OVERVIEW OF THE INTEGRATED NAVIGATION SYSTEM RESEARCH STATUS AND ITS DEVELOPMENT INTEGRATED WITH 5G COMMUNICATION

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ABSTRACT:

GNSS (Global Navigation Satellite Systems)/INS (Inertial Navigation Systems) has been the research hotspot in the field of navigation and positioning. while the small-area densification of 5G communication technology and the technical means of large-scale array antennas have provided new developments for integrated navigation research. The GNSS/INS integrated navigation mode was introduced in this paper, the research status of integrated navigation at home and abroad was investigated and analyzed, several improved Kalman filter algorithms were described: unscented Kalman filtering algorithm, adaptive improved algorithm, neural network improved algorithm, deep learning improved algorithm. GNSS/INS/5G integrated navigation system was discussed. Finally, the application prospect of integrated navigation system was given in location service.

1. INTRODUCTION

In order to achieve safe, reliable location services and meet the needs of accurate positioning in many fields such as real-time navigation, vehicle positioning and traffic management, the integrated navigation system GNSS/INS, as the main research technical means, can provide accurate and all-round integrated space-time location information. The research on improving positioning accuracy has become a trend. With the rapid development and application of 5G, the era of interconnection of all things has come. The research of integrating 5G and integrated navigation system is of great significance for realizing high-precision location services, as well as building a smart economic society.
The integrated navigation mode can complement, modify and dynamically compensate the information between different navigation sources to obtain high-precision and robust positioning performance. As a classical information fusion algorithm, Kalman filter is only suitable for linear and Gaussian distribution problems. In order to optimize the performance of navigation algorithm in nonlinear problems, researchers have proposed other improved algorithms, such as lossless Kalman filter algorithm, adaptive filter algorithm, network improved algorithm, deep learning improved algorithm and so on.
Starting with GNSS/INS, this paper introduces its basic working principle and several improved navigation algorithms, and finally expounds the development prospect of integrated navigation under 5G.

2. RESEARCH STATUS OF INTEGRATED NAVIGATION

In different scenarios, scholars at home and abroad have proposed different integrated navigation and positioning methods to improve positioning accuracy, and realized the application of navigation and positioning system in corresponding scenarios, as shown in the following table：

Integrated navigation mode	Advantages	Disadvantages
Denoising stereo vision odometer VO/INS/GPS integrated navigation	About 54% higher than GNSS/INS navigation system performance	The navigation accuracy depends on the vision sensor accuracy when satellite signal failure
Integrated GPS/INS navigation based on TDCP	Compared with traditional integrated navigation, the performance is improved by 60%	TDCP measurement modeling is contrary to KF model, and the optimal solution cannot be obtained
Distributed GNSS/INS integrated navigation based on Vector VT tracking control	It has strong robustness in weak signal environment	Highly influenced by filtering algorithms and filters
GNSS/IMU/ODO / LIDAR-SLAM integrated navigation system using IMU/ODO pre-integration	High precision, good robustness, small error	High cost and time-consuming data fusion

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UWB assisted GNSS / INS Integrated Navigation System	The calculation is small, and the accuracy is improved when GNSS signal fails	Need to ensure mutual communication between UWB module platforms
MIMU/GPS integrated navigation assisted by heading information	High precision, good reliability, moderate calculation volume	Positioning accuracy cannot be guaranteed for long periods of time

Table 1. Comparison of research methods of different integrated navigation methods.

In addition, as for the integrated navigation information fusion algorithm, due to the limitations of the traditional Kalman filter algorithm, scholars at home and abroad have made many improvements to improve the robustness and positioning accuracy of the integrated navigation system. The following four navigation algorithms with good application are introduced, as shown in the following table：

Navigation Fusion Algorithm	Features
Unscented Kalman filter algorithm	It has good processing capacity for nonlinear systems, simple calculation and easy implementation
Adaptive Kalman filtering algorithm	Simple principle, good real-time
Neural network-assisted filtering algorithm	Adapt to time-varying, good real-time performance and good network predictability.
Deep learning improvement algorithm	Simple, easy to learn, no need for systematic mathematical models

Table 2. Four main improved navigation filtering algorithms.

