phase when pedestrian walks. This movement depends on the pedestrian's behavior. For normal walk, there is almost no movement during the stance phase. However, for irregular walk, the movement cannot be ignored during the stance phase.

The heel strike impulse also makes some problem to estimate position because the transient and large acceleration and angular velocity, which is cannot measured by the accelerometer and the gyroscope, occurs momentarily by the heel strike impulse [6]. To reduce the heel strike impulse, the modified error covariance matrix related to the velocity are used in [7]. However, the velocity measurement update during the stance phase cannot estimate the accurate error states because the velocity is not reliable after heel strike.

In this paper, in order to consider the movement which cannot be ignored during the stance, we proposed PDR system using estimated velocity during the contact phase. The contact phase includes the phase that the shoe is attached to the ground with movement. It can help estimate the accurate error state by using the velocity measurement with movement. In order to estimate velocity, we assume that the shape of the shoe outsole is similar to the ellipsoid. If the shape of the outsole is similar to the ellipsoid, we can calculate the position of the contact point between ground and shoe by using roll and pitch angle. Since the shoes is rotated around the contact point, we can estimate the velocity by using the assumption. And in order to consider the heel strike, we use adaptive EKF which reflect the heel strike impulse.

The paper is structured as follows. In Section 2, we explain the adaptive EKF considering the heel strike impulse. In Section 3, we explain the estimated velocity during the contact phase using the assumption that the shape of the sole outsole is similar to ellipsoid. In Section 4 the experimental results show that the improved filter performance by comparing the proposed algorithm and conventional algorithm.

II. ADAPTIVE EKF CONSIDERING THE HEEL STRIKE IMPULSE

In this section, we proposed adaptive EKF which considers the unmeasured acceleration and angular velocity by heel strike impulse as shown in Fig. 1. The proposed algorithm detects the heel strike phase when the acceleration is not properly measured and reflects the heel strike affect to the process noise Q. In order to consider heel strike, we detect heel strike by using measured acceleration because accelerometer measures the large acceleration although the magnitude of the acceleration is small compared to the actual acceleration [7].

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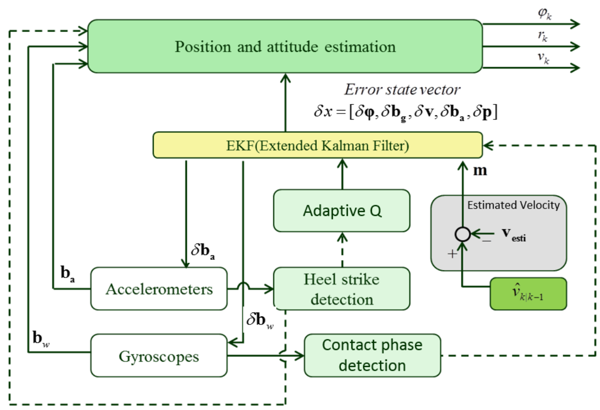

Figure.1 The block diagram of adaptive EKF considering the heel strike impulse and using estimated velocity during the contact phase.

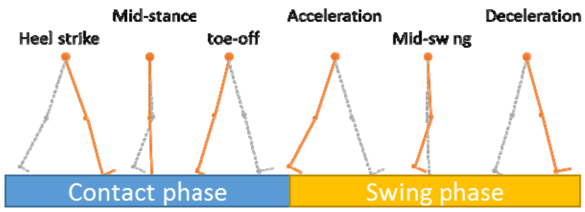

Figure.2 Step phase classification

In order to reflects the heel strike affect to the process noise Q, we use the EKF based INS with 15 error states. 15 error states is expressed as follows: $\delta x = [\delta \boldsymbol{\varphi}, \delta \mathbf{b}_g, \delta \mathbf{v}, \delta \mathbf{b}_a, \delta \mathbf{p}]$, which are contain the errors in attitude ($\delta \boldsymbol{\varphi}$), velocity ($\delta \mathbf{v}$), position ($\delta \mathbf{p}$), gyro bias ($\delta \mathbf{b}_g$), and accelerometer bias ($\delta \mathbf{a}^b$). The state transition matrix is

