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Zero-Velocity Detection Method Based on Ultrasonic Ranging Assistance

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Abstract: The accumulated error in inertial pedestrian navigation can be transplanted through the zero-velocity correction algorithm, and the zero-velocity detection algorithm at this stage has the problems of single threshold, easy to miss detection and false detection, large calculation amount and large calculation delay. In order to solve these problems, an ultrasonic ranging auxiliary zero-velocity detection method is proposed. The foot spacing is measured in real time by an ultrasonic sensor placed on both feet, and then a time constraint is added to the Generalized Likelihood Ratio (GLRT) method using the time relationship between the shortest foot spacing and the zero-velocity interval. Experiments show that the accuracy of the proposed algorithm is better than that of the single threshold method under different gait states, and the average accuracy is above 95%. And due to the characteristics of high ultrasonic short-distance accuracy and small size, this method has simple calculation and small delay, which has practical application value.

Keywords: Inertial navigation; Zero-velocity detection covered; Ultrasonic ranging.

1. Introduction

Nowadays, the increasingly complex traffic environment and the increasing number of special working environments urgently require accurate and stable navigation and positioning systems, especially in special industries such as fire rescue, power grid survey, pipeline operations, and individual combat. Among them, the Global Navigation Satellite System (GNSS) is a common solution for outdoor navigation and positioning [1]. However, in scenes such as forests, tunnels, urban canyons, and indoor environments, GNSS positioning results can produce huge errors due to signal rejection or interference. The positioning system based on Inertial Measurement Unit (IMU) has high anti-interference and autonomy [2]. It can realize navigation and positioning only by relying on the carrier attitude data measured by inertial sensors, without relying on external signals. Therefore, IMU-based pedestrian inertial positioning technology has become a current research hotspot [3].

The basic principle of inertial positioning is to integrate the inertial data provided by IMU to obtain the position, velocity and attitude of the object. However, the error of the inertial device will accumulate with the integration, and the precise positioning result cannot be output in the long-term positioning process. In order to solve the problem of accuracy reduction in inertial positioning, Foxlin E proposed Zero Velocity Update (ZUPT) algorithm in 2006[4]. The ZUPT algorithm corrects the IMU cumulative error by detecting the static state in the gait cycle. The key to the success of the ZUPT algorithm is whether the zero-velocity phase can be accurately detected. The acceleration amplitude detection and acceleration variance detection only use the specific force measured by the accelerometer, and the angular velocity energy detection only requires gyroscope data [5]. Based on the study of acceleration variance, acceleration amplitude and angular velocity energy, Skog I combine the three detection models by logic ' and ' to derive the generalized likelihood ratio detection (GLRT) method [6]. The discriminant threshold of the above four detection methods is single, which is easy to miss or misjudge. Wang Y used Bayesian method to determine the threshold of zero velocity detection under different gaits, so that the zero-velocity detector could adapt to different gait patterns [7]. Wagstaff proposed a zero-velocity detection method based on deep learning, which realized zero-velocity estimation under various gait conditions [8]. In order to improve the efficiency of learning, Chen proposed a zero-velocity detection method based on comparative learning, which accelerates the convergence velocity of learning by pre-classifying inertial data [9]. The data-driven algorithm has good adaptability to different motion gaits, but the premise requires a lot of experiments and uses data containing various motion states to train the model.

Aiming at the problem that the above zero-velocity detection method is easy to miss and misjudge, the calculation amount is large, the delay is large, or a large number of training models are required. By analyzing the relationship between the shortest foot spacing and the zero-velocity interval in time, this paper uses the ultrasonic ranging data to add time constraints to the generalized likelihood ratio method, and proposes a zero-velocity detection method based on ultrasonic ranging assistance. The experimental results show that the detection accuracy of this method is better than that of single threshold zero velocity detection method under different gaits, and the calculation delay is small.

2. Ultrasonic ranging assisted zero velocity detection

2.1. Foot spacing was measured by ultrasound

Foot spacing is measured by ultrasonic sensors installed on both feet. The schematic diagram of ranging is shown in figure 1. where, R_{i1}, R_{i2}, R_{i3} are the position of the right foot at the beginning of the swing stage, the projection position on the horizontal plane at the middle time and the position at the end time. l_{i-1}, l_i are respectively the distance between feet of no.$i-1$ and no.i step, this distance is the maximum distance between the feet, d is the shortest distance between feet.

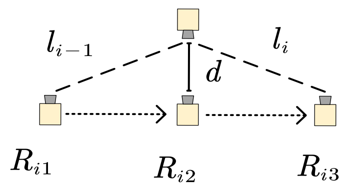

Fig. 1 Schematic diagram of ultrasonic ranging

Considering the stability of the ultrasonic sensor device itself, the data collected by it will be jitter, which may bring errors to the subsequent selection of zero velocity interval. Therefore, this paper uses Locally Weighted Scatterplot Smoothing (LOWESS) to preprocess the data to reduce data jitter.

