The design and implementation of vehicle-mounted satellite communication on the move based on MEMS gyro

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Abstract. As an important satellite communication technology, mobile communication has broad application prospects in the field of military and civilian applications. Low cost and high reliability have become one of the goals and difficulties in engineering design. In order to overcome the shortage of course information provided by inertial navigation or electronic compass, a beacon space search algorithm without course information is designed. A low cost gyro stabilization platform based on ARM and MEMS gyroscope is designed for the high mobility and complex working conditions of vehicles. The servo motor and photoelectric encoder are used to construct the multi-closed-loop control system to improve its fast response ability, and the pitch compensation and beacon space search algorithm are used to improve the precision of the system for star and tracking. It has good engineering application and popularization value.

1. Introduction
Satellite communication has attracted more and more attention because of its long communication distance, large coverage area and flexibility. It has been widely used in military communications, emergency communications, anti-terrorism relief, news broadcasting and other fields [1]. The growing need for ubiquitous mobile communication services in land, maritime, and aeronautical environments pushes the development of satellite communication on the move applications [2]. Satellite communication on the move is a kind of satellite communication device installed on mobile carriers such as aircraft, vehicles and ships. It can eliminate the interference of carrier motion and other disturbances to satellite communication system through its own stabilization device in the course of carrier movement, and then realize stable and uninterrupted mobile satellite communication [3]. As a result of the combination of mechatronics technology, automatic control technology, satellite communication technology and other multi-disciplinary technologies, satellite communication on the move has a broad application prospect in engineering. Recent technology advancements have allowed for significant improvement in satellite communication system capacity and provided “true” broadband real-time satellite communication on the move capability to both commercial and military users [4], which has also led to its large-scale application and transformation from high-cost to low-cost.

Because of the strong mobility and complex surrounding environment in the course of vehicle driving, the satellite communication on the move system requires that the communication antenna and
satellite always keep continuous communication during the course of vehicle driving. Therefore, on the one hand, the antenna servo system is required to have a high dynamic response ability, which can quickly capture and track the target satellite after the vehicle passes through obstacles such as bridges, trees, buildings, mountains and tunnels. On the other hand, when the vehicle encounters severe disturbance caused by bad road conditions, the stabilized platform is required to effectively isolate the influence of carrier disturbance on antenna pointing. Through the isolation of the stabilized platform, the antenna can accurately point to and track the target satellite to ensure the quality of communication. Accurate tracking of the satellite is the essential requirement of the satellite communication on the move system, and which is also the core of the design of the satellite communication on the move system.

2. Current major issues
The key of the satellite communication on the move system is the accurate pointing and stable tracking of the antenna. At present, the following tracking methods are commonly used in vehicle [5].

(1) Program tracking
The system mainly uses high-precision integrated inertial navigation system to provide carrier's attitude and position information. According to the real-time inertial navigation information and target satellite's position information, the servo control system outputs the azimuth, elevation and polarization angles of the antenna pointing to the target satellite in the carrier coordinate system through real-time coordinate transformation and calculation, and drives the antenna pointing to the target satellite in real-time. The system is simple to implement, but it requires high precision and high cost for the integrated inertial navigation system. In addition, the system relies heavily on INS. Influenced by the accuracy of antenna pedestal, installation accuracy and system calibration accuracy, if the inertial navigation performance is poor, the tracking accuracy and reliability of the system are low when it is used in various complex working conditions.

(2) Monopulse tracking
The so-called monopulse tracking means that in a pulse interval, the automatic tracking system can obtain complete information of the azimuth and elevation angle of the target deviating from the antenna axis, and can drive the servo system to make the antenna quickly align with the target satellite. The system uses a monopulse tracking antenna. The antenna is complex. It requires the antenna to generate both azimuth and pitch sum and difference beams. Through the demodulation of the tracking receiver, the angular error information of the antenna deviating from the target is output to the servo control unit to complete the antenna tracking. The tracking accuracy of the system is high, but the system is complex and costly, which is not conducive to large-scale application.

(3) Electronic compass and beacon tracking
The attitude information of the carrier (course, pitch and roll) is obtained by electronic compass, and the closed-loop feedback system is directly stabilized by using rate gyroscope. The current position information of the carrier is measured by GPS. The attitude information of the antenna is calculated by coordinate transformation in the control unit, and the antenna pointing is maintained by the driving unit. At the same time, the extreme value tracking is composed of the satellite beacon level signal received by beacon receiver. The cost of the system is low, but because the electronic compass is susceptible to interference and its angular measurement accuracy is low, when it is applied to the vehicle-mounted mobile communication system, the response speed and tracking accuracy of the system are low and the reliability is low.

