Performance Assessment of Single Frequency GNSS RTK/MEMS-IMU Combined Positioning

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Abstract. With the increasing demand for high-precision positioning of civilian positioning terminals, the combination of single-frequency global navigation satellite system (GNSS) Real-Time Kinematics (RTK) and Inertial Measurement Unit of the Micro Electronic Mechanical System (MEMS-IMU) has been selected for high-precision positioning in the industry with its advantages of low cost, miniaturization and high precision. Based on the extended Kalman filter single-frequency RTK and Ultra low-cost MEMS-IMU loose combination positioning algorithm, the data is collected and tested in static scenes, and dynamic scenes. The experimental results show that: (1) In the static scenes, the combined positioning accuracy is better than 1.5cm, which is equivalent to the accuracy of the dual-frequency commercial receiver; (2) In the dynamic scenes, the single-frequency GNSS RTK positioning accuracy is better than 3cm, and the combined positioning accuracy is better than 5cm. In general, the combined positioning in static and dynamic modes can provide reliable high-frequency centimeter-level positioning.

1. Introduction

With the rise of civil mobile positioning terminal markets such as drones and smart wearable devices, the need for high-precision positioning is becoming increasingly apparent. At present, civil mobile positioning terminals mostly use a combination of global navigation satellite system (GNSS) single-point positioning technology and MEMS IMU positioning, but the positioning accuracy is only 10m, which cannot meet their high-precision requirements [1] [2]. Due to the high cost of dual-frequency GNSS RTK, it cannot be widely used in the civil mobile positioning terminal market. Literature [3-6] further studied the short-baseline single-frequency GNSS RTK positioning performance. Under the condition of using a geodetic receiver antenna, the single-frequency GNSS RTK positioning accuracy is equivalent to the dual-frequency RTK positioning. Literature [7] analyzed the performance of civilian consumer-grade single-frequency GNSS antennas. Consumer-grade antennas still have good performance. However, there are few studies on the application of single-frequency GNSS RTK / IMU combined positioning in civil mobile positioning terminals, and most of them still use GNSS single-point positioning.

Therefore, this paper studies the dynamic and static positioning performance of single-frequency GNSS RTK and MEMS-IMU combined positioning of consumer-grade mobile terminals. Based on the self-developed single-frequency GNSS RTK processor and the consumer IMU sensor MPU9250 for loosely combined positioning, combined positioning and commercial multi-frequency GNSS receiver positioning data in static, dynamic scenes were record, and finally the dynamic and static positioning performance of combined positioning were compared and analyzed.
2. Combined filtering algorithm

Single-frequency GNSS RTK / MEMS-IMU loose combination algorithm uses extended Kalman filter (EKF) to fuse RTK and MEMS-IMU data (gyro, accelerometer and magnetometer data), and estimates the speed, position, IMU error and other parameters.

2.1. A. Equation of State

Because the ultra low-cost MEMS-IMU device is relatively noisy, the state differential equation used in this article is optimized. The state differential equation of the position velocity quaternion is as follows [2] [8] [9]:

\[
\begin{bmatrix}
\dot{q} \\
\dot{V} \\
\dot{P}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2}q \otimes (\omega - C^b_a \omega^g_n) \\
C^w_a a_i + \begin{bmatrix} 0 & 0 & g^T \end{bmatrix} \\
V
\end{bmatrix}
\]  

(1)

In the formula, \( \dot{q} \), \( \dot{V} \) and \( \dot{P} \) are respectively the time derivative of the quaternion, the speed and the position vector; \( \otimes \) is the quaternion multiplication; \( C^b_a \), \( C^w_a \) are the rotation matrix, respectively, the transformation from the carrier coordinate system to the NED coordinate system and the NED coordinate system to the carrier coordinate system; \( \omega_i \), \( a_i \) are the real output value of the gyroscope and the real output value of the accelerometer; \( \omega_n^b \) is the earth’s rotational acceleration at the current position, and \( g \) is the acceleration of gravity.

