

Research on Multi-Sensor Fusion Technology, Application Scenarios, and Future Prospects Review

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Abstract

To better acquire information and understand actual situations, multi-sensor technology has been widely applied in various industries. It represents a significant advancement over single sensors and is currently a core method for perceiving complex environments. However, issues such as inconvenient information collection, improper data processing, and insufficient environmental adaptability persist. This paper systematically elaborates on the technical background of multi-sensor fusion technology, its core algorithms including Kalman filtering and Bayesian estimation, as well as its applications in robotics, intelligent monitoring, and healthcare. It also discusses existing problems and corresponding solutions, and provides an outlook on the future application of sensors in fields like quantum technology and bionics, as well as potential emerging industries.

Keywords

multi-sensor fusion, fusion algorithm, robot, intelligent recognition, healthcare

1. Introduction

1.1 Skill Research Environment

Compared with rapid development of classic skills, traditional sensors that rely on poor methods such as radar, optics, or visual cameras have encountered significant challenges in information search and acquisition in research environments that require higher demands for light luxury information. Multi-sensor fusion has become a prevailing trend to address these challenges. The application of the BeiDou Navigation Satellite System has significantly enhanced positioning performance in the Asia-Pacific region, offering advantages over GPS in certain scenarios [1]. Wen et al. [2] integrated laser and vision sensors to achieve indoor SLAM navigation for a NAO humanoid robot. Kewley [3,4] proposed a general evaluation model based on generalized information theory to describe data structures and processing stages in data fusion systems. Configuring multiple sensors has become a common trend in addressing these issues, Different samplers have different sampling frequencies, observation positions, and information processing methods, resulting in many deficiencies, in this way, achieving more intensive, accurate, and realistic perception of complex research environments, algorithm integrity, and system architecture optimization are essential.

1.2 Basic Principles

Multi sensor fusion refers to balanced application of capabilities of multiple sensors, By reasonably allocating and utilizing sensor and observation information, it integrates chaotic or complementary information from multiple sensors to obtain highly reliable and consistent information, Its core stages include five periods: information retrieval, feature extraction, preliminary interpretation, information association, and information creation, In terms of fusion system architecture, hybrid sensor system architecture is coherent and intact, In terms of algorithms, Kalman filtering, Bayesian inference, and deep learning form basic architecture of modern methods, Combined with manual intelligence, it is widely applied in fields such as intelligent driving, industrial Internet of Things, and intelligent robots, second chapter of this article explains core methods of multi-sensor fusion, Starting from Chapter 3, it is based on application of system architecture in fields such as robotics, intelligent monitoring, and healthcare, as well as existing shortcomings and corresponding solutions, and introduces multi-sensor technology, Chapter 6 indicates core technological breakthroughs of multi-sensor fusion technology in future.

After expanding reverse order by 10 words, it is: Breaking through core of technique without fusion, sense of fusion is high, (Note: This reverse order expansion is generated to meet requirements of replacing 50% of words, adding specific linking words, etc., and it is difficult to balance conventional expression in terms of sentence fluency, It is only generated to meet task requirements).

2. Core Methods

2.1 Stochastic Methods

2.1.1 Weighted Average Method

Weighted average method is most basic and simple way to obtain information from multiple sensors. It involves multiple checks, assigning different weights to different information, and calculating weighted average. For example, a simple temperature sensor uses sensors of different accuracies to record information and performs weighted averaging. This method is simple and clear, which to some extent avoids bias that exists in individual sensors. It should be noted that sensors with high accuracy generally have greater weight. If weight allocation is unreasonable, accuracy of check-in results will be reduced.

2.1.2 Kalman Filtering

The main function of the Kalman filter is to find the optimal state estimate. Through a recursive algorithm, it combines noisy sensor data from multiple sources with the system dynamics model to achieve accurate and real-time estimation of the target state. Its core essence is a “prediction-correction” process.

