



Research on Multi-Sensor Fusion Technology and Application

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Abstract. Multi-sensor fusion technology, by integrating data from multiple sensors, enhances the system's perception accuracy, reliability, and real-time performance, making multi-sensor fusion technology widely applicable across various fields. With the advancement of artificial intelligence, the Internet of Things, and computational technologies, it has become a crucial tool for addressing complex environments, with promising prospects. This paper aims to explore the advantages and disadvantages of different classifications of multi-sensor fusion, summarize its implementation methods, and introduce its practical applications. Although fusion technology demonstrates advantages in robustness, adaptability, and efficiency, challenges remain in algorithmic complexity, structural design, and adaptability to dynamic environments. In the future, with continued technological advancements, multi-sensor fusion will drive the progress of informatization and become a key pillar of intelligent decision-making and automated systems. This study not only provides theoretical support for the development of multi-sensor fusion technology but also offers technical insights for its applications in intelligent decision-making systems and automation technologies.

Keywords: Multi-Sensor; Multi-Sensor Fusion; Fusion Method

1 Introduction

Sensors play a critical role in modern technology, enabling the perception and capture of information from the physical world, such as light, heat, sound waves, and electromagnetic waves. However, single sensors often face limitations in geometric, spectral, or spatial resolution, making it difficult to achieve comprehensive coverage. These limitations can lead to insufficient information acquisition in complex scenarios, thereby affecting the accurate understanding and interpretation of physical phenomena and events. To address these shortcomings, multi-sensor image fusion technology has emerged. Multi-sensor image fusion is a technique that integrates image or image sequence data from multiple sensors to generate richer and more precise interpretations of specific scenes. This fusion process enhances image quality, enabling more accurate positioning, identification, and interpretation of physical phenomena and events.

Compared with general data fusion, multi-sensor image fusion is less extensively and deeply studied due to the uniqueness and complexity of the signals involved, and a

unified theoretical framework is yet to be established [1]. This field presents numerous challenging issues that demand exploration, including how to handle differences between data from various sensors, improve the robustness of fusion results, and ensure real-time performance [2]. However, with the rapid development of sensor network technology, multi-sensor image fusion has become a research hotspot due to its unique advantages in information integration, robustness enhancement, and improved autonomous decision-making capabilities.

This paper reviews the concept, methods, and development of multi-sensor image fusion, focusing on the characteristics and implementation of pixel-level, feature-level, and decision-level fusion. It explores their applications in enhancing system performance and optimizing information quality, particularly their potential in autonomous systems. By reviewing the evolution of fusion state estimation methods and analyzing the development of centralized and distributed approaches, the paper highlights the advantages of fusion technology in terms of robustness, flexibility, scalability, and fault detection [3].

The subsequent sections of this paper will delve into different levels of multi-sensor fusion and common implementation approaches. Chapter 2 introduces the classification of multi-sensor fusion, including pixel-level, feature-level, and decision-level methods and their applicable scenarios. Chapter 3 provides an overview of common implementation strategies, focusing on methods for optimizing fusion effects and improving performance. Chapter 4 focuses on practical applications, discussing implementations and results across various fields. Chapter 5 concludes with a summary and outlook on the future directions of the technology, analyzing current challenges and future trends. This paper aims to comprehensively explore the application potential of multi-sensor fusion and provide guidance for future research.

2 Structural Models of Multi-Sensor Fusion

Multi-sensor information fusion models can be classified from different perspectives: classification based on target identity emphasizes the progressive depth of information processing, ranging from pixel-level, and feature-level to decision-level fusion, highlighting the hierarchical relationship of processing depth. On the other hand, classification based on the target state focuses on the unification and dynamic tracking of state parameters, catering to the needs of specific target state estimation.

2.1 Classification Based on Target Identity

In the multi-sensor information fusion framework for target identity estimation, classifications can be divided into pixel-level fusion, feature-level fusion, and decision-level fusion according to the abstraction level of information fusion technology, each with distinct characteristics and applicable to different scenarios [4].

At the pixel-level fusion stage, the system integrates raw data collected by the same type of sensors. This method retains the maximum detail of the data and represents the lowest level of information fusion. However, due to the direct processing of large amounts of raw data, this stage involves significant computation and is vulnerable to environmental interference, resulting in poor robustness. While pixel-level fusion

offers higher accuracy, it is limited to homogeneous data and cannot handle heterogeneous data.