The true output values of the gyroscope and accelerometer in equation (1) can be obtained by the following equation [9]:

\[
\begin{bmatrix}
\omega_m^b \\
\omega_m^a
\end{bmatrix} = \begin{bmatrix}
\omega_i + b_{\omega} + \epsilon_{\omega} \\
a_i + b_{a} + \epsilon_{a}
\end{bmatrix}
\]  

(2)

In the formula, \( \omega_m^b \), \( \omega_m^a \) are the observation measurement of the gyroscope and the accelerometer; \( b_{\omega}, b_a \) are the zero bias vector of the gyroscope and the accelerometer; \( \epsilon_{\omega}, \epsilon_{a} \) are the driving white noise of the gyroscope and the accelerometer observation.

\[
\begin{bmatrix}
\dot{b}_{\omega} \\
\dot{b}_{a}
\end{bmatrix} = \begin{bmatrix}
w_{\omega} \\
w_{a}
\end{bmatrix}
\]  

(3)

In the formula, \( \dot{b}_{\omega}, \dot{b}_a \) are the derivative of the zero offset vector of the gyroscope and accelerometer with respect to time, respectively; \( w_{\omega}, w_{a} \) are the zero offset unstable noise value of the gyroscope and accelerometer.

Using equation (2) as the input value of the state equation, equation (1) can be written as a linearized matrix:

Where \( x=[q \ V \ P \ b_{\omega} \ b_a]^T \) are the state recurrence vector; \( F, \Psi, \Gamma \) are the state vector coefficient matrix, the input vector coefficient matrix, and the process noise coefficient matrix of the
state differential equation, expression reference [8]; \[ w = \begin{bmatrix} w_{\omega} & w_{a} & w_{b_{\omega}} & w_{b_{a}} \end{bmatrix}^T \] is the process noise vector, where \( w_{\omega} \), \( w_{a} \) is the gyroscope and accelerometer bias instability noise value.

From this, the state vector, input vector coefficient, and process noise coefficient matrix of the state equation can be obtained.

2.2. Measurement equation
In the single-frequency GNSS RTK/ MEMS-IMU combined filtering algorithm, the speed, position of the RTK and heading of the magnetometer are used as the kalman filter observations.

\[
Z = \begin{bmatrix} V_{RTK} \\ P_{RTK} \\ \phi_{yaw} \end{bmatrix} = \begin{bmatrix} V \\ P \\ \arctan\left(\frac{2(q_1 q_2 - q_3 q_4)}{q_0^2 - q_1^2 + q_2^2 - q_3^2}\right) \end{bmatrix}
\]

(4)

Where \( Z \) is the observation vector; \( V_{RTK}, P_{RTK} \) are the single-frequency GNSS RTK speed and position observation; \( \phi_{yaw} \in [-\pi, \pi] \) is the heading value calculated by the MEMS-IMU magnetometer, and the expression between it and the quaternion is related to the Euler angle rotation order for details, please refer to [9].

The magnetometer output is the three-axis magnetic intensity of the carrier, which is converted into the heading observation value by the following formula:

\[
\phi_{mag} = \arctan\left(\frac{M_z}{M_n}\right) + \psi_{\text{decline}}
\]

(5)

Where \( \psi_{\text{decline}} \) is the correction value of the magnetic declination angle; is the magnetic intensity of the carrier coordinate system obtained through the transformation of the rotation matrix, which does not rotate the yaw direction.

Formula (4) can write as a linearized matrix:

\[
Z = Hx + R
\]

(6)

In the formula, \( H \) is a matrix of measurement coefficients, the expression is described in [2]; \( R = [e_s, e_p, e_v]^T \) is the white noise matrix of the speed, position, and heading.

2.3. Algorithm framework
The algorithm framework mainly includes: filter state initialization, state prediction, single-frequency GNSS RTK module, MEMS-IMU error estimation, measurement update and other processing modules. The state equations and measurement equations are given in Sections 2.1 and 2.2. The algorithm uses direct method kalman filtering for navigation state prediction, IMU error estimation and measurement update, and finally outputs to the navigation result data. The single-frequency GNSS RTK algorithm can refer to the reference [5] [10]; the state initialization, the residual removal in the state update module refer to the reference [2] [9]; the random noise and bias instability parameters in MEMS-IMU error estimation refer to the reference[11].

3. Experimental settings And analysis

3.1. Experimental settings
In order to analyze the dynamic and static positioning performance of single-frequency GNSS RTK / MEMS-IMU integrated navigation on civilian positioning terminals, this article is based on a self-
developed single-frequency GNSS RTK processor and embedded Ublox M8T module, as shown in Figure 1 (a), which is connected to civilian positioning. The terminal helical antenna, as shown in Figure 1 (b), accesses the Qianxun GNSS network differential correction service, and performs loosely combined positioning with the consumer-level IMU sensor MPU9250. The original data of a commercial multi-frequency GNSS receiver as the reference was recorded.