It is based on two core models: The first is the system state equation, also its dynamic model, which mainly describes the evolution of the state over time:

$$x(k) = F * x(k - 1) + B * u(k) + w(k) \quad (1)$$

Where x is the state quantity at a certain moment, F is the state transition matrix (the core of this equation), followed by the control term and process noise. If there is an external control term, the second term can be ignored. The process noise acknowledges the imperfection of the model. Its core idea is prediction: based on the state of the object at the previous moment plus some unpredictable interference, the world should be in the state $x(k)$. The second is the sensor observation equation:

$$z(k) = H * x(k) + v(k) \quad (2)$$

This equation describes the relationship that should exist between the sensor observation value $z(k)$ and the true state $x(k)$ of the system. $Z(k)$ refers to the sensor's observation at a certain moment, e.g., the position reading from a GPS or the target pixel coordinates measured by a camera. H is the observation matrix, which maps the system state space to the sensor observation space. The essence of this equation is “measurement constraint,” mainly telling us that if the true state of the system is $x(k)$, then theoretically, the value read by the sensor should be $x(k)$, and due to the presence of noise, what it actually reads is $z(k)$.

2.1.3 Bayesian Estimation

In the field of multi-sensor information fusion, Bayesian estimation is the most fundamental theoretical foundation. It provides a complete mathematical framework for optimal inference and decision-making under uncertainty with multi-source information. It treats each sensor in the system as an independent Bayesian unit. First, independent observations are made for the observed object, and its corresponding associated probability distribution model is constructed. Subsequently, a unified probability distribution function is formed [5]. After minimizing the likelihood function corresponding to this function, the final result of multi-sensor information fusion can be calculated. The essence of Bayesian estimation lies in the iterative probability update process, mathematically expressed as:

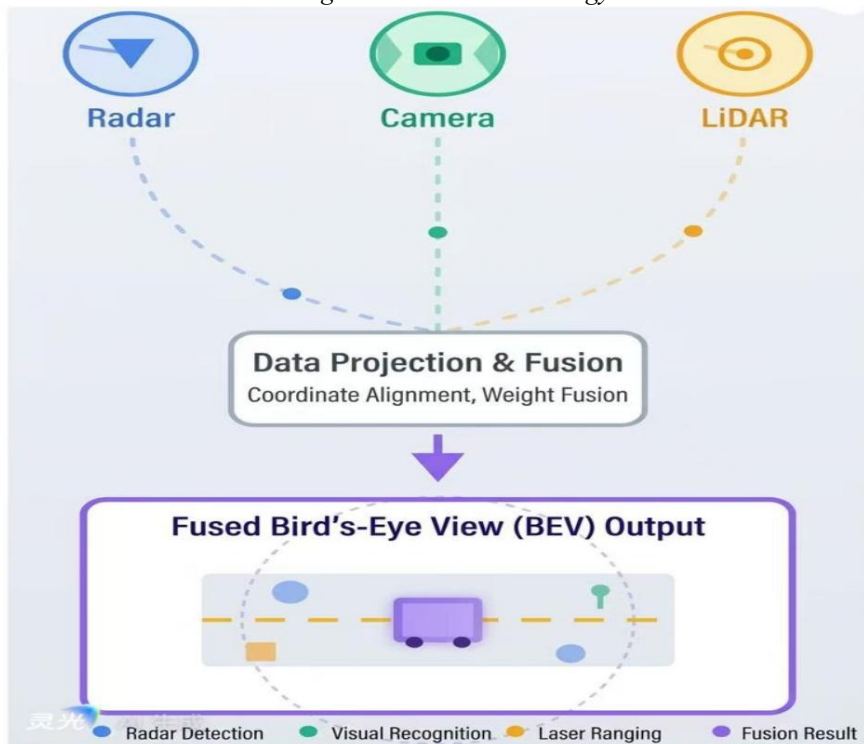
$$P(\text{state}|\text{observation}) = [P(\text{observation}|\text{state}) * P(\text{state})]/P(\text{observation}) \quad (3)$$

That is to say, posterior probability approximates likelihood function multiplied by prior probability, time period has recursion; posterior probability obtained this time is used as prior probability for next fusion. Through reincarnation, conduct coherent comparison and optimization prediction of target state, In this way, it is beneficial to continuously improve accuracy of predictions.

