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Janus 配置的激光多普勒测速仪的陆用组合导航

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摘　要:为了抑制车辆颠簸、倾角变化对传统激光多普勒测速仪的影响,设计了基于 Janus 配置的分光再利用结构激光多普勒测速仪,该测速仪由两个激光多普勒测速仪子系统镜像安装而成,可补偿倾角变化对速度测量的影响,因此对倾角变化不敏感.车载实验结果表明该测速仪的测速相对误差为 0.3%,在 55.6 km 的行程中组合导航的最大位置误差为 5.8 m.该结构激光多普勒测速仪能够抑制车辆颠簸、倾角变化对速度测量的影响,提高组合导航定位精度,更适合陆用组合导航.

关键词:应用光学;激光多普勒测速仪;Janus 配置;速度测量;分光再利用;惯性导航系统;组合导航系统;定位精度

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Land Integrated Navigation of Laser Doppler Velocimeter Based on Janus Configuration

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Abstract: To suppress the influence of the vehicle jolts and the inclination variations on conventional laser Doppler velocimeters, a split-reuse laser Doppler velocimeter based on Janus configuration is designed. The velocimeter is composed of two velocimeter subsystems which are mirror-mounted and insensitive to the inclination variations by compensating the influence of the inclination variations on the velocity measurement. The vehicle experiment results show that the relative error of the velocimeter is 0.3% and the maximum position error of its integrated navigation is 5.8 m in a 55.6 km journey. The proposed laser Doppler velocimeter can effectively suppress the influence of the vehicle jolts and the inclination variations on velocity measurement and improve the positioning accuracy of integrated navigation systems, so it is more suitable for land integrated navigation.

Key words: Applied optics; Laser Doppler velocimeters; Janus configuration; Velocity measurement; Split-reuse; Inertial navigation systems; Integrated navigation systems; Positioning accuracy

OCIS Codes: 280.3340; 280.7250; 280.3420

0 Introduction

Strapdown Inertial Navigation Systems (SINS) are self-contained, nonradiating, nonjammable, dead reckoning navigation systems which provide dynamic information through direct measurements[1]. However, the initial alignment error and inertial sensors errors lead the positioning error of SINS to

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accumulate along with time[2], so one of the trends of inertial navigation technology is integrated navigation[3]. At present, the common land inertial integrated navigation methods are SINS/Global Positioning System (GPS) integrated system and SINS/Odometer (OD) integrated system. SINS/GPS integrated system can inhibit the divergence of the navigation positioning error[4], but GPS signal is instable and susceptible to electronic interference and buildings, and the integrated system is nonautonomous[5]. OD is capable of providing the velocity and mileage information for SINS/OD integrated system[6]. However, the scale factor of OD is greatly influenced by the temperature, pressure and surface wear of tyres and the measurement will also appear a large deviation when the wheels jump and skid[7-8].

Since the confirmation in 1964 that the velocity of a fluid can be obtained using the laser Doppler frequency shift technique[9], a Laser Doppler Velocimeter (LDV) has been widely used in the fields of aerospace, mechanics, medicine and so on because of its high precision, good linearity, rapid dynamic response, large measuring range and non-contact measurement[10-12]. In recent years, LDV is also used in the area of land navigation, and combined with SINS to provide the speed of vehicle[13-14]. However, when the ground is uneven and the vehicle is bumpy, the inclination of a conventional reference-beam LDV will change, resulting in a large measurement error. In order to reduce the error caused by the vehicle bump, our research group proposed a reference-beam LDV based on Janus configuration[15-16], but only the simulation and simple experimental verification were carried out. Because of the high Signal-to-Noise Ratio (SNR) and reliable performance of the split-reuse LDV which is more suitable for the field of land navigation[17-18], this paper designs a split-reuse LDV based on Janus configuration and implements a vehicle integrated navigation experiment to test the performance of the LDV.