$$\boldsymbol{\Phi} = \begin{bmatrix} \mathbf{I}_{3\times3} & \mathbf{C}_b^n \cdot \mathbf{dt} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_{3\times3} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ -\mathbf{S} \cdot \mathbf{dt} & \mathbf{0} & \mathbf{I}_{3\times3} & \mathbf{C}_b^n \cdot \mathbf{dt} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_{3\times3} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_{3\times3} \cdot \mathbf{dt} & \mathbf{0} & \mathbf{I}_{3\times3} \end{bmatrix} \quad (1)$$

where $\mathbf{C}_b^n$ is the rotation matrix that transforms value from the body (b) to the navigation (n) frame, dt is the sample interval between two discrete samples, and $\mathbf{S}$ is the skew symmetric matrix for accelerations in the navigation frame. Generally, process noise Q determined by sensor performance. In this case, we change process noise very large at the heel strike phase for considering heel strike affect. The process noise Q at the moment is

$$Q = \left[\mathbf{I}_{3\times3} \cdot (0.5\deg/s)^2 \quad \mathbf{0} \quad \mathbf{I}_{3\times3} \cdot (0.3m/s)^2 \quad \mathbf{0} \quad \mathbf{0} \right] \quad (2)$$

The values mean the angle and velocity which can be changed at the heel strike with unmeasured acceleration and angular velocity.

III. THE ESTIMATED VELOCITY DURING THE CONTACT PHASE

In this section, in order to consider the movement which cannot be ignored during the stance, we proposed PDR system using estimated velocity during the contact phase as shown in Fig. 1. The contact phase includes the phase that the shoe is attached to the ground with movement. It can help estimate the accurate error state by using the velocity measurement with movement. In order to estimate velocity, we assume that the shape of the shoe outsole is similar to the ellipsoid. If the shape of the outsole is similar to the ellipsoid, we can calculate the position of the contact point between ground and shoe by using roll and pitch angle. Since the shoes is rotated around the contact point, we can estimate the velocity by using the assumption.

A. *Contact phase detection*

The contact phase includes the phase that the shoe is attached to the ground with movement as shown in Fig. 2. Therefore, we can use the heel strike detection algorithm because the contact phase is immediately after heel strike for contact phase detection. The end of the contact phase can be detected by comparing the velocity based on INS with the estimated velocity based on the ellipsoid assumption. At the moment the contact phase ended, the estimated velocity cannot show the accurate velocity. Therefore, the difference between INS based velocity and the ellipsoid assumption based velocity can be used for detecting the end of contact phase.

B. *Estimated velocity using the ellipsoid assumption*

In order to estimate velocity, we assume that the shape of the shoe outsole is similar to the ellipsoid. If the shape of the outsole is similar to the ellipsoid, we can calculate the position of the contact point between ground and shoe by using roll and pitch angle. The contact point is

$$\begin{gathered} \mathbf{p_A} = f(\phi, \theta) \\ \frac{{p_{Ax}}^2}{a^2} + \frac{{p_{Ay}}^2}{b^2} + \frac{{p_{Az}}^2}{c^2} = 1 \end{gathered} \quad (3)$$

Where ϕ is roll angle of the sensor and θ is pitch angle of the sensor. If we can calculate the p_A, we can get the velocity by using angular velocity $\mathbf{w}$

$$\begin{gathered} \mathbf{r_s} = \mathbf{p_B} - \mathbf{p_A} \\ \mathbf{v_{esti}} = \mathbf{w} \times \mathbf{r_s} \end{gathered} \quad (4)$$