Figure 1 Experimental settings

This experiment was conducted in an open football field (latitude: 29.57 ° longitude: 106.46 °). In a static experiment, a commercial GNSS multi-frequency receiver base station set up in an open environment, and the rover station is set up nearby. The commercial GNSS multi-frequency receiver is fixed with a tripod, and a small steel plate is fixed to the triangle and installed on it. And using a laptop computer to connect the network to send Qianxun correction service to single-frequency RTK processor, and collect data for 30 minutes at the same time (commercial receiver sets the sampling frequency 20hz, single-frequency RTK processor sampling 5hz, IMU gyroscope, accelerometer sampling rate 250hz, magnetometer sampling rate 100hz), as shown in Figure 1 (c). In the dynamic experiment, the commercial GNSS multi-frequency receiver base station is still set up in an open environment, and the rover station is set up on the mobile measuring rod. The integrated navigation equipment is still connected to the commercial GNSS multi-frequency receiver through a small rigid board, as shown in Figure 1 (d), and collected dynamic data (sampling frequency is the same as static experiment).

3.2. Experimental analysis

The single-frequency GNSS RTK / MEMS-IMU integrated device collects a large amount of data, and the data is obtained through the embedded device's real-time processing data (up to 250 HZ) stored on the SD card, which is likely to cause data loss. Positioning results obtained by post-processing raw data; commercial multi-frequency GNSS receiver data is processed using the RTKLIB [10] program to obtain single-frequency GPS + BDS, multi-frequency GPS, dual-frequency BDS, and dual-frequency GPS + BDS positioning data, respectively. Among them, the four schemes of RTK processing parameters are the same. Due to the base station data provided by Qianxun service is used in the integrated navigation equipment, the differential processing of the commercial receiver uses the self-built base station. The two devices are fixed by small steel plates in dynamic and static experiments. The coordinate system is the same, but the starting point of the coordinate system is different. The relative accuracy between the two can be determined by the following formula:

\[ \delta r = r_e - r_c + O_{ce} \]  

Where \( \delta r \) is the distance between the single-frequency antenna of the integrated navigation equipment and the commercial receiver antenna; \( r_e, r_c \) are the coordinate values of the integrated navigation equipment and the commercial receiver; \( O_{ce} \) is the coordinate starting point of the Qianxun base station and the commercial receiver base station fixed difference.
The data between the two devices is synchronized via GPS time, the distance between each epoch combined navigation device and the commercial receiver antenna (including the difference between the starting point of the fixed error coordinate) is calculated, its average value is subtracted, and its accuracy is evaluated.

3.3. Static analysis
The static processing output difference data of each epoch is shown in Figure 1 below. The up side shows the accuracy of the antenna distance value between the single-frequency GNSS RTK and the commercial receiver used by the civilian positioning terminal, and the single-frequency GNSS RTK / MEMS-IMU combined positioning. The difference in antenna distance between commercial receivers, from top to bottom, is single-frequency GPS + BDS, dual-frequency BDS, dual-frequency GPS, dual-frequency GPS + BDS. There are four comparison schemes, among which the single frequency is recorded SF, dual frequency is recorded as DF, GPS is recorded as G, BDS is recorded as B, GPS + BDS is recorded as G + B.

![Figure 2 Static antenna distance difference](image)

Calculate the standard deviation of schemes in Figure 2, as shown in Table 1, where std1 is the standard deviation of the difference and std2 is the standard deviation after removing the gross error.

From Figure 2, Table 1 can be seen:

1. There is a large gross error in the data of about two minutes. This error is caused by network problems or Qianxun service failures. This also causes the RTK accuracy in Table 1 to be greater than 4cm, and the combined accuracy to be greater than 15cm. Therefore, it is particularly important to ensure the stability of differential services in the use of positioning terminals.

2. In the single-frequency GPS + BDS and dual-frequency GPS + BDS solutions, a small jump occurs between the RTK positioning and the combined positioning results within 0 ~ 300s, but it does not appear in the dual-frequency GPS and dual-frequency BDS. It has not been fixed for a period of time, so the small jump is caused by the RTK cycle slip of the commercial receiver. The increase in the number of satellites speeds up the fixed time, but also causes the problem of cycle slip.