1 Split-reuse LDV based on Janus configuration

1.1 Conventional reference-beam LDV

The relationship betweenthe Doppler frequency f_D of a reference-beam LDV and the velocity v of the vehicle carrier is as follow

$$f_D = 2v\cos\theta/\lambda \tag{1}$$

where λ is the laser wavelength and θ is the inclination of the laser beam to the ground.

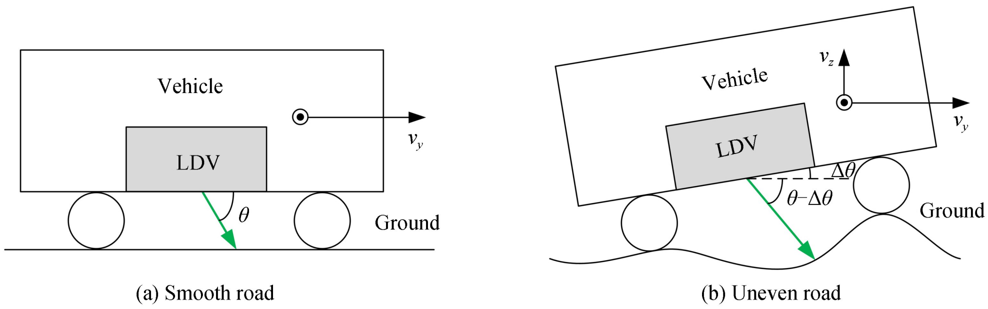


Fig.1 Vehicle with a conventional reference-beam LDV runs on different kinds of roads

As shown in Fig. 1(a), when the vehicle runs on a smooth road at a speed of v_y, the Doppler frequency f_D is

$$f_D = 2v_y\cos\theta/\lambda \tag{2}$$

From Eq. (2), we can obtain

$$v_y = f_D\lambda/(2\cos\theta) \tag{3}$$

However, in the actual driving, the road is always uneven, thus causing the vehicle to have a vertical velocity v_z and the inclination of LDV to have a variation $\Delta\theta$, as shown in Fig. 1(b), and the Doppler frequency f_D' is

$$f_D' = 2[v_y\cos(\theta-\Delta\theta) - v_z\cos(\theta-\Delta\theta)]/\lambda \tag{4}$$

The apparent velocity v_y' of the vehicle can be calculated by

$$v_y' = f_D'\lambda/(2\cos\theta) \tag{5}$$

Hence, the relative error of the velocity measurement for the conventional reference-beam LDV is given by

$$\left|\frac{\Delta v_y}{v_y}\right| = \left|\frac{v_y' - v_y}{v_y}\right| = \left|\tan\theta\sin\Delta\theta + \cos\Delta\theta - \frac{v_z}{v_y}(\tan\theta\cos\Delta\theta - \sin\Delta\theta) - 1\right| \tag{6}$$

It can be seen from Eq. (6) that the relative error of the conventional reference-beam LDV is related to the inclination θ, the inclination variation $\Delta\theta$ and the ratio of the vertical velocity to the forward velocity of the vehicle v_z/v_y.

1.2 LDV based on Janus configuration

To reduce the measurement error caused by the vehicle bump, a LDV based on Janus configuration is chosen. The LDV installed at the bottom of the vehicle consists of two LDV subsystems, one of which looks forward and the other looks backward with the same inclination angle, and their Doppler frequencies are measured at the same time, as shown in Fig.2.

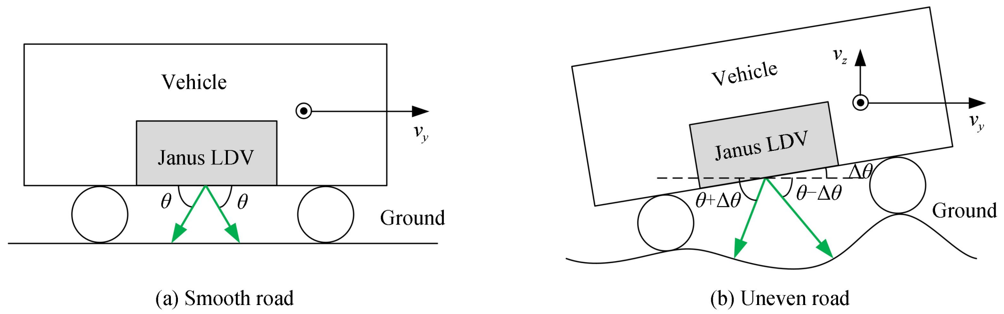


Fig.2 Vehicle with a LDV based on Janus configuration runs on different kinds of roads

