WM-INS: A Wheel Mounted IMU Based Integrated Navigation System for Wheeled Robots
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Abstract—Microelectromechanical systems (MEMS) based inertial navigation systems (INS) are widely used for robot navigation as they are self-contained and low-cost for motion perception. Various methods have been utilized to restrict the error growth caused by the inherent inertial sensor noises. Inspired by the rotation-modulation INS that using intentional rotation to mitigate the drift errors, we propose an integrated navigation solution for mobile robots based on a single wheel mounted MEMS IMU. The IMU is leveraged to produce odometry measurements with wheel radius and estimate the wheel motion. Zero-type constraints and the vehicle motion constraints are also introduced to limit the navigation errors. Field experiments prove that the rotation scheme can effectively reduce the heading error. The horizontal position accuracy of the proposed system is two times better than the conventional odometry aided INS for large-scale polylne trajectory tests. The cancellation effect of the track on navigation errors drift is also illustrated.

NOMENCLATURE
a) Matrices are denoted in upper case bold letters.
b) Vectors are denoted in lower case bold italic letters.
c) Scalar is denoted in lower case italic letters.
d) The coordinate frames involved in the vector transformation are denoted as superscript and subscript.
   For vectors, the superscript denotes the projected coordinate system.
e) ̂, estimated or computed values.
f) ̂, observed or measured values.
g) \( a_x \), element of vector \( a \) on \( x \) axis.

I. INTRODUCTION

Highly precise real-time localization is essential for ground wheeled robots, e.g. planetary rovers [1], autonomous driving cars [2], indoor robots [3], etc. Inertial navigation system (INS) is extensively exploited for mobile robots navigation with the rapid development of microelectromechanical systems (MEMS) [4-6]. However, the positioning solution of a stand-alone INS drifts unboundedly with time because of its inherent sensor noises [7]. Thus external sensors with complementary properties are required to correct the accumulated errors, for example, Global Navigation Satellite Systems (GNSS), camera and odometer.

GNSS [8-10] is a significant positioning technology for outdoor robots navigation, such as the Global Positioning System (GPS), Galileo, BeiDou Navigation Satellite System (BDS) and so on. Although the GNSS is able to provide accurate positioning even on centimeter-level [11] in open-sky environments, it deteriorates due to multipath and signal blockage in complex environments like urban canyons and forests. Moreover, it is totally unavailable for indoor application. Over last decades, extensive researches have focused on vision based state estimation approaches for autonomous robots, such as simultaneous localization and mapping (SLAM) [12-14] and visual odometry (VO) [15-18]. However, visual systems suffer from illumination variation, less texture, motion blur, and high power consumption. And the restricted motion that ground robots often undergo renders certain, additional Degrees of Freedom (DoF) unobservable of vision-aided inertial navigation system (VINS) [19].

As a relative positioning sensor with nice short-distance stability, wheel odometer is utilized to provide either distance or velocity information along the vehicle trajectory to aid the INS [20-22]. Motion of a wheeled robot on land is generally governed by two non-holonomic constraints (NHCs) [23, 24], referring to the fact that the vehicle does not jump off the ground or slide on the ground. It is worth noting that the skid-steer rover [1], differential drive mobile robot and autonomous driving car [24] always conform to this restriction, nevertheless, it is not the case for the omnidirectional robot chassis with three wheels or four Mecanum wheels [25]. It was proven that odometer and NHCs contributes much to suppress both the positioning and attitudes errors drift and enhance the stability of INS [26, 27]. However, integrating with external system is not easy-to-implement due to different standards, data transfer synchronization and difficulties in obtaining reliability information along with the data [28, 29]. Additionally, state-aware pseudo-measurements also significantly improve the state estimation accuracy of INS [22, 24], for instance, zero velocity updates (ZUPTs) and zero integrated heading rate measurements (ZIHRs). These constraints come from the fact that the velocity and angular rate of land vehicle are zero when it keeps stationary.

Besides introducing external aiding information to INS, rendering the Inertial Measurement Unit (IMU) rotate in an intentional scheme also has the potential to reduce the navigation error growth, i.e. indexed IMU [10] or rotary INS [30]. Through rotating the IMU with a certain angular rate, the constant inertial bias can be modulated into periodical sine or cosine signals; hence, the negative impact caused by the bias on the navigation solution is able to be canceled by integration the sensor data over a complete period. Authors in [31] demonstrated that heading drift is well limited by rotating around horizontal axis in the foot-mounted IMU based INS. However, these methods require an additional heavy, high-cost and complicated rotation platform which takes away...