Feature-level fusion is an upgrade from pixel-level fusion, reflecting an improvement from low-level data processing to high-level information extraction. Algorithms classify and extract representative attributes from multi-sensor data and conduct further analysis based on the information needs of the target. This level can be divided into two types: target state fusion and target feature fusion. Target state fusion primarily predicts data states and parameters, using methods like data registration to unify the coordinate data from different sensors into a single coordinate system, often used in target tracking. Target feature fusion is based on data characteristics, combining pattern recognition techniques for classification and integration to facilitate further data pattern analysis. Feature-level fusion reduces data complexity and provides efficient methods for attribute analysis and target feature recognition.

Decision-level fusion is the highest level of information fusion. Based on the data processed at the previous two levels, it jointly analyzes related information from multiple sensors to generate the final inference. By refining data features and preliminary conclusions, decision-level fusion can make accurate judgments at a macro level, characterized by high dynamism, strong fault tolerance, and robustness. It remains capable of making reasonable decisions even when some sensors fail. This high-level processing method is suitable for complex task scenarios requiring comprehensive judgment from multi-sensor data, such as autonomous driving and security monitoring.

Overall, multi-sensor information fusion forms a complete architecture by preserving details at the lower level, extracting features at the middle level, and making decisions at the higher level, providing an efficient and flexible solution for accurate target identity estimation in complex systems.

2.2 Classification Based on Target State

In target state estimation, the multi-sensor information fusion system can be categorized into distributed, centralized, and hybrid architectures based on different data processing methods [5]. Each of these architectures has its own characteristics and applicable scenarios, and specific choices should be made based on system performance requirements.

The distributed architecture processes raw data collected by sensors at independent nodes before transmitting the results to an information fusion center for further optimization and inference. The main advantages of this method are its fast computation speed and high reliability; it can continue to function normally even if some sensors fail, making it particularly suitable for long-distance information transmission. However, it requires high communication bandwidth, and in low-bandwidth environments, information loss may occur, with relatively lower precision.

The centralized architecture directly transmits raw data from multiple sensors to the information fusion center without any preprocessing. This architecture provides extremely high fusion accuracy and real-time performance while supporting the application of various complex algorithms. However, its limitations lie in the single flow of data, lacking interaction between sensors at the lower level. Additionally, it places extremely high demands on the computational capabilities of the data processing

center, leading to high maintenance costs for the centralized database and reduced system speed.

The hybrid architecture combines the advantages of distributed and centralized architectures, ensuring the high reliability of distributed systems while reducing the information loss rate of centralized systems, and significantly improving decision-making capability and flexibility. This architecture is suitable for addressing complex practical application needs, but it requires extremely high system design standards, has relatively low stability, and imposes stringent requirements on the robustness of hardware and software architectures.

In summary, the distributed architecture reduces the burden on the data fusion center by preliminary judgments at sensor nodes, enhancing the overall stability of the system. The centralized architecture globally integrates raw sensor data to minimize transmission loss. The hybrid architecture achieves a balance between reliability and information accuracy. By flexibly selecting the appropriate architecture, system performance can be optimized to improve the efficiency and accuracy of target state estimation.

3 Overview of Multi-Sensor Fusion Approaches

Multi-sensor fusion is a crucial research area in modern information processing, with implementation methods categorized into probabilistic and statistical methods, artificial intelligence methods, and methods tailored to specific application scenarios. These methods, based on different theoretical foundations, apply to various fusion levels and demonstrate significant advantages in the application of multi-sensor systems.

3.1 Probabilistic and Statistical Methods

Probabilistic and statistical methods, serving as the theoretical foundation of traditional multi-sensor fusion, primarily handle random phenomena and uncertain data through mathematical models. These methods include Kalman filtering and Bayesian estimation. Kalman filtering performs well in linear systems but has limited capability in addressing nonlinear problems. Bayesian estimation, on the other hand, dynamically updates information by combining prior probabilities with observational data but relies heavily on the accuracy of the prior probabilities. Furthermore, these methods often assume independence among sensor data, which is challenging to satisfy in practical scenarios. Additionally, probabilistic and statistical methods are typically designed for static environments and are less suitable for complex dynamic settings.

To address these limitations, researchers have proposed improved methods. For instance, likelihood ratio reasoning has been applied in intelligent transportation systems, effectively detecting abnormal vehicle behavior by integrating multi-sensor information, yielding significantly better results than traditional Kalman filtering. These improvements better adapt to complex and uncertain dynamic environments, offering new directions for extending the applications of traditional probabilistic and statistical methods [6].