When the vehicle runs on a smooth road, as shown in Fig.2(a), the Doppler frequencies of the two subsystems are given by

$$f_{D1} = 2v_y\cos\theta/\lambda \tag{7}$$

$$f_{D2} = 2v_y\cos\theta/\lambda \tag{8}$$

The running speed of the vehicle is

$$v_y = \lambda(f_{D1} + f_{D2})/(4\cos\theta) \tag{9}$$

However, as shown in Fig.2(b), when the road is always uneven and the vehicle is bumpy, the Doppler frequencies of the two subsystems are

$$f_{D1}' = 2[v_y\cos(\theta - \Delta\theta) - v_z\cos(\theta - \Delta\theta)]/\lambda \tag{10}$$

$$f_{D2}' = 2[v_y\cos(\theta + \Delta\theta) + v_z\cos(\theta + \Delta\theta)]/\lambda \tag{11}$$

Considering the fact that $v_z \ll v_y$, the inclination variation $\Delta\theta$ can be approximated to $\Delta\theta'$.

$$\Delta\theta' = \arctan\left[\frac{f_{D1}' - f_{D2}'}{(f_{D1}' + f_{D2}')\tan\theta}\right] \tag{12}$$

The calculated velocity v_y' of the vehicle is

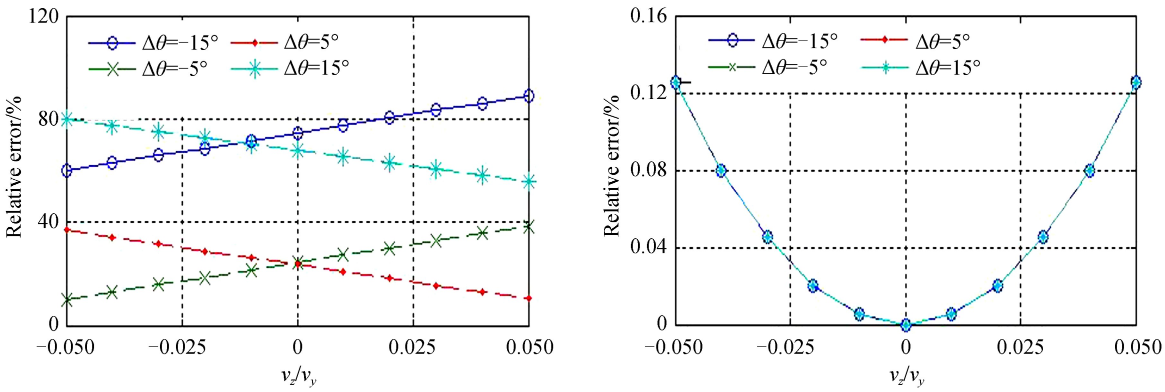
$$v_y' = \lambda(f_{D1}' + f_{D2}')/(4\cos\theta\cos\Delta\theta') \tag{13}$$

Obviously, Eq. (9) is a special case of Eq. (13) when the road is ideal and the vertical velocity $v_z = 0$, so Eq. (13) is a general formula for the measurement of the reference-beam LDV based on Janus configuration. The relative error of the velocity measurement is

$$\left|\frac{\Delta v_y}{v_y}\right| = \left|\frac{v_y' - v_y}{v_y}\right| = \sqrt{1 + (v_z/v_y)^2} - 1 \tag{14}$$

It can be seen from Eq. (14) that the relative error of the reference-beam LDV based on Janus configuration is only related to the ratio of the vertical velocity to the forward velocity of the vehicle v_z/v_y.