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the advantages. In 2014, Dr. Collin placed a MEMS IMU on the wheel of the car and provided a two dimensional dead-reckoning (DR) [32, 33] system which treated the accelerometer as virtual odometer [29].

In this paper, we propose a pose estimation system for the mobile wheeled robots based on a single wheel attached MEMS IMU. The main contribution of our work are:

- We exploited the gyroscope measurements and the wheel radius to obtain the wheel speed to aid the INS.
- ZUPTs, ZIHRs and NHCs are also employed to improve the heading and position accuracy through an Extended Kalman Filter (EKF) whenever it is available.
- We propose a method to estimate the misalignment angles of the IMU w.r.t. the wheel which is easy to be carried out.
- Through field experiments, we prove that the position and heading accuracy of the proposed system is much higher than the odometry aided INS. The effect of motion trajectory on cancelling error growth of the navigation system is also discussed.

This paper is organized as follows. In section II, the INS mechanization and the error state model of the EKF is firstly introduced. Then the odometry and zero-type constraints as well as the calibration algorithm are presented. Experimental evaluations of the proposed system are provided and discussed in section III. Finally, section IV draws some conclusions and future work.

II. METHODOLOGY

The installation relationship between the IMU and the wheel of the vehicle is given in Fig. 1.

![Fig. 1. This figure presents the definition of the axes direction for the IMU coordinates (b-frame) and the vehicle coordinates (v-frame). The b-frame axes are the same as the IMU’s body axes. The v-frame is aligned with the roll, pitch and heading axes of a vehicle, i.e. forward-transversal-down. In order to avoid the singularity in the pitch angle of the IMU, the x-axis of the IMU is aligned as the rotation axis. The misalignment between the b-frame (in red) and the wheel frame (in black) is also depicted.](image)

It is assumed that the x axis of the wheel is parallel to the y axis of the vehicle and we think the wheel hub as a rigid body. First of all, we use the inertial data to carry out the forward INS mechanization as the three dimensional state prediction of the EKF. As a side-product, we use the gyroscope output to obtain wheel speed. Then the odometer information is treated as measurement updates with NHCs. At the same time, we detect the static state of the vehicle and then integrate ZUPTs and ZIHRs as long as it is available. The residual sensor errors estimated by the EKF are feedback to correct IMU output. Fig. 2 presents a graphical depiction of the proposed navigation system.

![Fig. 2 The flowchart of the proposed algorithm](image)

A. INS Mechanization

The strapdown inertial navigation algorithm is widely utilized in the INS[22, 34]. For a MEMS IMU, it is unable to directly measure the Earth’s rotation because of the terrible noise. And the change of local navigation frame with the move of the vehicle can be ignored for a small scale area, therefore we use a simplified model here:

\[
\begin{align*}
  \dot{v}^n &= C^n_b f^b + g^n \\
  \dot{C}^n_b &= 0 \\
  \dot{h} &= -v_D \\
  \dot{C}^e_t &= C^n_b (\omega^b_{ab} \times)
\end{align*}
\]

where \( n \) indicates the navigation frame (n-frame) which has its origin coinciding with that of the vehicle frame; \( v^n \) is the IMU velocity resolved in n-frame; \( f^b \) denotes the special force vector of the b-frame; \( g^n \) is the local gravity projected to the n-frame; \( C^n_e \) is the direction cosine matrix from the n-frame to the e-frame(earth-centered earth-fixed coordinates frame); \( h \) is the height of the IMU in e-frame; \( v_D \) denotes the downward velocity; \( C^n_b \) denotes the direction cosine matrix from the b-frame to the n-frame; and \( \omega^b_{ab} \) represents the angular rate vector of the b-frame with respect to the inertial frame projected to the n-frame.

