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Research on Multi Sensor Fusion and Precise Positioning Technology in Intelligent Warehousing

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Abstract: In order to improve the positioning and navigation accuracy in intelligent warehousing systems, the application of multi-sensor fusion and precise positioning technology was studied. The data preprocessing and fusion algorithms of visual sensors, LiDAR, and inertial measurement units were analyzed, and the results showed that this method can significantly optimize the efficiency and accuracy of warehouse management.

Keywords: Intelligent warehousing; Multi-sensor fusion; Precise positioning technology

Introduction

The development of intelligent warehousing systems is increasingly relying on high-precision positioning technology, and multi-sensor fusion provides a solution that greatly improves the accuracy and efficiency of positioning and navigation by optimizing sensor data processing and fusion algorithms. In order to promote the improvement of warehouse automation and intelligence, this article explores the application of multi-sensor systems in intelligent warehousing.

1. Multi sensor fusion technology in intelligent warehousing

1.1 Overview of Multi Sensor Systems

Multi sensor systems in intelligent warehousing typically include visual sensors, laser radar, inertial measurement units (IMUs), and ultrasonic sensors (Figure 1). These sensors have their own characteristics, complement each other, and together form the foundation for comprehensive perception of the storage environment. Visual sensors provide rich image information, suitable for object recognition and environmental understanding; Lidar has high-precision distance measurement capability, suitable for spatial modeling and obstacle detection; IMU can provide high-frequency attitude and motion information; Ultrasonic sensors perform well in detecting obstacles at close range. The collaborative work of multi-sensor systems can overcome the limitations of a single sensor, improve the comprehensiveness and robustness of perception, and lay the foundation for accurate positioning and navigation of intelligent warehousing.

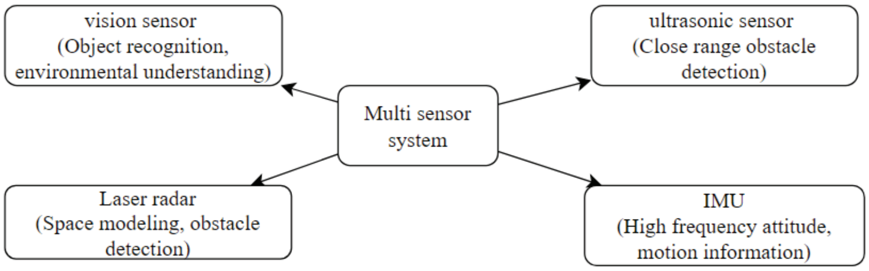


Figure 1. Schematic diagram of multi-sensor system

1.2 Sensor Data Preprocessing

Sensor data preprocessing is a key step in multi-sensor fusion, mainly including data cleaning, synchronization, and calibration. Data cleaning is used to remove outliers and noise, usually using methods such as median filtering or Kalman filtering. Data synchronization solves the problem of inconsistent sampling frequency of different sensors, and common techniques include timestamp alignment and interpolation. Sensor calibration is the foundation for ensuring that multi-sensor data can be fused in the same coordinate system, involving both internal and external parameter calibration. Taking the extrinsic calibration of vision LiDAR as an example, the Zhang Pless method can be used, with the objective function being:

$$\min(\sum R_i \cdot p_j + t - P_j^2)$$

Where R_i and t are the rotation matrix and translation vector, respectively, p_j and P_j are the corresponding laser points and image points. By minimizing this objective function, the precise transformation relationship between two sensors can be obtained.

1.3 Multi sensor fusion algorithm

Multi sensor fusion algorithms can combine the advantages of multiple sensors to provide more accurate and reliable environmental perception results. Common fusion algorithms include Kalman filtering, particle filtering, and evidence theory fusion. Taking Extended Kalman Filter (EKF) as an example, its prediction and update steps can be expressed as:

(1) Prediction:

$$\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}, u_k)$$

$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k$$

(2) Update:

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

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k + h(\hat{x}_{k|k-1}))$$

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

Where x is the state vector, P is the covariance matrix, K is the Kalman gain, and z is the observation value. EKF achieves efficient estimation of robot pose through linearization of nonlinear systems and is a widely used fusion algorithm in intelligent warehousing.