Set the inclination angle $\theta = 70°$, v_z/v_y is $-0.05 \sim 0.05$, and the inclination variation $\Delta\theta$ is $-15°$, $-5°$, $5°$, $15°$ respectively, the relative errors of the conventional reference-beam LDV and the Janus configuration LDV are simulated numerically, and the results are shown in Fig. 3. It is apparent that the relative error of the conventional reference-beam LDV grows with the increase of the absolute value of $\Delta\theta$ and the LDV based on Janus configuration is insensitive to $\Delta\theta$. But in general, the relative error of the conventional reference-beam LDV is far greater than that of the Janus configuration LDV. For example, when $v_z/v_y = 0.05$ and $\Delta\theta = 5°$, the velocity relative error of the conventional reference-beam LDV is 10.3% and the relative error of the Janus configuration LDV is only 0.12%.



(a) Conventional reference-beam LDV (b) LDV based on Janus configuration

Fig.3 Relative errors of different kinds of LDVs

1.3 Structure of the split-reuse LDV based on Janus configuration

The split-reuse LDV is a deformation of the conventional reference-beam LDV, and still belongs to the reference-beam LDV. As shown in Fig. 4, the split-reuse LDV based on Janus configuration is comprised of two split-reuse LDV subsystems which are mirror-installed. Each subsystem has the same structure. The light source is a solid-state green laser operating in a single longitudinal mode and the TEM_{00} transverse mode with a power of 50 mW and a wavelength of 532 nm. The laser beam is collimated by the collimation and compensation lens, and then divided by the beam splitter BS_1 whose reflectivity is 50% into a transmitted beam and a reflected beam. The transmitted beam hits the ground through the centre hole of the mirror M_1. The reflected beam is divided by the beam splitter BS_2 whose reflectivity is 98%. The reflected beam is reflected by the mirrors M_2 and M_1, and then irradiates the ground in the same direction. The part of scattered light propagating along the opposite direction is half reflected by the beam splitter BS_1, and then enters into the avalanche photodiode detector after passing through the polaroid, optical filter and pinhole diaphragm. This is the signal beam. The transmitted beam of the beam splitter BS_2 is also incident to the detector after being reflected by the mirror M_3. This is the reference beam. The reference beam and the signal beam interfere on the photosensitive surface of the detector to form a Doppler beat signal.

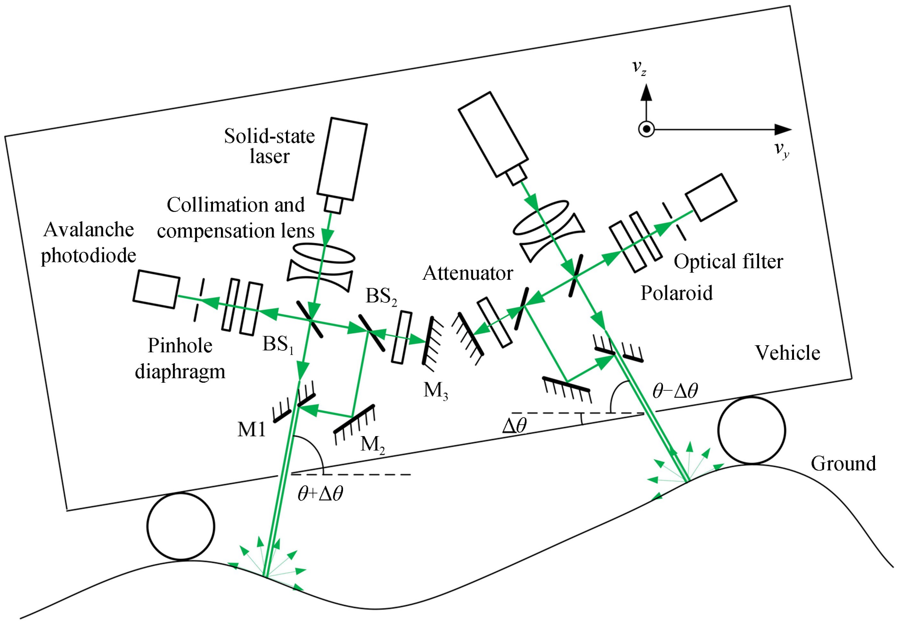


Fig.4 Optical structure of thesplit-reuse LDV based on Janus configuration

It can be seen that the attenuated laser power in the conventional reference-beam LDV is also incident to the ground after being reflected by BS_2. That is to say that the laser utilization rate of the split-reuse