About integrated navigation filtering algorithm, there are many other improved algorithm, such as extended Kalman filtering algorithm, the optimal fixed interval smoothing algorithm, the improved adaptive algorithm, and artificial intelligence into the navigation filtering algorithm, such as radial basis function (RBF) neural network, neural network and high-order neural networks to predict GNSS failure when the position error of inertial navigation system.

3. COMPOSITION AND WORKING PRINCIPLE OF GNSS/INS

GNSS/INS integrated navigation system is realized in three parts: antenna, satellite receiver and inertial measurement unit in hardware, and integrated processing module in software.

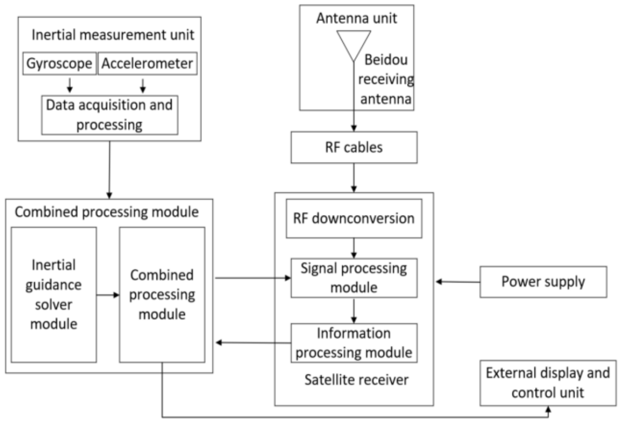

Figure 1. Structure diagram of GNSS/INS integrated navigation system.

3.1 Hardware structure introduction

Antenna unit: The function of this module is to receive multi-frequency signals from satellites, and anti-jamming antenna based on array can be adopted according to actual requirements.
Receiver unit: The receiver unit is mainly composed of four parts: rf module, baseband signal processing module and data processing module. As an important part of the whole receiver, rf unit is responsible for rf signal reception, frequency conversion, if signal generation and so on. The baseband signal processing module is mainly responsible for the acquisition, demodulation and decoding of received satellite navigation signals. The data processing module locates the pseudo-range, message, ephemeris and other information given by the baseband signal processing module, and transmits the pseudo-range and the rate of pseudo-range change to the combined filter module.
Inertial measurement unit: The module mainly consists of three-axis gyroscope, three-axis quartz accelerometer and related power supply and control unit, and the control unit can complete the sampling and processing of gyroscope and accelerometer output signals.

3.2 Software introduction

The combined processing module of the software is divided into two main parts: Inertial navigation solution and combination information fusion. Inertial navigation algorithm can achieve high precision strapdown inertial navigation, gyroscope measure the angular velocity information is transmitted to the strapdown inertial navigation calculating module, attitude matrix is calculated and extract the carrier attitude, which attitude matrix would accelerometer measured than force acceleration information transform into the navigation system, can compute the position and speed of the vehicle.
The gyroscope measured angular velocity information is transmitted to the GI solver module to calculate the attitude matrix and extract the carrier attitude, and then the attitude matrix transforms the accelerometer measured specific acceleration information to the navigation coordinate system to calculate the position and velocity of the carrier. The integrated processing unit can perform integrated navigation filtering on the information of satellite navigation and inertial navigation measurement, estimate the error state of satellite navigation and strapdown inertial navigation, finally correct the error in the inertial period by using the estimated error state, assist the receiver tracking by Doppler estimation, and finally output the integrated navigation solution to the display and control unit.

4. INFORMATION FUSION ALGORITHM FOR INTEGRATED NAVIGATION SYSTEM

Kalman Filtering is an optimal state estimation algorithm, which is widely used in navigation filtering algorithms. However, due to its shortcoming of only applying to linear problems, it causes interference to the positioning accuracy of navigation. Therefore, many improved filtering algorithms have been proposed by many scholars.