3. std2 in Table 1 removes data due to Qianxun service failures and unfixed data at the beginning of the figure. In static mode, single-frequency GNSS RTK / MEMS-IMU combined positioning performance is better than commercial receivers Dual-frequency BDS, single-frequency GPS + BDS mode, dual-frequency BDS, but the difference is not large, the positioning accuracy and dual-frequency GPS are quite better than 1.5cm, of which the accuracy of dual-frequency BDS is the lowest, and the initialization time of dual-frequency GPS is the slowest.
### Table 1. Static relative precision standard deviation

| Position Mode                  | Std1(m) | Std2(m) |
|--------------------------------|---------|---------|
| SF RTK/SF-G+B                  | 0.049   | 0.031   |
| SF RTK-IMU/SF-G+B              | 0.151   | 0.032   |
| SF RTK/DF-G                    | 0.043   | 0.015   |
| RTK-IMU/DF-G                   | 0.156   | 0.018   |
| SF RTK/DF-B                    | 0.051   | 0.032   |
| RTK-IMU/DF-B                   | 0.156   | 0.034   |
| SF RTK/DF-G+B                  | 0.044   | 0.021   |
| RTK-IMU/DF-G+B                 | 0.152   | 0.023   |

### 3.4. Dynamic Analysis

The trajectory in the dynamic mode environment is shown in Figure 3. Due to the good observation conditions, this article only gives the trajectory map of single frequency GPS + BDS. On the left is the single-frequency GPS + BDS RTK and on the right single-frequency RTK / MEMS-IMU combined positioning trajectory; the antenna distance difference is shown in Figure 4, which is consistent with the sequence and abbreviation in the static mode.

![Figure 3 trajectory of the dynamic mode](image)

As can be seen from Figure 3, the positioning trajectories of commercial receiver RTK positioning, single-frequency GNSS RTK, and combined positioning equipment are good, and there are no abnormal points.

![Figure 4. Difference of dynamic unobstructed antenna distance](image)

Table 2 shows the standard deviation of the distance of the dynamic mode. It can be seen from Figure 4 and Table 2:

1. The difference between the single-frequency GNSS RTK and the commercial receiver on the up in Figure 4 has almost the same waveforms in the four modes. According to Table 2, the standard
deviation of the distance difference in the four schemes is about 3.3 ~ 3.6cm. Single frequency GNSS RTK dynamic point accuracy is better than 3cm.

(2) In the positioning difference chart between the single-frequency RTK / MEMS-IMU combination device and the commercial receiver on the down in Figure 4, the commercial receiver is positioned in single-frequency GPS + BDS, dual-frequency GPS, and dual-frequency GPS + BDS modes. There are a small number of unfixed points, but the error is not large. It may be that the ambiguity of a GPS satellite signal is fixed error and the floating point solution is generated. As can be seen from Table 2, the standard deviation of the distance difference in the four schemes is 5.2 ~ 5.4cm, so the single-frequency GNSS RTK / MEMS-IMU combined positioning point accuracy is better than 5cm.

| Position Mode       | Std(m) |
|---------------------|--------|
| SF RTK/SF-G+B       | 0.033  |
| SF RTK-IMU/SF-G+B   | 0.053  |
| SF RTK/DF-G         | 0.034  |
| RTK-IMU/DF-G        | 0.054  |
| SF RTK/DF-B         | 0.036  |
| RTK-IMU/DF-B        | 0.054  |
| SF RTK/DF-G+B       | 0.034  |
| RTK-IMU/DF-G+B      | 0.052  |

4. summary
This paper conducts research on the dynamic and static positioning performance analysis of single-frequency GNSS RTK / MEMS-IMU combined positioning on civilian positioning terminals. First, an extended Kalman filter algorithm for RTK / MEMS-IMU combined positioning is given. Based on this, a self-developed single-frequency GNSS RTK processor is used to connect a single-frequency GNSS spiral antenna and access to the Qianxun network correction service. The raw data from the combined positioning with the ultra low cost IMU sensor MPU9250 in a static, dynamic mode and two commercial multi-frequency GNSS receivers was recorded, and finally the dynamic and static positioning performance of combined positioning were compared and analyzed. The experimental results show that: (1) in the static mode, under the condition of normal differential service, the single-frequency GNSS RTK / MEMS-IMU combined positioning accuracy is better than 1.5cm, which is equivalent to the accuracy of the dual-frequency commercial receiver; (2) In the dynamic experiment, the positioning accuracy of single-frequency GNSS RTK is better than 3cm, and the combination accuracy with MEMS-IMU is better than 5cm; In general, the combined positioning in static and dynamic modes can provide reliable high-frequency centimeter-level positioning.

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