B. Error State Model

The error state vector constructed in the n-frame is written as

\[
  x(t) = \begin{bmatrix}
    (\delta r^n)^T \\
    (\delta v^n)^T \\
    \phi^T \\
    b_g^T \\
    b_a^T \\
    s_g^T \\
    s_a^T
  \end{bmatrix}^T
\]

where operator \( \delta \) denotes the error of a variable; \( \delta r^n \) and \( \delta v^n \) are the INS indicated position and velocity errors resolved in the n-frame, respectively; \( \phi \) indicates the attitude error; \( b_g \) and \( b_a \) are the residual bias errors of the gyroscope and the accelerometer, respectively; and \( s_g \) , \( s_a \) are the residual scale factor errors of the gyroscope and accelerometer, respectively. The time derivatives of the state
variables must be calculated to obtain the state model of the EKF. The phi-angle error model[22] is applied here.

\[ \dot{\phi} = -\omega^w_n \times \phi - C^w_b \omega^b_w \]  

(3) \[ \delta \dot{v}^a = C^b_b \delta f^b_f + C^n_n f^b_f \times \dot{\phi} + \delta g^n \]  

(4) \[ \delta r^n = \delta v^a \]  

(5) where \( \omega^w_n \) denotes the angular rate vector of the n-frame w.r.t. the e-frame projected to the n-frame which is calculated by \( \omega^w_n = \omega^e_n + \omega^n_e \); \( \delta \omega^b \) indicates the gyroscope’s measurement error; \( \delta f^b_f \) refers to the accelerometer’s measurement error; and \( \delta g^n \) is the local gravity error in the n-frame.

The variables \( b_x, b_a, s_g \) and \( s_a \) are modeled by first-order Guass-Markov process[35, 36].

\[ \dot{x} = -\frac{1}{T} x + w \]  

(6) \[ x_{k+1} = e^{-M_{nT}} x_k + w_k \]  

where \( T \) is the correlation time of the process, and \( w \) is the driving white noise process.

As shown in (3) and (4), the attitude and velocity errors are affected by the multiplication of \( \delta \omega^b \), \( \delta f^b_f \) and \( C^b_b \). To illustrate the INS error modulation, we assume that the x axis of the IMU point to the north and the rotation speed is constant without loss of generality. Then the angular rate error in n-frame can be represented as:

\[ C^w_n \delta \omega^b = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega t & -\sin \omega t \\ 0 & \sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} \]  

(7)\[ = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \cos \omega t - \varepsilon_z \sin \omega t \\ \varepsilon_y \sin \omega t + \varepsilon_z \cos \omega t \end{bmatrix} \]  

where \( \omega \) is the IMU rotation rate, \( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are the gyroscope errors on the x, y and z axes. It is shown that the error terms on y and z axes vary periodically according to sine and cosine functions. This however is not the case for the x axis since it is the rotation axis. The errors will be completely canceled over a whole period if they are constant during the time interval, same with the acceleration error. Thus the indexed IMU is significant in eliminating the constant error terms on IMU axes that are perpendicular with the rotation axis. Refer to [31, 37] for more details regarding the procedure.

C. NHC and Odometry Updates

A rover is a non-holonomic system if its number of controllable DoF is less than its total DoF [1]. Under ideal conditions, the velocity of the vehicle in the plane perpendicular to the forward direction (x-axis) is almost zero [22]. These motion constraints can be introduced as measurement updates for the EKF,

\[ v^v = \begin{bmatrix} v_x^v & 0 & 0 \end{bmatrix}^T \]  

(8) As the IMU mounted on the rear wheel of the vehicle, we can obtain the velocity of the wheel directly given the radius \( r \).

\[ \dot{v}_w = \dot{v}_w^r = \hat{\phi}_{w} \]  

(9) It is difficult, if not impossible, to determine the attitude of the vehicle without other sensors as the IMU is rotating with the wheel. Given the practical application scenario, it is supposed that the vehicle moves on a horizontal plane. Then there is only heading angle exists between the v-frame and the n-frame, i.e.

\[ \phi^n_v = 0, \quad \theta^n_v = 0 \]  

(10) \[ \psi^n_v = \psi^n_v - \pi / 2 \]  

where \( \phi, \theta \) and \( \psi \) are the roll, pitch and heading angles.