Because of unscented Kalman's good processing ability and simple calculation for nonlinear system; The improved UKF algorithm of BP neural network is suitable for time-varying system, and BP neural network is simple and classical. The optimal Sage-Husa adaptive Kalman filter algorithm has simple principle and good real-time performance. Deep learning network GI-NN has strong learning ability and is suitable for the scenario where GNSS signal fails for a long time. Therefore, this paper mainly introduces these four algorithms.

4.1 Unscented Kalman filter algorithm

Julier and Uhlmann proposed an unscented Kalman filter algorithm based on UT transform, namely UKF algorithm. The basic principle of the algorithm is to approximate the probability distribution of nonlinear systems, and it has good nonlinear processing ability.

4.1.1 UKF filtering algorithm steps: Step 1: initialize the estimated value of system state vector and its error covariance matrix. The formula is as follows:

$$\hat{X}_0 = E(X_0)$$
$$P_{x_0} = E[(X_0 - \hat{X}_0)(X_0 - \hat{X}_0)^T] \quad (1)$$

Step 2: Solve 2n+1 Sigma points. the formula is as follows:

$$\begin{cases} \chi_{0,\ k-1} = \hat{X}_{k-1} \\ \chi_{i,\ k-1} = \hat{X}_{k-1} + (\sqrt{(n+\lambda')P_{X,k\text{-}1}})_i \quad ,\ i = 1,2,\cdots,n \\ \chi_{i+n,\ k-1} = \hat{X}_{k-1} - (\sqrt{(n+\lambda')P_{X,k\text{-}1}})_i \quad ,\ i = 1,2,\cdots,n \end{cases} \quad (2)$$

Step 3: time update. The formula is as follows:

$$\overset{*}{\chi}_{i,k/k-1} = f(\chi_{i,k-1}) \qquad \text{i=0,1,2,.....,2n}$$
$$\hat{\chi}_{k/k-1} = \sum_{i=0}^{2n} W_i^{(m)} \overset{*}{\chi}_{i,k/k-1}$$
$$p_{X,k/k-1} = \sum_{\text{i=0}}^{\text{2n}} W_i^{(c)} \left(\dot{\chi}^*_{i,k/k-1} - \hat{X}_{k/k-1}\right)\left(\dot{\chi}^*_{i,k/k-1} - \hat{X}_{k/k-1}\right)^{\text{T}} + Q_{k-1}$$
$$Z_{i,k/k-1} = h(\overset{*}{\chi}_{i,k/k-1}) \qquad \text{i=0,1,2,...,2n}$$
$$\hat{Z}_{k/k-1} = \sum_{i=0}^{2n} W_i^{(m)} Z_{i,k/k-1} \quad (3)$$

Step 4: enter the measurement update stage. The formula is as follows:

$$P_{Z,k} = \sum_{i=0}^{2n} W_i^c \left(Z_{i,k/k-1} - Z^{\wedge}_{k/k-1}\right)\left(Z_{i,k/k-1} - Z^{\wedge}_{k/k-1}\right)^T + R_k$$
$$P_{XZ,k} = \sum_{i=0}^{2n} W_i^c \left(\overset{*}{\chi}_{i,k/k-1} - \hat{X}_{k/k-1}\right)\left(Z_{i,k/k-1} - \hat{Z}_{k/k-1}\right)^T$$
$$K_k = P_{XZ,k} P_{Z,k}^{-1}$$
$$\hat{X}_k = \hat{X}_{k/k-1} + K_k\left(Z_k - \hat{Z}_{k/k-1}\right)$$
$$P_{X,k} = P_{X,k/k-1} - K_k P_{Z,k} K_k^T \quad (4)$$

4.2 Improved UKF filtering algorithm based on BP neural network

As a classical network, BP feedforward neural network has been mature in theory, with simple structure and small calculation. The improved integrated navigation algorithm can make the system suitable for time-varying system. BP neural network consists of three layers: one input layer, one output layer and N hidden layers. BP neural network can make the output information reach the expected value as much as possible only through continuous training.