LDV is nearly twice that of the conventional reference-beam LDV and its scattered light power is also nearly twice. The SNR of the split-reuse LDV is

$$\mathrm{SNR}=\eta W_S/h\upsilon\Delta f \tag{15}$$

where η is the quantum efficiency coefficient, h is the Plank coefficient, υ is the center frequency of the laser, Δf is the bandwidth of the detector and W_S is the scattered light power. Therefore, compared with the conventional reference-beam LDV, the SNR of the split-reuse LDV is greatly improved, which is more suitable for land navigation.

2 Integrated navigation experiment

In order to verify the performance of theproposed split-reuse LDV based on Janus configuration, the following integrated navigation experiment is designed. Fig.5 shows the experimental system, which is composed of an Inertial Measurement Unit (IMU), the Janus configuration LDV, a Differential GPS (DGPS) receiver, a navigation computer and batteries. The IMU consists of three laser gyroscopes with drift rate of 0.003°/h and three quartz accelerometers with bias of 50 μg, with a sampling frequency of 100 Hz. The positioning accuracy of the DGPS is 0.1 m, and the data update frequency is 10 Hz. The navigation computer collects data and the batteries supply power to the whole system. The route of the vehicle is shown in Fig.6. The starting and ending points are marked by blue pentagrams and the turning points are amplified and marked by black rectangles. The whole journey is 55.6 km in 2.1 h.