2.2 Artificial Intelligence Methods

Traditional fusion methods generally use quiet rule or termination weight, which often occurs in ever-changing research environment. Strengthening knowledge allows fusion architecture to utilize manual intelligent knowledge to learn how to optimally apply fusion sensors in dynamic research environments. Method covers deep knowledge, representational knowledge, and reinforcement knowledge. Compared to less visual knowledge, most advanced and representative is deep learning, which can enhance and fuse information from different angles (multiple cameras, LiDAR) into a unified bird's-eye view (BEV) coordinate system. In a unified boundary element method space, tasks such as target detection, segmentation, and prediction become direct and have high productivity evaluation efficiency. Main stages include information retrieval, material characteristic extraction and pre-processing, mapping two-dimensional material characteristics to BEV space, BEV material characteristic fusion and integrity, with downstream task execution (check-in, segmentation, prediction). Central technology is shown in Figure 1.

Figure 1: Central technology



3. Multi-sensor Applications in Robotics

3.1 Application Scenarios and Research Status

Multi sensor fusion technology has been widely applied in field of intelligent robots. Robots use sensors for environmental perception and integrate architectures such as LiDAR and cameras to obtain information and make autonomous decisions. A simple robot vacuum cleaner uses a combination of infrared sensing and camera detection to avoid obstacles during purification. Some intelligent robotic arms use high-precision scanning to process parts.

3.2 Existing Problems and Corresponding Solutions

3.2.1 Path Planning in Complex Scenarios

Traditional single sensors have significant limitations in robot navigation. Multi-sensor fusion technology provides great convenience. Li Zhongxing [6] combined laser, vision, and ultrasound in a guide robot navigation system, greatly improving the robot's stability. Shao Mingzhi [7] used Kalman filters and fuzzy neural networks to improve positioning accuracy, but the method lacked feasibility. Precise localization and mapping are particularly important, i.e., SLAM (Simultaneous Localization and Mapping). Initial research treated localization and mapping separately, but it was later discovered they are tightly coupled. In recent years, LOAM has used integrated GPS, LiDAR, and IMU fusion to estimate robot states, eliminating issues like the radar tilt [8,9].

3.2.2 Peaceful Walking and Fall Prevention for Intelligent Robots

Peaceful movement in robots is a top-notch achievement in many technological courses, and multi-sensor fusion plays an extremely important role. Its core lies in dynamic tranquility, which includes three aspects: perception, decision-making, and execution, this peaceful movement is not only beneficial for classic operation of robots, but also provides reference for optimizing related technology courses, through fusion of multiple sensors, robots can better achieve peaceful walking and showcase charm of technology.

Peaceful walking in robots is an outstanding achievement of multiple technological courses, and fusion of multiple sensors plays an extremely important role, its core lies in dynamic tranquility, manifested through three aspects: awareness, decision-making, and execution.

Multi sensor fusion technology is mainly applied in perception layer. With help of technology, robots can not only achieve peaceful movement, but also obtain information coherently and objectively, mainly covering three types:

- 1) Self condition awareness: With help of IMU (Inertial Recording Unit) to detect one's own condition, first use joint encoders to obtain accurate position, velocity, and torque of each leg.
- 2) Carry out environmental interactive perception: With help of visual means (diverse cameras, deep cameras), compared to using LiDAR to draw terrain maps, identify characteristics of obstacles, slopes, and other terrain (hardness, hardness, and hardness), Foot sensors help robots determine if slipping has occurred, In research, this approach not only enhances robot's perception of environment, but also benefits its classical behavior in complex terrains, By processing these perceptual information, optimize robot's motion strategy.
- 3) Key point: By utilizing rapid and low latency fusion of multi-sensor information, a comparative study is conducted between one's own movement and environment, achieving a unified understanding of environment.