2. Research on Precise Positioning Technology for Intelligent Warehousing

2.1 SLAM based localization method

The SLAM (Simultaneous Localization and Mapping) based localization method is one of the widely used technologies in intelligent warehousing. The SLAM algorithm estimates robot pose and constructs environmental maps simultaneously through sensor data, mainly divided into two categories: filter based and graph based optimization. In visual SLAM, ORB-SLAM2 is a typical monocular/binocular/RGB-D SLAM system based on keyframes, with pose estimation accuracy up to centimeter level. In terms of laser SLAM, cartographers have utilized sub map technology and loop detection to achieve large-scale, real-time 2D/3D SLAM. Visual laser fusion SLAM, such as VINS Fusion, combines rich visual information with precise laser ranging, and performs well in complex storage environments. The key to SLAM technology lies in feature extraction, data association, and backend optimization. Its application in warehousing environments requires consideration of factors such as dynamic obstacles and lighting changes.

2.2 High precision positioning based on UWB

The positioning technology based on ultra wideband (UWB) has been widely used in intelligent warehousing due to its high accuracy, low power consumption, and strong penetration. UWB positioning is mainly based on the Time Difference of Arrival (TDOA) principle, which determines the location by measuring the propagation time difference of signals from multiple base stations to tags. In a typical UWB positioning system, the positioning accuracy can reach 10-30cm. The mathematical model of UWB positioning can be expressed as:

$$d_i - d_j = c \cdot (t_i - t_j)$$

Where d_i and d_j are the distances from the tag to two base stations, t_i and t_j are the signal arrival times, and c is the speed of light. By solving this set of nonlinear equations, the three-dimensional coordinates of the label can be obtained. In practical applications, Taylor series expansion and least squares method are often used for solving. The performance of UWB positioning systems is affected by factors such as base station layout, signal multipath effects, and non line of sight propagation. It is necessary to improve positioning accuracy by optimizing base station layout and adopting advanced signal processing algorithms.

2.3 Multi source information fusion positioning algorithm

The multi-source information fusion positioning algorithm aims to combine the advantages of multiple positioning technologies to improve the accuracy, reliability, and robustness of positioning. Common fusion methods include Kalman filtering, particle filtering, and factor graph optimization. Taking the fusion of UWB and IMU as an example, Extended Kalman Filter (EKF) can be used for fusion. The state equation and observation equation are as follows:

(1) Equation of State:

$$X(k+1)=F \cdot X(k)+G \cdot W(k)$$

(2) Observation equation:

$$Z(k)=H \cdot X(k)+V(k)$$

Where X is the state vector (including position, velocity, and attitude), F is the state transition matrix, G is the process noise matrix, W is the process noise, H is the observation matrix, and V is the observation noise. Through two steps of prediction and update, EKF can effectively integrate the absolute positioning information of UWB and the high-frequency relative positioning information of IMU, achieving centimeter level positioning accuracy. In complex warehousing environments, multi-source information fusion algorithms need to consider issues such as sensor fault detection and adaptive weight adjustment to improve the robustness of the system.

3. Intelligent warehousing applications based on precise positioning

3.1 Design of Intelligent Handling Robot System

The design of the intelligent handling robot system is based on precise positioning technology, integrating multiple sensors and actuators. The system architecture includes positioning module, navigation module, control module, and execution module. The positioning module utilizes UWB and visual SLAM technology to achieve centimeter level accuracy; The navigation module is based on the A * algorithm and dynamic window method to achieve real-time path planning and obstacle avoidance; The control module adopts Model Predictive Control (MPC) algorithm to optimize the motion trajectory of the robot; The execution module includes a differential drive system and a lifting mechanism, enabling flexible movement and cargo handling. The mechanical structure of the robot adopts modular design, which is easy to maintain and upgrade. The system also integrates human-computer interaction interface and remote monitoring function, improving operational convenience and safety.

3.2 Intelligent Path Planning Algorithm

Intelligent path planning algorithm is the key to efficient operation of handling robots. This study adopts an improved RRT algorithm for global path planning, combined with dynamic window method for local path planning. The RRT algorithm generates the optimal path quickly through random sampling and tree structure extension. The improvement lies in the introduction of heuristic information and adaptive sampling strategy, which enhances the efficiency of the algorithm. Local path planning considers robot dynamics constraints and obstacle avoidance, generating smooth and safe trajectories in real-time. The mathematical model of the algorithm is as follows:

$$j(x) = \min_{u \in U}\{\alpha \cdot \text{heading}(x, u) + \beta \cdot \text{dist}(x, u) + \gamma \cdot \text{velocity}(x, u)\}$$

Among them, J (x) is the cost function, u is the control input, α, β, and γ are the weight coefficients. By adjusting the weights, safety, efficiency, and smoothness can be balanced. The experimental results (Table 1) show that the algorithm performs well in complex warehousing environments, with a planning success rate of over 95%.