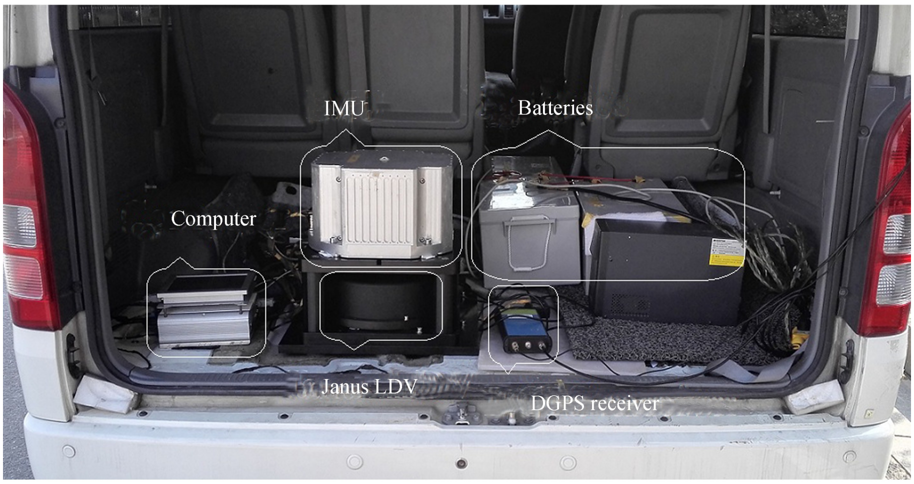


Fig.5 Installation diagram of the experimental system

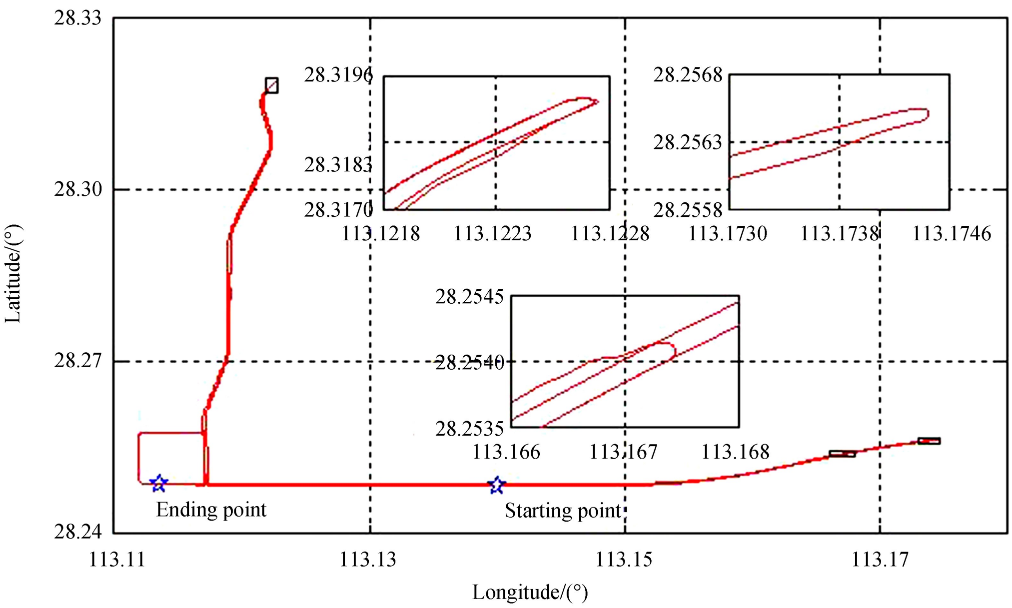


Fig.6 Route of the vehicle

The computer collects the velocity data of the Janus configuration LDV. As a contrast, the computer also collects the velocity data of an LDV subsystem at the same time. The results are shown in Fig.7, the solid line is the velocity of the Janus configuration LDV, which is recorded as v_1, and the dashed line is the velocity of the LDV subsystem, which is recorded as v_2. It can be seen that the change trend of v_1 and v_2 is consistent, but as a result of the effect reduction of the vehicle bumps and the inclination variations on the velocity measurement, v_1 reduces fluctuation and becomes smooth compared with v_2. This is the advantage of the Janus configuration LDV.

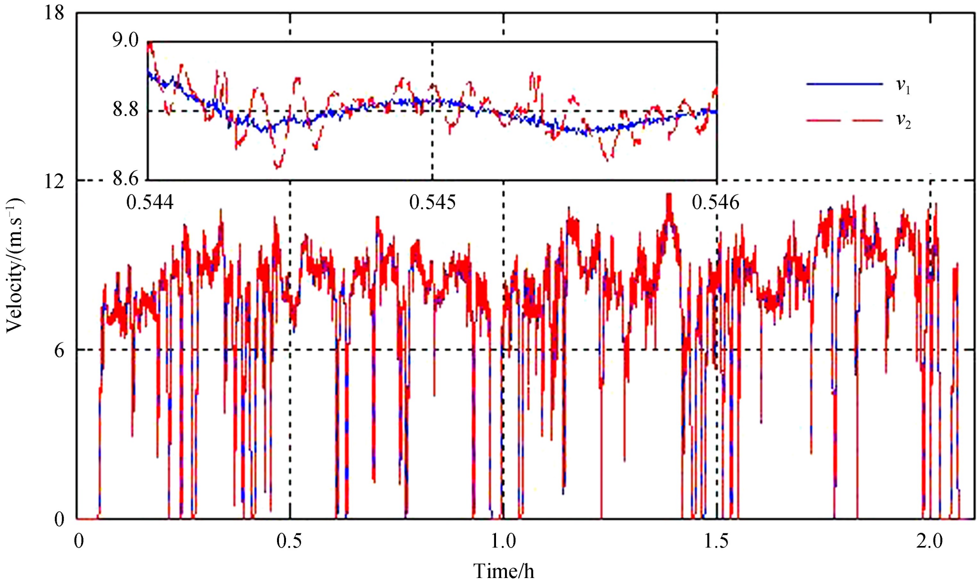
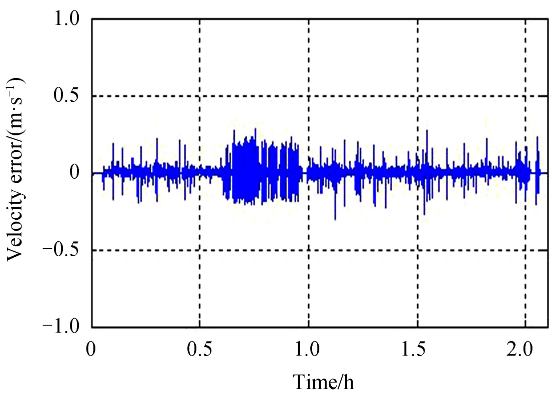