From the above analysis of several common tracking modes, we can see that the first two tracking modes have high cost, while the third tracking mode has low cost, but its tracking accuracy is low and easy to be disturbed, which is not conducive to large-scale popularization and application. In addition, in the initial pointing alignment of the antenna, the above three tracking methods all need to obtain the course information of the carries, and the carrier's course information needs to be obtained through integrated inertial navigation or electronic compass, which will directly affect the cost, accuracy and reliability of the system. In view of the above problems and shortcomings, this paper designs a low
cost vehicle-mounted satellite communication on the move system, which uses search algorithm and does not depend on course information in initial pointing. The equipment has been tested and verified in engineering.

3. Principle of two-axis gyro stabilization

3.1. Introduction of coordinate system

Carrier coordinate system $OX_bY_bZ_b$: It is abbreviated as b system, which is fixed with the carrier. Origin $o$ is the center of gravity of the carrier. The horizontal axis $OX_b$ points to the right side of the carrier, and the vertical axis $OY_b$ points to the head along the head and tail of the carrier, the axis $OZ_b$ is perpendicular to the plane of the carrier. The $OX_bY_bZ_b$ is right-handed rectangular coordinate system [6].

Azimuth loop coordinate system $OX_aY_aZ_a$: It is abbreviated as a system, which is fixed with azimuth loop. The axis $OZ_a$ is along the azimuth loop axis and points to the same direction as the axis $OZ_b$. Compared with the b system, the a system can only rotate around the axis $OZ_b$ to produce azimuth loop angle $\theta_a$.

Pitch loop coordinate system $OX_fY_fZ_f$: It is abbreviated as f system, which is fixed with the pitch loop. The axis $OX_f$ is along the pitch loop axis and points to the same direction as the axis $OX_a$. Compared with the a system, the f system can only rotate around the axis $OX_a$ to produce pitch loop angle $\theta_f$.

3.2. Coupling analysis of coordinate system

The basic principle of two-axis gyro stabilized platform to isolate the disturbance of carrier is to keep the spatial direction of the axis $OY_f$ unchanged through the isolation of platform when the motion of carrier produces angular velocity $\omega_b$. Let $(\omega_{bx}, \omega_{by}, \omega_{bz})$ be the component of the angular velocity $\omega_b$ of the carrier along three axes, $\delta_a^g$ and $\delta_f^g$ are the angular velocity of the azimuth servo drive and the pitch servo drive respectively. The relative position relations among the three coordinate systems of b, a and f are shown in Figure 1.

![Figure 1. The relative position relations among the three coordinate systems.](image)

(1) Coupling analysis of b system to a system

When the carrier coordinate system b has disturbance angular velocity $\omega_b$ $(\omega_{bx}, \omega_{by}, \omega_{bz})$, it can be known from the rotation theory of coordinate system that the total angular velocity on the azimuth
loop a is the superposition of the angular velocity directly coupled from b system to a system and the azimuth rotation angular velocity driven by the azimuth motor, i.e

$$
\begin{bmatrix}
\omega_{n} \\
\omega_{m} \\
\omega_{c}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
-\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\omega_{n} \\
\omega_{m} \\
\omega_{c}
\end{bmatrix}
= 
\begin{bmatrix}
\omega_{n} \cos \theta_{a} + \omega_{m} \sin \theta_{a} \\
-\omega_{n} \sin \theta_{a} + \omega_{m} \cos \theta_{a} \\
\omega_{c} + \dot{\theta}_{a}
\end{bmatrix}
$$

(1)

(2) Coupling analysis of a system to f system

Similarly, according to the rotation theory of coordinate system, the total angular velocity on the pitch loop f is the superposition of the coupling angular velocity from a system to f system and the pitch rotation angular velocity driven by the pitch motor, i.e

$$
\begin{bmatrix}
\omega_{n} \\
\omega_{m} \\
\omega_{c}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & \sin \theta \\
0 & -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\omega_{n} \\
\omega_{m} \\
\omega_{c}
\end{bmatrix}
+ 
\begin{bmatrix}
\dot{\theta}_{f} \\
0 \\
0
\end{bmatrix}
= 
\begin{bmatrix}
\omega_{n} \cos \theta_{a} + \omega_{m} \sin \theta_{a} + \dot{\theta}_{f} \\
-\omega_{n} \sin \theta_{a} + \omega_{m} \cos \theta_{a} + \dot{\theta}_{c} + \dot{\theta}_{f} \sin \theta_{f} \\
\omega_{c} + \dot{\theta}_{c}
\end{bmatrix}
$$

(2)

According to the essence of two-axis gyro stabilization, \(\omega_{n} = 0, \omega_{c} = 0\), therefore

$$
\dot{\theta}_{a} = -\left(\omega_{n} \sin \theta_{a} - \omega_{c} \cos \theta_{a}\right) \tan \theta_{f} + \omega_{c}
$$

(3)

$$
\dot{\theta}_{c} = -\left(\omega_{n} \cos \theta_{a} + \omega_{c} \sin \theta_{a}\right)
$$

(4)

These formulas are the general expressions of angular velocity compensation of two-axis gyroscope stabilized platform. The servo motor drives azimuth and pitch rotation to complete the stability control of the platform.