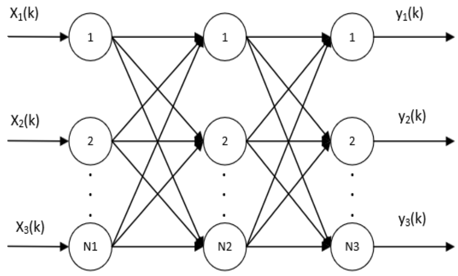

Figure 2. BP neural network structure diagram.

The three-layer neural network algorithms are listed as follows: The transfer function $f(x)$ is:

$$f(x) = \frac{1}{1+e^{-x}} \quad (5)$$

The output of the hidden layer node is:

$$y_i = f\sum_i(w_{ji}x_i - \theta_j) = f(net_j) \quad (6)$$

Output equation of the output node:

$$Z_l = f\left(\sum_i v_{lj} y_j - \theta_j\right) = f(net_l) \quad (7)$$

The above characters x_i, y_j , and z_l correspond to the input layer, the implicit layer, and the output node, respectively. w_{ji} is a weight between x_i and y_j , v_{lj} is the weight between y_j and z_l, and t_l is the expected value of z_l.

The error back-propagation algorithm is a feedback mechanism for traditional BP neural networks to adjust the weights of each layer, assuming that its objective function is:

$$E = \frac{1}{2}(t_l - z_l)^2 \quad (8)$$

The threshold correction column equation for the error function on the output node is:

$$\theta_l(k+1) = \theta_l(k) + \eta\frac{\partial E}{\partial \theta_l} \quad (9)$$

The threshold correction column for the error function on the nodes of the hidden layer is given by:

$$\theta_l(k+1) = \theta_h(k) + \eta \frac{\partial E}{\partial \theta_l} \tag{10}$$

4.2.1 BP neural network modified UKF algorithm: Mainly, the state estimator $\hat{X}_k = \hat{X}_{k/k-1} + K_k(Z_k - \hat{Z}_{k/k-1})$ is transformed as:

$$\hat{X}_{k/k-1} - \hat{X}_k + K_k \alpha_k = 0 \tag{11}$$

From the above equation, it is clear that the performance of the Unscented Kalman filter algorithm is disturbed by $\hat{X}_{k/k-1} - \hat{X}_k$, gain K_k, and α_k. Therefore, the BP neural network is used to train these three parameters, and the structure of the algorithm is shown below:

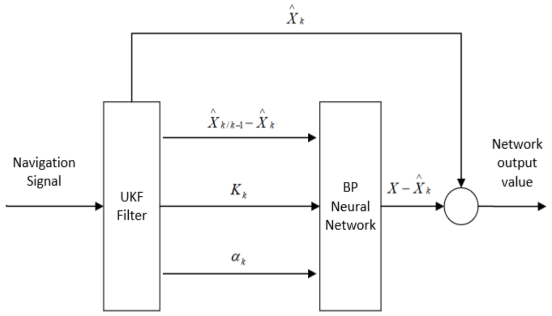

Figure 3. Principle diagram of BP neural network modified UKF algorithm.

4.3 Optimal Sage-Husa Adaptive Kalman Filtering algorithm

Optimal Sage-Husa adaptive Kalman filtering improves the filtering accuracy by means of determining the parameters to be adjusted based on the empirical values of the system. Suppose the equations of state and measurement of the linear system are as follows:

$$\begin{cases} X_k = \varphi_{k,k-1} X_k + \Gamma_{k-1} W_{k-1} \\ Z_k = H_k X_k + V_k \end{cases} \tag{12}$$