The comparison effect of ultrasonic data after smoothing and preprocessing is shown in figure 2. It can be seen from figure 2 that the overall change trend of ultrasonic data after smoothing and preprocessing has not changed. Due to the limitation of the measurement Angle of ultrasonic sensor and the jitter when the foot hits the ground, the data peak value is more fluctuated compared with the estimation, so the shortest foot spacing is more suitable for the subsequent ultrasonic ranging assisted inertial positioning algorithm than the maximum foot spacing. The smoothing preprocessing algorithm effectively filters out the mutation values in the data.

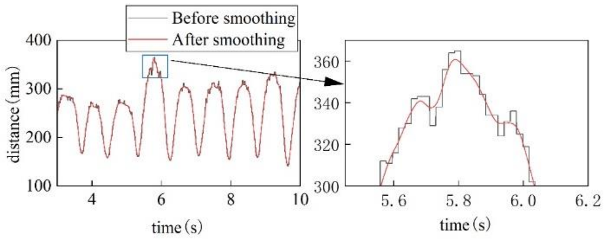

Fig. 2 Comparison of ultrasonic data before and after smoothing

In figure 2, it can also be seen that the foot spacing data measured by ultrasound are presented as a periodic signal as a whole. This is because the distance between the feet of pedestrians in normal walking shows a periodic change of maximum - minimum - maximum value. The peak of the data corresponds to the support phase when the pedestrian is walking. Therefore, it can be considered that during the stable gait, the beginning moment of the zero-velocity phase of the foot is separated by a stable time from the moment when the shortest foot spacing is measured.

2.2. Ultrasonic ranging assisted zero velocity detection

The flow chart of the ultrasonic ranging assisted zero-velocity detection algorithm proposed in this paper is shown in figure 3.

The ultrasonic ranging assisted zero-velocity detection algorithm firstly uses the ultrasonic ranging information to obtain the time value of the shortest foot spacing t_{min}, then on the basis of this time value, a time threshold is added to determine a preliminary zero velocity interval. Considering that the time threshold is affected by the system time accuracy and sensor time synchronization accuracy, the zero-velocity interval determined by time can only be used as a preliminary reference. The preliminary zero-velocity interval is expressed in the time axis as formula (1).

$$t_{zero} \in [t_{min} + \Delta t, t_{min} + \Delta t + t_0] \quad (1)$$

In the formula, Δt is the time interval between the moment when the minimum foot spacing is detected and the moment when the sole of the foot fully contacts the ground, which can be considered as one half of the duration of the pedestrian swing phase; t_0 is the duration of the zero-velocity phase.

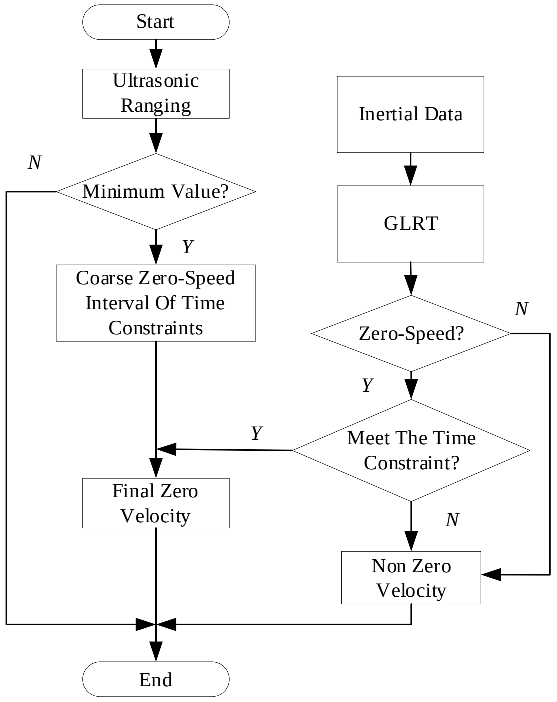

Fig. 3 Algorithm flow

Finally, the generalized likelihood GLRT method is used to determine whether each data point is a zero-velocity point, and then whether the time value of the detected zero-velocity data point satisfies formula (1). If so, the data point is determined to be the final zero-velocity point; if not, it is determined to be a non-zero-velocity point. Where, the calculation formula of GLRT is given by formula (2).

$$T_k = \frac{1}{W} \cdot \sum_{k=n}^{n+W-1} \left(\frac{1}{\sigma_a^2} \parallel a_k - g\frac{\overline{a}_k}{\|\overline{a}_k\|^2} \parallel + \frac{1}{\sigma_\omega^2} \parallel \omega_k^2 \parallel\right) \quad (2)$$

Where, a_k is the acceleration value; W is the window length; σ_a is the standard deviation of random noise of the accelerometer; $\overline{a}_k$ is the mean of the acceleration in the window; ω_k is the angular velocity value; σ_ω is the standard deviation of the random noise of the gyroscope; g is the local acceleration of gravity. Among them, the discriminant formula of GLRT is the formula (3). When the detection statistic T_k is greater than γ, it is judged to be non-zero velocity, otherwise it is non-zero velocity.

$$\begin{cases} T_k > \gamma \\ T_k \leq \gamma \end{cases} \quad (3)$$

3. Experiment

In order to verify the accuracy of the proposed method, the experiment is selected in the experimental scenario shown in Figure 4. The experimental scene includes stairs and platforms.