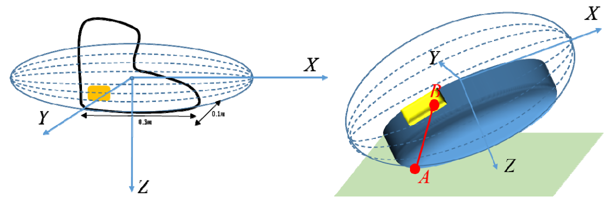

Figure.3 The shape of the shoe outsole which is similar to the ellipsoid

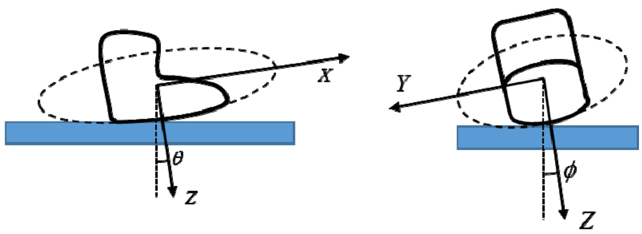

Figure.4 The slope of the ellipsoid surface

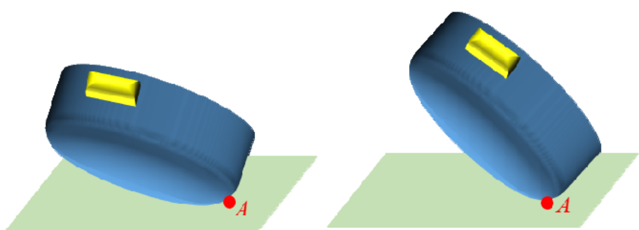

Figure.5 The contact point at the large pitch angle

The function $f(\phi,\theta)$ can be calculated by roll ,pitch angle and the slope of the ellipsoid surface as shown in Fig. 4. First, p_{Ax} is expressed by:

$$\tan\theta = \frac{dz}{dx}$$
$$\frac{d\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)}{dx} = \frac{2x}{a^2} + \cancel{\frac{2y}{b^2}\frac{dy}{dx}} + \frac{2z}{c^2}\frac{dz}{dx} = 0 \tag{5}$$
$$\frac{dz}{dx} = -\frac{2x}{a^2} / \frac{2z}{c^2} = -\frac{c^2}{a^2}\frac{x}{z}$$
$$P_{Ax} = -\frac{a^2}{c^2}\tan\theta \cdot z$$

p_{Ay} and p_{Az} is expressed by:

$$\tan\phi = -\frac{dz}{dy}$$
$$1 = \frac{1}{a^2}\frac{a^4}{c^4}\tan^2\theta \cdot z^2 + \frac{y^2}{b^2} + \frac{z^2}{c^2} = \left(\frac{a^2}{c^4}\tan^2\theta + \frac{1}{c^2}\right)z^2 + \frac{y^2}{b^2}$$
$$\frac{d\left(\left(\frac{a^2}{c^4}\tan^2\theta+\frac{1}{c^2}\right)z^2+\frac{y^2}{b^2}\right)}{dy} = \left(\frac{a^2}{c^4}\tan^2\theta+\frac{1}{c^2}\right)2z\frac{dz}{dy} + \frac{y}{b^2} = 0 \tag{6}$$
$$P_{Ay} = \tan\phi\left(\left(\frac{a^2}{c^4}\tan^2\theta+\frac{1}{c^2}\right)\right)b^2 z$$

$$P_{Az} = \sqrt{\frac{1}{\frac{a^2}{c^4}\tan^2\theta + \left(\frac{a^2}{c^4}\tan^2\theta+\frac{1}{c^2}\right)^2 b^2\tan^2\phi + \frac{1}{c^2}}} \tag{7}$$

Therefore, the function $f(\phi,\theta)$ is expressed by:

$$f_x(\phi,\theta) = -\frac{a^2}{c^2}\tan\theta \cdot f_z(\phi,\theta)$$
$$f_y(\phi,\theta) = \tan\phi\left(\left(\frac{a^2}{c^4}\tan^2\theta+\frac{1}{c^2}\right)\right)b^2 f_z(\phi,\theta) \tag{8}$$
$$f_z(\phi,\theta) = \sqrt{\frac{1}{\frac{a^2}{c^4}\tan^2\theta + \left(\frac{a^2}{c^4}\tan^2\theta+\frac{1}{c^2}\right)^2 b^2\tan^2\phi + \frac{1}{c^2}}}$$

When the angles are small, the contact point follow the function $f(\phi,\theta)$. However, when the angles are large, the contact point is almost fixed as shown in Fig. 5. Therefore, we determine the angle limit for using the function. The angle limit is determined by the shape of the shoes.