Where $\varphi_{k,k-1}$ is the one-step transfer array from moment t_{k-1} to t_k, Γ_{k-1} is the system noise driven array, H_k is the measurement array, V_k is the measurement noise sequence, and W_{k-1} is the system intense noise sequence. The steps of its filtering algorithm are shown below:

$$\hat{X}_{k/k-1} = \phi_{k,k-1} \hat{X}_{k-1}$$

$$\hat{X}_k = \hat{X}_{k,k-1} + \bar{K}_k (Z_k - H_k \hat{X}_{k,k-1})$$

$$K_k = P_{k,k-1} H_k^{\mathrm{T}} (H_k P_{k,k-1} H_k^{\mathrm{T}} + R_k)^{-1}$$

$$P_{k/k-1} = \varphi_{k,k-1} P_{k-1} \varphi_{k,k-1}^T + \Gamma_{k-1} \hat{Q}_k \Gamma_{k-1}^T$$

$$P_k = (I - K_k H_k) P_{k/k-1} (I - K_k H_k)^T + K_k P_{k/k-1} K_k^T P_k$$

$$= (I - K_k H_k) P_{k/k-1}$$

$$\varepsilon_{\mathrm{k}} = Z_{\mathrm{k}} - H_{\mathrm{k}} \hat{X}_{k/k-1}$$

$$G_{\mathrm{k-1}} = [\Gamma_{k-1}^{\mathrm{T}} \Gamma_{\mathrm{k-1}}]^{-1} \Gamma_{k-1}^T$$

$$r_k = (1 - d_{k-1}) r_{\mathrm{k-1}} + d_{\mathrm{k-1}} (Z_{\mathrm{k}} - H_k \hat{X}_{k/k-1})$$

$$R_k = (1 - d_{k-1}) R_{k-1} + d_{k-1} (\varepsilon_k \varepsilon_{\mathrm{k}}{}^T - H_k P_{k/k-1} H_k{}^T)$$

$$q_k = (1 - d_{k-1}) q_{k-1} + d_{k-1} [G_{k-1} (\hat{X}_{k-1} - \Phi_{k,k-1} \hat{X}_{k-1})]$$

$$Q_k = (1 - d_{k-1}) Q_{k-1} + d_{k-1} [G_{k-1} (K_k \varepsilon_{\mathrm{k}} \varepsilon_k{}^T K_k{}^T + P_{Ki} - \Phi_{k,k-1} P_{\mathrm{k-1}} \Phi_{\mathrm{k,k-1}}{}^{\mathrm{T}}) G_{\mathrm{k-1}}{}^T] \tag{13}$$

in the formula $d_k = \frac{1-b}{1-b^k}, 0 \le b \le 1$, The general range of values for the forgetting factor is: $0.95 \le b \le 0.99$

4.4 Deep learning improvement algorithm

When the GNSS satellite navigation signal is interrupted, the navigation performance can be improved by using deep learning algorithms to assist inertial navigation systems. A method to improve the GNSS/INS integrated navigation accuracy with a deep learning network GI-NN has been proposed by some scholars, that is, convolutional neural network (CNN) and gated recursive unit (GRU) are integrated into GNSS / INS at the same time. and the feature space of IMU is extracted from the sensor by GI-NN, which can not only reduce the amount of calculation but also improve the measurement accuracy.

Deep learning is mainly used to learn the velocity, attitude specific force and angular velocity between navigation information and INS output. It is not dependent on the mathematical model of the system and is very suitable for nonlinear systems. The GNSS/INS integrated navigation system based on deep learning is divided into two modes: one is when GNSS can provide signals, the system enters the online training mode, as shown below:

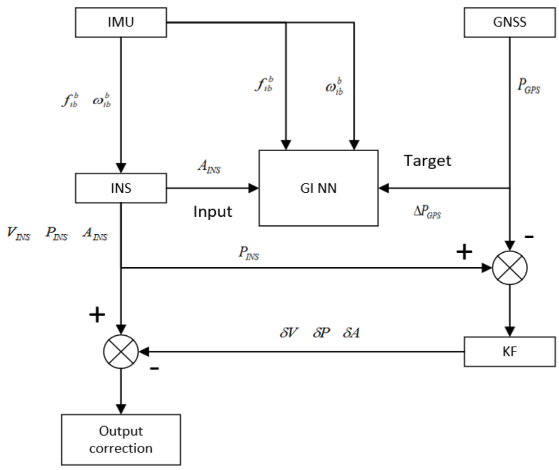

Figure 4. Structure diagram of GI-NN auxiliary GNSS/INS integrated navigation system during online training.