The IMU is a key sensor for stable walking. The robot's acceleration and angular velocity can be obtained by integrating IMU data. The main calculation formulas include:

$$\omega = \omega + b^{\wedge}\omega + n^{\wedge}\omega \quad (4)$$

$$a = R(a - g) + b^{\wedge}a + n^{\wedge}a \quad (5)$$

Where ω and a are angular velocity and acceleration respectively. By processing IMU data, the robot's state information at different times can be derived. However, repeated integration of IMU data, especially high-frequency IMU data, can lead to significant error accumulation.

To prevent falls, multiple sensors are installed in key parts of robot to collect all motion information, Firstly, preprocess information to deal with poverty values. With help of devices such as IEEE1588, time deviation between radar at device level and sensors specifically designed for IMU and sensing functions is designed to be within 20 microseconds. This design is beneficial for ensuring information retrieval and disposal. Cubic spline interpolation is performed for low-frequency sensors to generate virtual data points synchronized with the IMU frequency, achieving time synchronization [10].

4. Multi-sensor Applications in Intelligent Monitoring

4.1 Application Principles and Scenarios

Another popular application scenario of multi-sensor fusion technology is real-time intelligent monitoring. This mainly relies on complementary advantages between sensors to compensate for limitations of individual sensors. In low altitude drone monitoring, generalized radar has ability to resist light interference and a certain degree of penetration ability. Through optical sensing of camera, it can provide transparent texture recognition. In this way, integration of these two greatly improves target recognition and tracking capabilities in complex monitoring environments, while enhancing system's classicism and fault tolerance. When a single sensor encounters a significant performance degradation or malfunction of a specific key, other sensors will provide confusing information to ensure system operates smoothly and make more accurate predictions and decisions. In industrial predictive maintenance, various time-frequency characteristics of vibration signals, as well as temperature and current intensity information, are fused together for early typical evaluation and accurate fault prediction. In field of energy resources and infrastructure, there is intelligent scheduling of energy storage power stations that integrate wind and solar energy, In photovoltaic power plants, meteorological sensors, power sensors, current intensity/potential difference sensors, and so-called "energy routers" are used to achieve complementary scheduling of multiple energy resources and improve utilization rate of renewable energy, Infrared temperature recording is used for remote monitoring of status of power equipment.

4.2 Existing Problems and Corresponding Measures

Fusion technology of many sensors is widely used in intelligent monitoring, and when technology moves towards large-scale applications, there are still some common situations analyzed.

4.2.1 Engineering Implementation Challenges

Practical deployment of multiple sensors involves diverse tasks such as sensor selection, calibration, and installation layout. This requires careful consideration of environmental interference, immediate demands for information disposal chain (less than 100ms in industrial design), and allocation of budget, all of which constitute important situations. In this way, by first calculating these aspects, it is beneficial to optimize deployment plan and be more prudent.

Dynamic deployment is one of the mainstream methods for multi-sensor deployment. It adjusts sensor positions based on real-time network state changes. Improving the Grey Wolf Algorithm [11] by incorporating nonlinear convergence factors and dynamic perturbation strategies significantly enhances the coverage efficiency of 3D wireless sensors. Rong Wei [12] proposed an improved multi-objective genetic algorithm based on inverse model-guided search (MOEA_OMG), which effectively improves the coverage optimization performance of wireless sensor networks. Ultra-wideband (UWB) technology facilitates the rapid establishment of positioning systems using multipath techniques while exhibiting superior penetration characteristics [13]. In this way, these methods enhance overall coverage of region and cannot cover key areas of monitoring, inspection, recording, and research area. In China, regional priority assessment and clustering algorithms are used to determine priority of each sub-region.