$$p_A \begin{cases} p_A = \mathrm{f}(\phi,\theta) & 3° > |\phi|,\ 8° > \theta > -25° \\ p_A = \mathrm{f}(3°,\theta)\ \ or\ \ \mathrm{f}(-3°,\theta) & 8° > \theta > -25°,\ |\phi| > 3° \\ p_A = \mathrm{f}(\phi, 8°) & \theta > 8°,\ |\phi| > 3° \\ p_A = \mathrm{f}(\phi,-25°) & -25° > \theta,\ |\phi| > 3° \end{cases} \tag{9}$$

The position of the sensor and the radius of the ellipsoid is also determined by the shape of the shoes and attached position of the sensors. As shown in the equation (4), velocity can be estimated by roll and pitch angle.

IV. Experimental Results

The tests were performed in three type of the walk by using foot mounted IMU and the Xsens MTx sensor was used in our experiments. In our system, we use IMU data sampled with 100Hz for the tests. Before walking, the gyro held completely motionless for 5 second in order to measure the static gyro bias. The tests were performed in normal walk, running and squat walk in a square trajectory of 2-meter-long side with ten laps (three laps in squat walk). In order to verify the performance, we get the reference data by using Vicon motion capture system.

In normal walk, the proposed algorithm shows a litter bit better performance in comparison with conventional algorithm. In running and squat walk, the proposed algorithm shows a much better performance in comparison with conventional algorithm because the estimated velocity much more accurate than zero velocity in irregular motion.

TABLE I

RESULTS OF PROPOSED ALGORITHM COMPARING WITH CONVENTIONAL ALGORITHM (UNIT: M)

RMSE (root mean square error)	Normal walk	Running	Squat walk
Conventional algorithm	0.104m	0.380m	0.288m
Proposed algorithm	0.087m	0.158m	0.156m

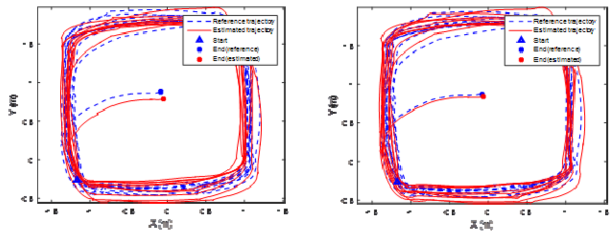

Figure.6 The result of the estimated position in normal walk using conventional algorithm (left) and proposed algorithm (right)

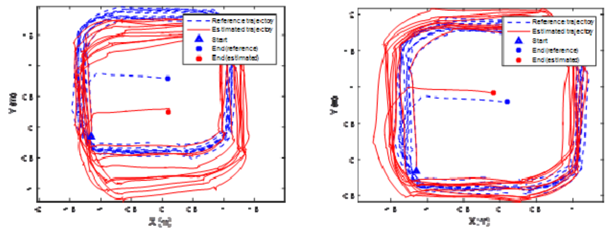

Figure.7 The result of the estimated position in running using conventional algorithm (left) and proposed algorithm (right)

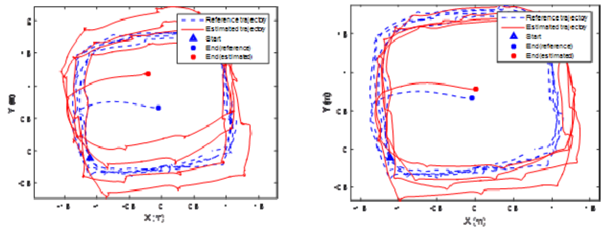

Figure.8 The result of the estimated position in squat walk using conventional algorithm (left) and proposed algorithm (right)

V. CONCLUSIONS

In this paper, we propose foot mounted inertial navigation system using estimated velocity during the contact phase. In order to estimate the velocity during the contact phase, the proposed algorithm detects the contact phase that the shoe is attached to the ground with movement and assumes that the shape of the shoe outsole is similar to the ellipsoid. The experiment results show that conventional algorithm has large errors especially when the pedestrian walks irregularly but proposed algorithm can reduce the error by using estimated velocity. Lately, foot mounted INS has been used in various fields such as motion capture system. This approach can help improve the estimation performance various systems, as well as PDR system

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