When the GNSS signal fails to provide a normal signal, the system immediately enters the prediction mode, during which the KF estimates remain constant, and its system structure is shown in the following diagram:

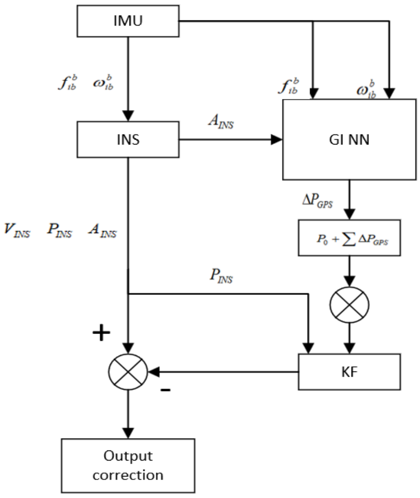

Figure 5. GI-NN auxiliary GNSS/INS integrated navigation system structure diagram when predicting mode.

The structure diagram of GI-NN is shown below, which consists of multiple convolution layers and recursive layers. The convolution layer mainly learns sparse feature representation, and at the same time establishes the mathematical model of implicit dependence between various sensors. The recursive layer can dynamically simulate the time of feature map activation.

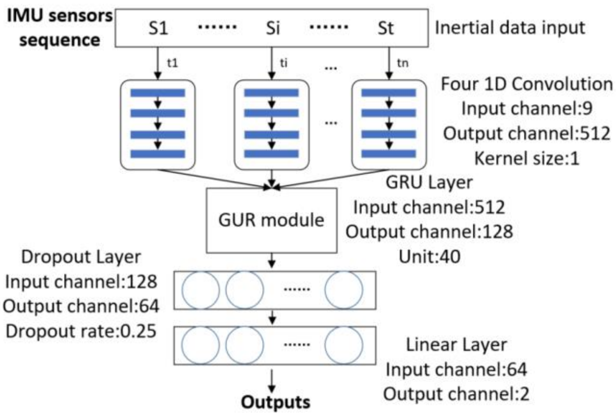

Figure 6. GI-NN system structure diagram.

5. INTEGRATION OF 5G COMMUNICATION AND INTEGRATED NAVIGATION SYSTEM

5.1 5G Technology Introduction

5G is the 5th generation mobile networks (5G). The essential difference between 5G and previous 4G technologies is that users can use 5G networks to stay online all the time. 5G communication technology will be officially put into commercial use in 2019. With the development of 5G technology, using 5G technology to improve indoor and outdoor positioning accuracy will be a major research direction of navigation system in the futures.

The main technical advantage of 5G communication lies in its strong inclusiveness, which can integrate multi-function network and wireless transmission technology, and achieve greater improvement in communication performance, transmission time, network coverage, and user experience. With the adoption of more advanced wireless mobile network technology, 5G mobile technology will develop in a more professional, intelligent and comprehensive direction in the future, and the efficiency and stability of the network will also be better improved.

5.2 Development of GNSS/INS integrated navigation system under 5G

At present, using 5G technology for indoor and outdoor positioning has become a hot research direction. The research of indoor and outdoor positioning algorithm based on 5G technology is mainly 5G millimeter wave positioning method, and the positioning accuracy of the relevant algorithm has reached sub-meter level. Based on the integrated navigation system GNSS/INS, the research and integration of schemes based on 5G technology can provide a robust navigation and positioning scheme for air or ground vehicles in various scenarios. The research shows that the 5G base stations on both sides of the expressway can effectively improve the accuracy and robustness of the navigation system of vehicles driving on the road. At the same time, when GNSS fails, the use of 5G signals for navigation positioning can ensure the continuity and high precision of navigation.