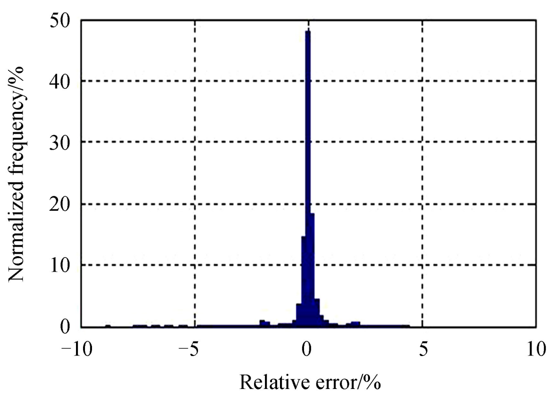
Fig.7 Comparison of output velocities of the Janus configuration LDV and the LDV subsystem

Taken the velocity derived from the output position of DGPS as the benchmark, the velocity errors of the Janus configuration LDV and the LDV subsystem are shown in Figs.8(a)～(d). Figs.8(a)～(b) are the velocity errors and the relative error histogram of the Janus configuration LDV respectively and Figs.8(c)～(d) are the velocity errors and the relative error histogram of the LDV subsystem respectively. It is clear that the velocity error of the Janus configuration LDV is far less than that of the LDV subsystem. According to the calculation, the relative error of the Janus configuration LDV is 0.3%, while the relative error of the LDV subsystem is 1.02%.

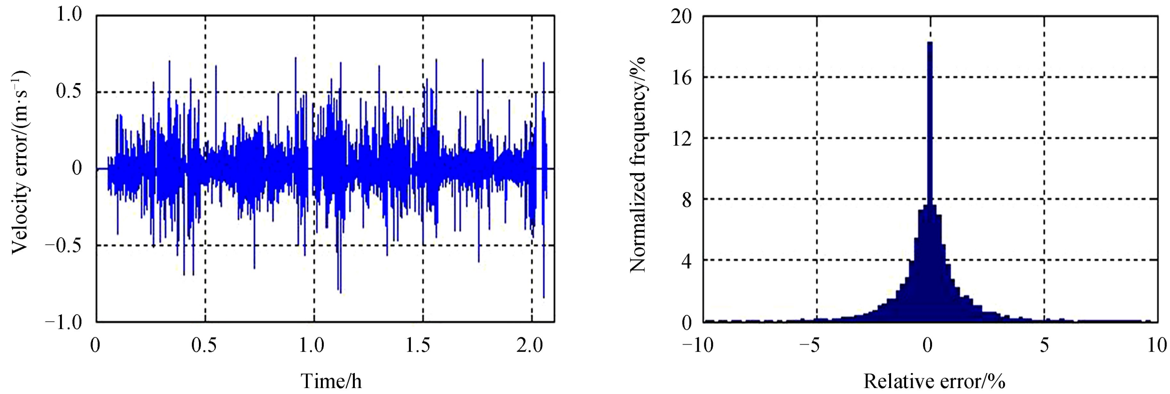
The integrated navigation system consists of the split-reuse LDVbased on Janus configuration and the IMU, and its data processing procedure is shown in Fig.9. First, the rapid initial alignment of 13 min is completed by the IMU. Then, dead reckoning is performed by the outputs of the LDV and the three gyroscopes of IMU. Finally, the position error is calculated based on the output position of DGPS. The result is shown in Fig.10 and the maximum position error is 5.8 m. As a comparison, the position errors of the IMU pure inertial navigation and the dead reckoning of the LDV subsystem are given in Figs.11 and 12.