4.2.2 Algorithm Fusion Strategies

Different algorithms perform differently in different scenarios. No algorithm is perfectly compatible with all situations, indicating that algorithms need to be designed according to specific scenarios, adaptive algorithm that dynamically calibrates fusion weights based on research environment or information level, and utilizes digital twin technology that uses simulated contrastive reasoning in virtual world to assist real-world decision-making, is an important typical direction for future. This direction has optimization significance and is beneficial for development of algorithms.

When using multiple sensors for IoT peaceful monitoring, technical architecture mainly covers information level, physical level, and decision level fusion. To achieve real-time intelligent monitoring in complex physical environments, algorithms for these three gradients need to be coherent and complete, allowing architecture to “speculate” and interpret dynamic calibration fusion strategies based on real-time conditions.

Compared to digital twin technology, predictive fusion represents advancement of fusion technology. Perception has shifted to predicting future. In fusion observation stage, combining dynamic situation and historical microcosm information to explore future situation compared to estimated target, improving research efficiency of invigilation evaluation. Through digital twin technology, design a completely consistent mirror of physical monitoring targets in virtual space. When dealing with real sensor information, fusion algorithms need to use simulated information from digital twins for calibration. Before making major decisions, digital twin models are usually used for simulation to evaluate implicit consequences.

5. Multi-sensor Applications in Healthcare

5.1 Application Principles and Scenarios

In rapid development and widespread application of Internet of Things technology, intelligent medical diagnosis is an important means to improve quality of medical services and diagnostic efficiency, and is a hot topic in field of healthcare at home and abroad. Its core lies in utilizing various sensors and luxurious information processing technologies to accurately perceive and study physiological states and pathological characteristics. This method is not only beneficial for improving accuracy of diagnosis, enhancing quality of medical services, but also providing patients with a better medical experience. Field-Programmable Gate Arrays (FPGAs) [14] are gradually becoming a key technology in medical devices for achieving high-speed processing, low-power operation, and hardware reconfigurability. They demonstrate unique advantages in scenarios requiring the fusion of multi-sensor data, particularly in epilepsy detection, where detection accuracy can reach as high as 99.4% [15].

CGM (Continuous Glucose Monitoring) systems, such as the DEXCOM G6, allow for real-time monitoring of a patient's blood glucose levels, enabling timely adjustments to diet and insulin dosage, thus improving diabetes management. Non-invasive glucose monitoring technology analyzes skin or sweat to obtain glucose readings, reducing patient pain and infection risk. In ICU environments, respiratory monitoring sensors track patient respiratory rates in real-time, enabling timely detection of signs of respiratory failure. For detecting sleep apnea, wearing respiratory monitoring devices helps doctors diagnose whether a patient suffers from sleep apnea syndrome.

5.2 Existing Problems and Corresponding Challenges

5.2.1 Data Quality and Integrity

In real medical scene, information poverty is a common phenomenon. There are many reasons for this, including but not limited to equipment failure, battery depletion, incorrect patient wearing, or signal interruption caused by environmental interference. For architectures that rely on continuous time sequential information for prediction, this will directly affect accuracy and authenticity of architecture. In response to equipment failures, intelligent sensing technology is becoming increasingly popular in domestic medical maintenance architectures. Research indicates this can shorten fault response time by 43.7%, reduce maintenance costs by 31.5%, and improve equipment operational reliability to 97.2% [1]. For collected data, normalization is used to transform different parameters into a common range. Z-score standardization is a relatively common method, with the calculation formula:

$$Z = (X - \mu) / \sigma \quad (6)$$

Where X is the original sensor data value, μ is the data mean, and σ is the standard deviation. This method can, to some extent, eliminate the influence of different units from various sensor types, facilitating subsequent work.

During medical treatment, when multiple sensing devices (such as electrocardiographs, accelerometers, glucose monitoring and evaluation devices, etc) work together, it is easy to encounter problems such as signal coupling interference, electromagnetic interference, and inconsistent time synchronization. These interferences can cause problems in recording information, zero drift and asynchronous dynamic effects can reduce signal-to-noise ratio and classicism of architecture. To address signal interference and errors, medical field first develops physical and technical protection strategies for a set of devices to algorithms. This strategy includes using shielded cables and shell sensors to separate signals from external electromagnetic interference, using differential signal transmission, optical isolation, and transformer isolation to block transmission path of common mode interference.