4. System design

Aiming at the characteristics of strong maneuverability and complex surroundings in the course of vehicle movement, this paper designs a new beacon space search algorithm to complete the initial pointing and dynamic tracking of antenna, which does not rely on inertial navigation or electronic compass to provide heading information, and uses low-cost MEMS gyroscope as the main structure of stabilized platform to isolate the disturbance of carrier. It solves the shortage of course information provided by inertial navigation or electronic compass in traditional design. At the same time, the servo motor is used as driving element, the photoelectric encoder is used as feedback element, and multi-closed-loop control algorithm is used to improve the system’s rapid response ability, so as to improve the environmental adaptability and reliability of the system.

4.1. System composition and function

The composition of the vehicle-mounted mobile communication system is shown in Figure 2.

From above, the vehicle-mounted mobile communication system is mainly composed of antenna microwave module, servo control unit and modem. The antenna microwave components complete the radio frequency signal transmission and reception, including antenna, BUC, LNB and power divider, etc.. The servo control unit can drive and control the motor, and complete the construction of gyro stabilized platform, which is mainly composed of servo controller, motor, encoder, gyro, accelerometer and GPS. The modem mainly completes the baseband signal modulation and demodulation.

The main function of this system is to construct the attitude measurement unit through its own inertial and position sensors, and to construct the gyro stability platform according to the gyro stability control technology, so as to isolate the influence of various disturbances on the antenna pointing in the process of vehicle moving. At the same time, combining the GPS data and the signal size of the satellite beacon level received by the beacon receiver, the spatial search algorithm is used to control the antenna always pointing to the target satellite, so that the antenna pointing is not affected by the vehicle disturbance, and the stability of the communication is guaranteed.
4.2. Hardware design

As the control core of the system, the servo controller plays an important role in the system. In this system, the servo controller takes ARM as the core, and STM32F405 is selected as the main control element to design the DC servo motor control system based on ARM. The DC servo motor is selected as the driving element in the system, and absolute value photoelectric encoder is used as the position and speed feedback element to complete the closed-loop control of the motor. At the same time, the MEMS gyro is used to construct the gyro stabilization platform, and the pointing, control and stable tracking of the antenna are completed by combining the output information of the accelerometer, GPS and beacon receiver. The principle block diagram of the servo controller is shown in Figure 3.

Figure 2. The composition of the vehicle-mounted mobile communication system.

Figure 3. The principle block diagram of the servo controller.
From above, the ARM is the control core of the servo controller. It collects the output data of the MEMS gyro and accelerometer, and completes the construction of the gyro stabilized platform. The pointing angle of the antenna to the star is calculated according to the GPS data of the vehicle and the satellite. According to the real-time feedback position information of the encoder, the closed-loop control of the motor is completed. The precise pointing and tracking of antenna are completed by satellite beacon value received by the beacon receiver.

4.3. Control loop design
In this system, the main purpose of the control loop design is to drive and close-loop control the azimuth and pitch motors \([7, 8]\), complete the control of gyro stabilized platform and fast pointing and tracking of antenna. The control structure of azimuth and pitch loop is basically the same. The following is the analysis of azimuth loop only. The Figure 4 is the control structure diagram of azimuth loop. It can be seen from the figure that the angular rate gyroscope is used to isolate the disturbance generated during the vehicle driving and realize the stabilization function. Gyro stabilized platform is a typical servo motion control system \([9]\). As the main feedback component of the system, gyro has an important impact on the system performance. When designing the control loop, the position loop is input after the angular rate is integrated, which can further improve the stability accuracy of the system. In addition, the current loop composed of current sampling unit can improve the anti-load torque disturbance ability of the system, and the position loop composed of photoelectric encoder and its differential speed loop can improve the control accuracy and dynamic response ability of the servo system.

![Figure 4](image)

Figure 4. The control structure diagram of azimuth loop.

4.4. Software algorithm design
The working process of the system is divided into two stages: initial alignment and dynamic tracking. Because the initial heading information of the vehicle is not provided by inertial navigation or compass in the system design, the traditional coordinate transformation method can not be used to calculate the initial pointing angle of the antenna. This paper designs a control algorithm based on pitch compensation and beacon search, which can effectively solve the lack of heading information and complete the initial alignment of antenna. After the initial alignment of the antenna is completed, the system automatically transfers to dynamic tracking according to the set threshold. That is to say, the complete antenna-to-satellite tracking process is completed. The flow chart of the control algorithm is shown in Figure 5.
The specific working process of the system is as follows. In the initial pointing, firstly, according to the GPS information of the target satellite and the antenna, the pitch angle of the antenna in the geographic coordinate system is calculated. Secondly, the pitch and roll angle information of the vehicle fused by the MEMS gyroscope and accelerometer is compensated after real-time solution, so that the antenna can point to the pitch angle of the target satellite in the carrier coordinate system, and the azimuth servo drives antenna for 360 degree search. According to the received beacon value, the antenna is driven to point to the beacon maximum point. Finally, when the azimuth and pitch are completed, the dynamic star tracking can be performed according to the sizes and thresholds of the beacon values until the task is completed.