Projecting the velocity to n-frame, the INS-indicated and measured velocity can be written as

\[ \dot{v}_w^v = \dot{v}_w^b \]  

(11) \[ C^w_v \delta \omega^b = -\hat{\omega}^v - \dot{f}^v_f + \dot{f}^v_f \times \phi + \delta g^v \]  

(12)\[ = \dot{v}_w^v + \delta \dot{v}_w^v - C^v_v \left( \delta f^v_f \times \right) \hat{\phi} + \delta g^v \]  

where \( diag(\bullet) \) denotes the diagonal matrix form of the vector; \( l^b_w \) is the lever-arm vector of the wheel center in the b-frame.

D. Zero Type Updates

Zero-type updates, including ZUPTs and ZIHRs, can be leveraged to improve the performance of the INS while the vehicle is stationary. The observation model for ZUPTs is shown as

\[ \hat{v}^n = \begin{bmatrix} 0 & 0 \end{bmatrix}^T + e_v \]  

(13) \[ \delta z_e = v^n_{IU} - \hat{v}^n \]  

(14) \[ = v^n_{IU} + \delta v^n_{IU} - v^n - e_v \]  

Referring to the linearized heading measurement model in [22], the ZIHR measurement model can be written as follow.

\[ \hat{\psi} = \arctan \left( \frac{C^n_b_{21}}{C^n_b_{11}} \right) \]  

(16) \[ \delta z_{\text{heading}} = \hat{\psi} - \psi \]  

(17)\[ = \begin{bmatrix} \frac{\partial \psi}{\partial \phi_{\text{roll}}} & \frac{\partial \psi}{\partial \phi_{\text{pitch}}} & \frac{\partial \psi}{\partial \phi_{\text{heading}}} \end{bmatrix} \phi - e_{\psi} \]
The IMU mounted on the wheel is more sensitive to the motion of the vehicle than that on the vehicle. We use the peak-to-peak value of the acceleration measurements in a window and to determine if the ZUPTs is available. And the peak-to-peak value of the gyroscope measurements in a window is calculated to determine if the ZIHRS is available.

E. Calibration

Obtaining accurate velocity measurement requires the knowledge of the inevitably existing misalignment in the attitudes of the IMU w.r.t. the wheel, i.e. mounting angle calibration, as shown in Fig. 1. Since the IMU is rotating with the wheel, it does not make sense to define the roll angle of the IMU w.r.t. the wheel which is completely irrelevant to the speed measurements. We only focus on the estimation of the pitch and heading mounting angle in the calibration procedure. The authors in [38] proposed a method to calibrate the mounting angles with theoretical analysis. Here, we introduce a more convenient approach which only needs the gyroscope’s outputs.

As mentioned in section II-A, we do not consider the earth’s rotation within the gyroscope’s measurements. Hence, the outputs of the gyroscope are produced by the rotating wheel.

\[
\begin{bmatrix}
\omega_b^x \\
\omega_b^y \\
\omega_b^z
\end{bmatrix} = \mathbf{C}_\text{wheel}^{b} \begin{bmatrix}
\omega_x^{\text{wheel}} \\
0 \\
0
\end{bmatrix}
\] (18)

\[
\mathbf{C}_\text{wheel}^{b} = \begin{bmatrix}
c\theta c\psi & -s\psi \\
-s\theta c\psi & c\theta s\psi
\end{bmatrix}
\] (19)

where \(c\) and \(s\) denote \(\cos\) and \(\sin\) respectively. Therefore,

\[
\begin{bmatrix}
\omega_x^{b} \\
\omega_y^{b} \\
\omega_z^{b}
\end{bmatrix} = \begin{bmatrix}
c\theta c\psi \cdot \omega_x^{\text{wheel}} \\
-s\psi \cdot \omega_x^{\text{wheel}} \\
\theta c\psi \cdot \omega_x^{\text{wheel}}
\end{bmatrix}
\] (20)

\[
\theta = \arctan\left(\frac{\omega_y^{b}}{\omega_x^{b}}\right)
\] (21)

\[
\psi = \arctan\left(\frac{-\omega_y^{b}}{\sqrt{(\omega_y^{b})^2 + (\omega_x^{b})^2}}\cdot \frac{\omega_x^{\text{wheel}}}{\omega_x^{\text{wheel}}}ight)
\] (22)

In practice, we mount the IMU on the wheel and lift up the robot. Then we rotate the wheel around a fixed direction and record the IMU data for several minutes. The average values are computed as the final calibration results.