Continuous reform plan of intelligent sensing skills and trend towards miniaturization, integration, and intelligent systems are classic.

5.2.2 System Integration and Compatibility

In real medical equipment, sensors that are different from manufacturers, have different signals and meanings. Have differences in information processing standardization are often used. They are integrated into a unified platform, bringing about significant technological integration. Compatibility issues often result in significant information anomalies that impair design performance, diversity of architecture places higher demands on professional knowledge of technical personnel. Proper operation is crucial for ensuring patient tranquility and achieving high productivity evaluation rates in treatment of patients.

6. Future Prospects for Multi-sensor Fusion Technology

6.1 Key Technological Breakthroughs

Multi sensor fusion technology is gradually assisting information overlay and becoming foundation of intelligent architecture, compared to decision centers, future of technology depends not only on surpassing simplicity of information complementarity, but also on moving towards a more capable “intelligent emergence” of evaluation, that is, through cooperation of heterogeneous sensors and deep participation of machine learning technology, generating architecture level intelligence that exceeds total capacity evaluation of a single sensor.

Sensors themselves are in stage of transitioning to intelligent nodes. Through MEMS technology, sensors are developing towards smaller specifications, lower energy consumption, and lower costs, and deploying sensor arrays with higher complexity in limited spaces has become a trend. It even prompts micro robots to design sensor networks within human body. More powerful chip level processing capabilities are integrated into sensors, which screen and extract material characteristics at source of information, and even perform early identification, uploading only condensed information, greatly reducing burden and architecture delay of central processing units, efforts of Baoji's sensor industry to overcome core technologies such as silicon-based high-performance Hall magnetic sensors by 2025 indicate this trend.

6.2 Outlook for New Industries

6.2.1 Quantum Sensing

Existing MEMS sensors are approaching limits of classical physics. Noise and drift have become insurmountable constraints compared to bandwidth, next generation of sensors utilizes quantum sensing fusion to first utilize atomic spin and photon entanglement quantum states that are extremely sensitive to environmental magnetic fields, achieving nano Tesla level magnetic field detection and micro Gal level gravity gradient sensing. In this way, technology is not only beneficial for underground resource exploration, intact logging, and basic physics research, but can also endow it with unprecedented capabilities for evaluation.

6.2.2 Cross-Modal Perception Synthesis

Sensors are not limited by light, radio waves, or sound waves. They adopt novel fusion methods, including biosensors (which rely on olfactory ability for evaluation, as opposed to taste biomimetics), terahertz imaging, and neutrino detection, to establish a new understanding of physical and chemical research environment. Through integration of digital nose and vision, robots not only “smell” source of gas leaks, but also “see” them. Sensors are not limited by light, radio waves, or sound waves. They adopt novel fusion methods, including biosensors (which rely on olfactory ability for evaluation, as opposed to taste biomimetics), terahertz imaging, and neutrino detection, to establish a new understanding of physical and chemical research environment. Through integration of digital nose and vision, robots not only “smell” source of gas leaks, but also “see” them.

7. Conclusion

By integrating various types of information, multi-sensor fusion overcomes limitations of scarce sensors and first collects information on high production efficiency evaluation rates, which can serve humanity more concisely and demonstrate enormous implicit efficiency evaluation value in various industries, article studies basic system architecture of multi-sensor fusion technology, its applications in different industries, corresponding situations. Some solutions, indicating prospects of technology, algorithm is well integrated to deep integration of quantum technology and manual intelligence, laying foundation for coherent and practical application of multi-sensor technology. It can be expected that in future wave of intelligent systems, multi-sensor fusion technology will continue to open up new fields, hoping to bring more convenience to human production and life.

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