![Flow chart of control algorithm](image)

**Figure 5.** The flow chart of control algorithm.

5. **Test and verification**

After the equipment debugging is completed, the satellite communication on the move is installed on SUV for test. The Figure 6 shows the developed equipment. The satellite communication test system is built by using Zhongxing-10 communication satellite and Ku band 6.2m ground station to verify the rationality of the system design and the applicability of search and tracking algorithm. The system test chart is shown in Figure 7. In order to verify the system comprehensively, the tests are carried out according to the items of static star alignment, dynamic star alignment, directional shielding, tunnel
shielding and bumpy road test, and each item is tested repeatedly. The Figure 8 is the graph output by the beacon receiver in the test process. The test results are shown in Table 1.

Figure 6. The satellite communication on the move and the SUV.

Figure 7. The system test chart.

Figure 8. The graph output by the beacon receiver in the test process.
Table 1. The system test items and results.

| Serial number | Test items               | Heading direction | One-click star time | Post-alignment beacon value | Success rate | Communication effect                      |
|---------------|--------------------------|-------------------|---------------------|------------------------------|--------------|-------------------------------------------|
| 1 Static star alignment | East                     | 27s               | 6.8v                | 100%                         | Normal Data, Fluent Audio and Video |
|               | South                    | 26s               | 6.7v                | 100%                         | Normal Data, Fluent Audio and Video |
|               | West                     | 27s               | 6.6v                | 100%                         | Normal Data, Fluent Audio and Video |
|               | North                    | 28s               | 6.8v                | 100%                         | Normal Data, Fluent Audio and Video |

| Serial number | Test items               | Motion state       | One-click star time | Post-alignment beacon value | Success rate | Communication effect                      |
|---------------|--------------------------|--------------------|---------------------|------------------------------|--------------|-------------------------------------------|
| 2 Dynamic star alignment | Straight line driving (80Km/h) | 42s                | 6.7v                | 100%                         | Normal Data, Fluent Audio and Video |
|               | Driving around in circles (10Km/h) | 30s                | 6.8v                | 100%                         | Normal Data, Fluent Audio and Video |

| Serial number | Test items               | Shielding time     | Pre-occlusion beacon value | Recapture time | Capture beacon values again | Communication effect                      |
|---------------|--------------------------|--------------------|----------------------------|----------------|----------------------------|-------------------------------------------|
| 3 Directional shielding | 2.5min                   | 6.9v               | 3s                         | 6.8v           | Normal Data, Fluent Audio and Video |
|               | 10min                    | 6.8v               | 5s                         | 6.7v           | Normal Data, Fluent Audio and Video |

| Serial number | Test items               | Speed | Initial beacon value | Maximum attenuation of beacon values | Communication effect                      |
|---------------|--------------------------|-------|----------------------|--------------------------------------|-------------------------------------------|
| 4 Tunnel shielding | 10min                    | 6.7v  | 8s                   | 6.7v                                 | Normal Data, Fluent Audio and Video |
| 5 Bumpy road   | 15km/h                   | 6.7v  | 0.2v                 | /                                    | Normal Data, Fluent Audio and Video |
|               | 25km/h                   | 6.7v  | 0.4v                 | /                                    | Normal Data, Fluent Audio and Video |

As can be seen from the test data in Table 1, the system can quickly and automatically align satellites with one key and establish dynamic communication links. In occlusion test and bumpy road test, the system performs well and can realize satellite communication under various working conditions and meet the design requirements.

6. Conclusions
In this paper, in view of the shortcomings of tracking methods commonly used in satellite communication on the move, a two-axis gyro stabilization platform based on low-cost MEMS gyro is designed according to the engineering practice. With the servo motor as the driving element, the multi-closed-loop control algorithm is adopted to improve the system's rapid response ability and control accuracy. On the premise of no heading information, the control algorithm of pitch compensation and beacon space search is used to realize the initial pointing and precise tracking of the antenna. Combining with the high dynamic servo control system, the antenna can be pointed quickly and accurately and work stably and reliably. Through static star alignment and dynamic test, it is verified that all the indexes meet the design requirements. Compared with the traditional inertial navigation program tracking or monopulse tracking, the cost of the system is reduced by about one-third. At the
same time, the system also shows better performance. This method can be used as a new design idea in airborne, shipboard and other fields.

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