III. EXPERIMENTAL RESULTS

A. Experiment Description

To prove the effect of rotation scheme on limiting heading error, as well as to validate the performance of the proposed system, field tests were conducted in Wuhan in July, 2019. The test platform, as shown in Fig. 3, included the following units:

- A Pioneer 3 DX\(^1\) robot as the test ground vehicle;
- A higher precision inertial integrated navigation system (POS320, MAP Space Time Navigation Technology Co., LTD, China) with GNSS antenna as the reference system;
- Two low-cost MEMS IMU (with an ICM20602\(^2\) chip) mounted on the wheel (IMU2) and vehicle (IMU1), respectively.

The test platform used in this work.

![Test Platform](image)

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![Table I](image)

Table I Technical Parameters of the MEMS IMU and POS320

| Parameters | MEMS IMU (System under test) | POS320 (Reference system) |
|------------|-----------------------------|---------------------------|
| Gyro bias stability (deg/h) | 200 | 0.5 |
| Angle random work (deg/√Hz) | 0.24 | 0.05 |
| Accelerometer bias stability (m/s\(^2\)) | 0.01 | 0.00025 |
| Velocity random work (m/s/√Hz) | 3 | 0.1 |

Table I gives the technical parameters of the two IMUs. Field tests were carried out in open-sky scenario, approximately 1 km and 15 minutes for each test. The average velocity of the robot in the test was 1.4 m/s. To demonstrate the effect of vehicle motion on the navigation errors drift, two different motion trajectories for the vehicle were exploited: one is moving in circles and the other is moving in polyline in large-scale environment, as shown in Fig. 4. The reference system (POS320) data were processed with the PPK (Post Processed Kinematic)/INS smoothing integration method. The results were converted to the center of the under-test-system (MEMS IMU) as the reference value of its position and attitude. Thereafter, the wheel mounted IMU based integrated inertial navigation method described above was employed with the collected MEMS IMU data. For the purpose of comparison, the odometry and NHCs aided inertial navigation method is also conducted. Since the wheel encoder data was not available, we utilized the vehicle encoder data.

\(^1\)https://cyberbotics.com/doc/guide/pioneer-3dx
\(^2\)https://www.invensense.com/products/motion-tracking/6-axis/icm-2060
velocity produced by the wheel mounted IMU as the odometry velocity (The average root mean squared error of the wheel velocity for all tests was 0.03 m/s). Then we set the initial heading angle and position of the two local reckoning approaches by the navigation results of the reference system to align the three tracks. Finally, the statistics of the horizontal position and heading angle errors were calculated to evaluate the performances of the two systems. Four tests were carried out for track #1 and two for track #2. The ODO/INS integrated navigation was only performed in test 3 and 4 of track #1 and the two tests of track #2.

Before field tests, we performed the method mentioned in section II-E to calibrate the misalignment angle between the IMU and the wheel. Fig. 5 depicts the calibration results.

**B. Results and Discussion**

Due to the horizontal plane assumption mentioned in section II-C, the position error on vertical direction as well as the roll and pitch errors are not analyzed. The heading errors of different methods within test 3 of track #1 are shown in Fig. 6.

It is evident that the heading angle obtained from the vehicle mounted IMU based INS (INS1) drifted fastest among the four methods because there was no external correction information to restrict it. However, it could be effectively limited with the aiding of the odometry speed and NHCs (see ODO/INS). Meanwhile, the heading of the INS based on the wheel mounted IMU (INS2) is also constrained since the rotation scheme cancels the constant bias of the gyroscope. With the further observations from odometry and NHCs, the WM-INS indicated heading presents the minimum error along the time. It can be noticed that the heading error curves of the two INS alone methods variate significantly when the host vehicle turns around due to the uncompensated scale factor error of the gyroscopes. However it does not affect our interpretation of the heading drift.

To demonstrate the performance of the proposed system, two navigation trajectories compared with the ground truth are shown in Fig. 7 and Fig. 8.