In this paper, data were collected for 10 s for four exercise states of walking, running, going upstairs and going downstairs. Considering that the intermediate data can express the motion characteristics more stably, the data from the 3rd to the 7th s of each motion state are intercepted as the original data for subsequent zero-velocity detection. The installation method of the experimental equipment is shown in Figure 5, in which the ultrasonic sensor is installed in the front of the feet, the IMU is installed on the heel, and the data is sent to the host computer through Bluetooth through two data collectors.

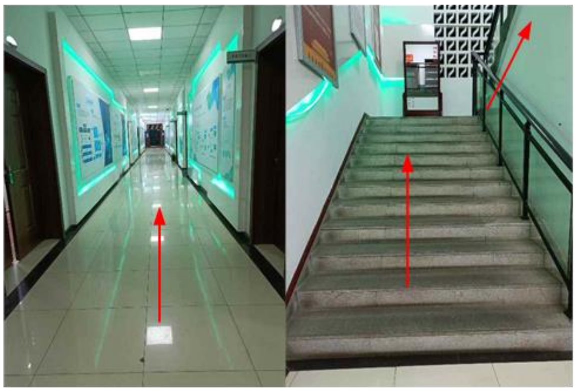

Fig. 4 Experimental scene

Fig. 5 Experimental equipment

In order to obtain the threshold of the zero-velocity detection method, this paper first performs Fourier transform on the original data in different states to obtain the gait period, then analyzes the proportion of the zero-velocity interval in each motion state, and finally determines the optimal detection statistics and sliding window by cyclic heuristic, the zero-velocity detection threshold in this paper is shown in Table 1.

Table 1. Zero-velocity detection threshold

	W	Δt	t_0	T_k
Walk	15	0.43 s	0.65 s	1.15×107
Jogging	5	0.31 s	0.13 s	2.19×107
Upstairs	20	0.51 s	0.47 s	4.48×106
Downstairs	20	0.50 s	0.51 s	3.81×106

In order to obtain the benchmark of zero-velocity detection, the zero-velocity interval is manually determined, and then the ultrasonic ranging auxiliary method and the detection results of GLRT are compared with the benchmark to obtain the accuracy, missed detection rate and false detection rate of detection, and the detection results are shown in Table 2.

From Table 2, it can be obtained that the accuracy of the two zero-velocity detection algorithms can reach more than 99% in the walking state. However, in running and going upstairs, the detection accuracy of the single threshold method decreased significantly, and although the ultrasonic ranging assisted zero-velocity detection method also declined, the accuracy rate remained above 95%. The results of zero-velocity detection experiment show that after adding time constraints to the zero-velocity interval by using the foot spacing measured by the ultrasonic sensor, the accuracy of zero-velocity detection and the adaptability to different motion states have been significantly improved compared with GLRT. The comparison chart of the zero-velocity detection effect is shown in Figure 6.

Table 2. Zero-velocity test results

	gait	Ultrasonic ranging assistance	GLRT
Accuracy (%)	Walk	99.4	99.1
	Jogging	98.2	86.9
	Upstairs	97.2	51.4
	Downstairs	96.5	53.6
False detection rate (%)	Walk	0.5	0.7
	Jogging	1.6	10.1
	Upstairs	2.4	45.1
	Downstairs	2.1	42.5
Missed detection rate (%)	Walk	0.1	1.2
	Jogging	0.2	3.0
	Upstairs	0.4	3.6
	Downstairs	1.3	3.9

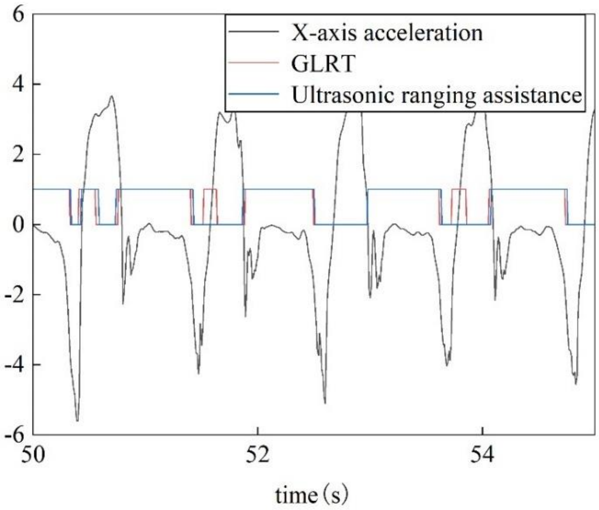

Fig. 6 Comparison of zero-velocity detection results

It can be seen from the figure that after adding time constraints by ultrasonic ranging, the pseudo-zero velocity interval caused by foot shaking when lifting the foot can be effectively removed.

4. Summary

Through the experiments in this paper, it is proved that the ultrasonic ranging assisted zero-velocity detection method proposed in this paper can effectively improve the accuracy and robustness of zero-velocity detection, and because the data used in this paper only needs simple smoothing operations, it has more practical value in terms of calculation amount and calculation delay.

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