Table 1. Performance Comparison of Path Planning Algorithms

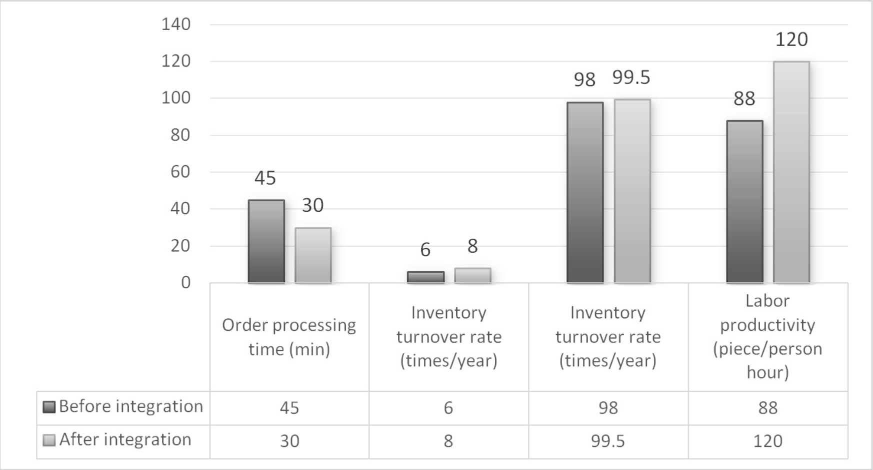
Algorithm	Average planning time (ms)	Path length optimization rate (%)	Success rate (%)
Traditional RRT*	150	85	92
Improve RRT*	120	92	97
A*	80	88	95

3.3 Multi robot collaborative operation strategy

Adopting market-based task allocation methods and consensus based formation control algorithms. The task allocation adopts auction algorithm, where each robot bids based on its own state and task characteristics, and the central control system allocates tasks according to the global optimal principle. The formation control adopts the virtual structure method to achieve coordinated motion of multiple robots by maintaining the virtual geometric structure. To address communication latency and packet loss issues, event triggering mechanisms and robust control strategies have been introduced. Experiments have shown that this strategy can effectively improve warehousing efficiency. When 10 robots work together, the task completion time is reduced by 40% compared to single machine operation, and the resource utilization rate is increased by 35%.

3.4 Integration of Warehouse Management System

The integration of warehouse management system (WMS) and robot system is the key to achieving intelligent warehousing. By designing an integrated system with a multi-layer architecture, including data layer, business logic layer, and user interface layer. The data layer adopts a distributed database to achieve high concurrency and data consistency; The business logic layer is based on microservice architecture, which improves the scalability and maintainability of the system; The user interface layer adopts a responsive design and supports multi terminal access. The system integrates functional modules such as inventory management, order processing, and robot scheduling, and interacts with the robot control system in real-time through RESTful APIs. Introduced machine learning algorithms to achieve intelligent warehouse allocation and order batch optimization. The system uses OAuth 2.0 for identity authentication to ensure data security. In practical applications (Figure 2), the system has increased storage efficiency by 30% and reduced error rates by 50%.



	Order processing time (min)	Inventory turnover rate (times/year)	Inventory turnover rate (times/year)	Labor productivity (piece/person hour)
▩ Before integration	45	6	98	88
▢ After integration	30	8	99.5	120

Figure 2. Performance comparison before and after integration of warehouse management system

3.5 System Performance Testing and Evaluation

The system performance testing and evaluation adopts a multidimensional and multi scenario testing method. The positioning accuracy test was conducted in different environments, and the results showed that the average error of UWB and visual SLAM fusion positioning was less than 5cm. Path planning algorithm testing includes static and dynamic obstacle environments, and evaluation indicators include planning time, path length, and smoothness. The collaborative performance of multiple robots is evaluated by simulating task scenarios of different scales, with a focus on task allocation efficiency and conflict resolution capabilities. The system integration testing adopts stress testing and long-term stability testing to verify the performance and reliability of the system under high load. The user experience evaluation adopts the System Usability Scale (SUS), with a score of 85, indicating good usability of the system. The comprehensive evaluation results indicate that the intelligent warehousing system has achieved the expected goals in terms of efficiency, accuracy, and reliability.

4. Conclusion

This article comprehensively analyzes the application of multi-sensor fusion and precise positioning technology in intelligent warehousing, and verifies its significant advantages in improving the efficiency and accuracy of warehousing systems. Future research can further explore the integrated optimization of sensor technology to achieve higher operational flexibility and system robustness.

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