It can be observed from Fig. 7 that the position error is larger on the north-south direction than on the west-east direction. Since the robot moved along the latitude line most of the time in this test, the heading error resulted in greater position error on longitude direction.
### Table II Position and heading angle errors comparisons for the experiments

| Test No. | System  | Position Error (m) | Heading Error (deg) |
|----------|---------|--------------------|---------------------|
|          |         | MAX RMS | MAX RMS | MAX% | MAX RMS |
| Track #1 | WM-INS  | 7.57 3.07 | 2.06 0.58 | 0.59% | 7.48 2.43 |
|          | WM-INS  | 7.10 2.44 | 4.41 1.77 | 0.58% | 7.48 2.43 |
|          | ODO/INS | 5.70 2.40 | 3.24 1.59 | 0.47% | 7.31 3.62 |
|          | ODO/INS | 7.98 2.44 | 3.10 0.81 | 0.63% | 15.04 5.15 |
| Track #2 | WM-INS  | 8.34 3.58 | 1.60 0.66 | 0.66% | 5.84 2.42 |
|          | ODO/INS | 7.80 2.81 | 4.16 0.86 | 0.61% | 13.43 6.18 |
|          | WM-INS  | 13.07 5.82 | 6.01 3.95 | 1.23% | 9.06 2.65 |
|          | ODO/INS | 30.77 14.39 | 26.79 10.25 | 2.93% | 11.24 4.80 |
|          | WM-INS  | 14.71 7.87 | 18.93 6.25 | 1.93% | 9.77 3.71 |
|          | ODO/INS | 24.60 12.83 | 35.01 16.48 | 3.48% | 13.09 5.81 |

Fig. 8 Position results of the WM-INS in test 1 of track #2 compared with the ground truth.

Based on the pose error comparison of the two systems in two test sets, the following information can be obtained.

- For the heading error, the proposed system was about two times smaller than the ODO/INS integrated system. As the z axis of the IMU perpendicular to the rotation axis of the wheel, the destruction from the constant gyroscope bias were canceled which consequently reduced the heading error.
- In track #1, the horizontal position accuracy of the two systems were at the same level (less than 1%). This was because the vehicle just moved back and forth in a small-scale environment. The navigation errors of INS always drifted in one direction along with the time, for instance, the heading angle error depicted in Fig. 6. Hence the ultimate absolute navigation error would be reduced if the vehicle moves in a loop path in small-scale scenes. This was the reason that the heading error of the ODO/INS was much larger than WM-INS but the position performance were similar in track #1 tests.
- The position errors in track #2 were larger than that in track #1 for both the two approaches. In this test sets, the robot moved along long polyline thus had no opportunity to counteract the drifting navigation error. This was why the heading accuracy was not deteriorated in track #2 compared to that of track #2 tests, however the position errors were increased by 2-3 times and 5-6 times for WM-INS and ODO/INS, respectively.

Without the cancellation effect of the trajectory, the relative position errors of the conventional ODO/INS were about twice that of the proposed system in experiments of track #2. The rotational modulation at both angular rate and acceleration integration contributed to the navigation performance improvement.

It worth mentioning that when the heading rate is significant, the dynamic condition of the vehicle and wheel become much different, which could make the wheel speed and the NHCs become less reliable. Hence high structure stability between the wheel and the host vehicle is required for the proposed system.

### IV. Conclusion

An integrated navigation system based on a wheel mounted MEMS IMU is proposed in this paper. The key thoughts of the algorithm is to spread the drift errors to all directions to get the cancellation effect to improve the heading and position accuracy. The IMU attached on the wheel is utilized for both pose estimation and odometry measurement. Through the EKF, aiding information from NHCs, ZUPTs and ZIHRs are utilized to correct the navigation states. A simple but effective method is proposed to calibrate the mounting angle between the IMU and the wheel. Field tests show that the proposed WM-INS has more accurate heading angle estimation compared with the conventional ODO/INS integrated navigation system. For the position error in the horizontal direction, the two systems perform similarly for the small scale loop tests. For large scale polyline track tests, the horizontal position error of the WM-INS reduced by about 50% comparing with the ODO/INS integrated system. The experiments also show the significant effect of the motion trajectory on reducing navigation errors of inertial navigation system. However, an important prerequisite of the proposed system is that the vehicle is moving on the horizontal plane, which means it is unable to perceive the tilt of vehicle.

Future works include extension of the proposed algorithm to detect the side-slip of the vehicle autonomously. Furthermore, we are investigating approaches to use the vehicle attitude indicated by another IMU placed on the vehicle to make our system appropriate for ramping ground.