An integrated IMU/5G millimeter wave positioning method has been proposed to improve positioning accuracy by fusing positioning data from both 5G millimeter wave and IMU systems in case of GNSS failure. The information output by the inertial navigation system is processed by the 5G millimeter wave positioning system, so as to effectively reduce the error divergence of the inertial navigation. Meanwhile, the inertial navigation can compensate the positioning error of the 5G millimeter wave positioning system and reduce the positioning error in the non-line-of-sight transmission. Its positioning structure is shown as follows:

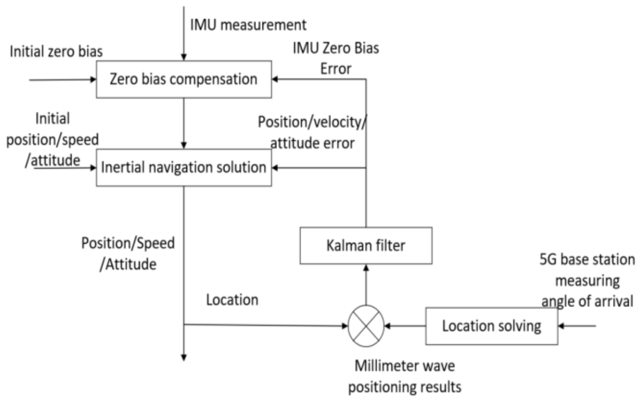

Figure 7. Structure diagram of IMU/5G millimeter wave integrated positioning system.

5.3 Application prospect of GNSS/INS integrated navigation system under 5G communication

The development of 5G communication technology will definitely realize the indoor-outdoor integration of navigation and positioning, which is important for the future development of location services, smart city construction and driverless technology.

Location Services: The current development of location services has diversified, not only limited to basic location positioning, but also includes in-car navigation systems, emergency help in distress, transportation management and other aspects, greatly enhancing the convenience of life. With the development of 5G communication technology for location services brings a new development situation, integrated satellite navigation system, inertial navigation system, 5G large-scale array base station and other sensor-assisted development of integrated navigation system, will achieve navigation and communication, indoor and

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outdoor integrated services to ensure that accurate location information services can be improved at any time and anywhere.
Smart Cities: The purpose of smart city construction is to make comprehensive use of various information technology, intelligent technology or innovative concepts to integrate various service systems and management systems of the integrated city, to dispatch resource utilization and distribution with high efficiency, and to improve the quality of life of residents. 5G plays a huge role in the smart city, which not only has high-speed communication capability, but also makes the era of Internet of everything come, which can realize the innovative integration of various industries such as artificial intelligence, big data and cloud data. The integrated navigation system relying on 5G means will realize efficient transmission of positioning information data in the construction of smart cities, as well as guarantee urban transportation, ecological environment safety detection, etc.
Driverless technology: Driverless technology refers to the automation of vehicle driving without relying on human power, using a combination of other sensor technologies, artificial intelligence technologies, navigation and positioning, and pattern recognition and other multi-disciplinary technologies. The traditional integrated navigation and positioning accuracy is limited and cannot meet the needs of autonomous driving. With the rapid development of 5G, driverless technology has also led to a new level of development. Driverless technology can not only use the high network speed and low delay characteristics of 5G technology to transmit the data collected by other sensors, and under the condition of the satellite navigation system signal is obscured, Using 5G large-scale array antenna technology, 5G millimeter wave positioning method, combined with inertial navigation and other vision sensors, can effectively improve the positioning accuracy and accuracy of unmanned vehicles.

6. SUMMARY

Current problem of integrated navigation system is mainly the nonlinear problem, in order to solve the problem, many scholars propose to integrate artificial intelligence technology into integrated navigation algorithm, so as to improve the universality and robustness of integrated navigation system, which is also the main direction of the development of integrated navigation algorithm. The integrated navigation system combined with artificial intelligence technology algorithm will be more robustly. However, the drawback of the integrated navigation system combined with artificial intelligence technology algorithm is that the calculation is huge, it requires a lot of data to support model training. The development of 5G millimeter wave technology has brought a new development direction to integrated navigation. Relying on 5G technology and cooperating with other sensor technologies will greatly improve the accuracy of navigation and positioning, improve the location service experience, and promote the development and construction of other fields such as smart city, driverless technology, transportation management, intelligent medical treatment and disaster detection management, etc. It is believed that 5G technology can be used to build a smart economy and smart society of "high-precision space-time foundation + communication" in the future.

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