(a) Velocity error of the Janus configuration LDV



(b) Histogram of relative error of the Janus configuration LDV



(c) Velocity error of the LDV subsystem (d) Histogram of relative error of the LDV subsystem

Fig.8 Velocity errors of different kinds of LDVs

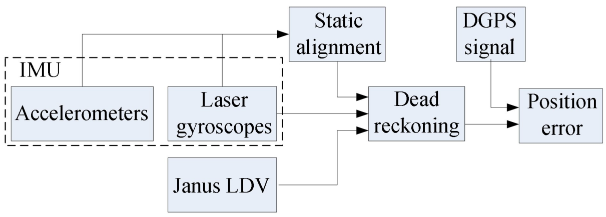


Fig.9 Data processing procedure of the integrated navigation system

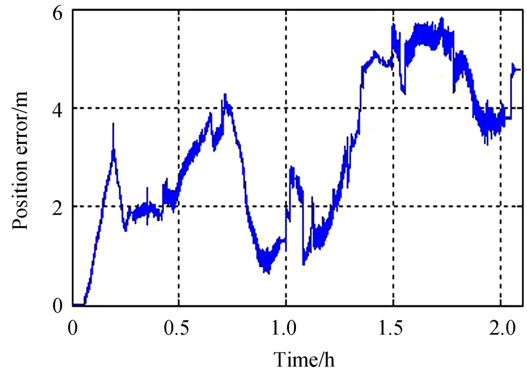


Fig.10 Position error of the integrated navigation system

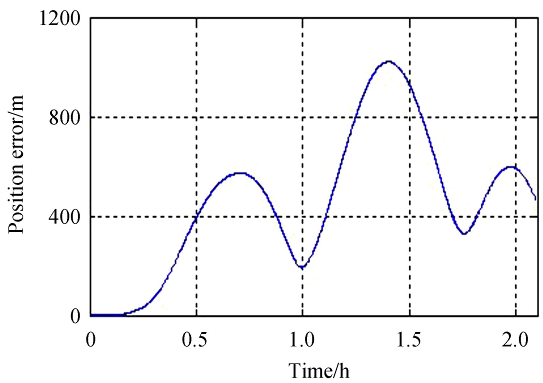


Fig.11 Position error of IMU

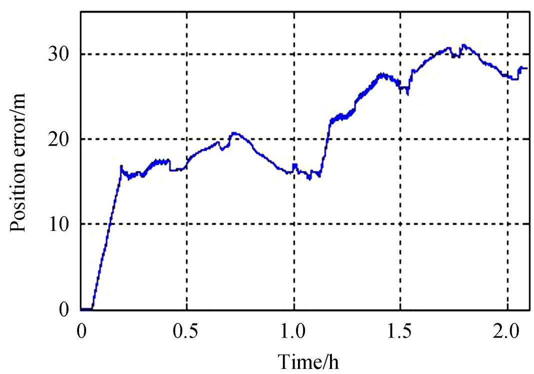


Fig.12 Position error of dead reckoning of the LDV subsystem

The maximum position errors are 1 020 m and 31 m respectively. It can be seen that the positioning accuracy of the integrated navigation system of the Janus configuration LDV is much higher than that of the IMU pure inertial navigation and the dead reckoning of the LDV subsystem. The high precision navigation result shows that the proposed split-reuse LDV based on Janus configuration can suppress the effect of the vehicle bumps and the inclination variations on the velocity measurement, and is very suitable for land integrated navigation.

3 Conclusion

In the field of land navigation, in order to reduce the influence of the vehicle bumps and the inclination variations on the velocity measurement of conventional LDVs, a split-reuse LDV based on Janus configuration is designed, and a vehicle integrated navigation experiment is implemented to verify its performance. The experimental results show that the Janus configuration LDV indeed can suppress the influence of vehicle bumps and the inclination variations on the velocity measurement, and improve the accuracy of the velocity measurement and the positioning accuracy of the land integrated navigation.

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