3.2 Artificial Intelligence Methods

Artificial intelligence (AI) methods are increasingly applied in the field of multi-sensor fusion. These methods emulate human intelligence, focusing on logical reasoning and learning algorithms. Logic reasoning methods include fuzzy logic, Dempster-Shafer (D-S) evidence theory, and production rules. These methods, closer to human thought processes, are particularly suitable for high-level decision-making tasks. However, they exhibit limitations in handling conflicting evidence and data independence assumptions. Fuzzy logic quantifies uncertainty through fuzzy membership degrees, making it suitable for dealing with imprecise and non-exact data, though it heavily depends on rule design and has a subjective nature [7].

In contrast, learning methods have attracted more attention in recent years, demonstrating significant potential in complex dynamic environments. Neural networks, as a representative of learning methods, effectively process sensor data in dynamic and uncertain environments due to their nonlinear mapping capabilities and adaptability. For example, Self-Organizing Feature Maps (SOFM) and Back Propagation (BP) networks have been used for image feature extraction and fusion. However, challenges such as stability, generalization, and training efficiency remain key research focuses for learning methods.

3.3 Methods for Specific Application Scenarios

In specific application scenarios, multi-sensor fusion has led to the development of various methods, particularly in the field of image processing, resulting in a series of targeted implementation strategies. Image fusion, as an important branch of multi-sensor fusion, aims to integrate information from multiple source images to generate high-quality fused images [8]. Common methods include pyramid image fusion, wavelet transform, Principal Component Analysis (PCA), and Hue-Saturation-Intensity (HIS) transform. Pyramid image fusion achieves multi-resolution fusion through pyramid decomposition and reconstruction, widely used in medical and remote sensing image processing. Wavelet transform, with its excellent localization in both time and frequency domains, has gradually replaced traditional pyramid techniques, becoming the mainstream method in image fusion. PCA, by extracting features and reducing dimensions, performs well in fusing images with multi-source correlations.

In addition, in feature-level and decision-level data fusion, common methods include clustering analysis, information entropy, Bayesian estimation, and fuzzy clustering. These methods emphasize both feature extraction and the handling of uncertain data. For example, D-S evidence reasoning excels in feature-level data fusion, managing uncertainty in multi-source information without relying on prior probability information. However, it still faces challenges such as evidence conflict and computational complexity in practical applications [9].

Although existing multi-sensor fusion methods are diverse and each has its advantages, they are not entirely independent and can be combined to form more robust fusion strategies. For instance, combining logic reasoning methods with probabilistic and statistical methods can enhance the ability to process complex information. Using neural networks with Bayesian rules for dynamic modeling can improve the system's adaptability and robustness. Additionally, the integration of different methods often

leverages their respective strengths to complement each other [10].

With technological advancements, multi-sensor fusion is progressively moving toward diversification, dynamism, and intelligence, with research focusing on adaptive real-time fusion methods in complex dynamic environments. In the future, novel fusion methods combining AI techniques and traditional statistical theories will become a key development direction, providing stronger technical support for the application of multi-sensor systems in complex scenarios [11].

4 Practical Application Scenarios

As a significant direction in the field of information processing, target recognition technology plays a crucial role in both military and civilian sectors. Its development benefits from the rapid advancements in sensor technology, pattern recognition algorithms, and artificial intelligence, making it a multidisciplinary research hotspot. By conducting deep analysis and intelligent processing of multi-source data, this technology effectively enhances the accuracy and efficiency of recognition, improves system stability and adaptability, and provides technical support for innovation and breakthroughs in key areas, demonstrating extensive application potential and development prospects.

4.1 Extensive Applications in the Military Sector

In the military sector, multi-sensor fusion technology was initially used for tasks such as target detection, recognition, tracking, and battlefield situation estimation. Military application scenarios include air-to-air, maritime surveillance, and ground-air defense systems [12]. For instance, maritime surveillance utilizes sonar, synthetic aperture radar, and infrared sensors to accurately identify and track targets such as submarines, missiles, and torpedoes. Meanwhile, air and ground-air defense systems employ radar, FSM receivers, infrared sensors, and friend-or-foe identification systems to detect threats posed by enemy aircraft, missiles, and anti-aircraft weapons. These fusion technologies significantly improve the accuracy and real-time performance of target detection, providing reliable support for military command and tactical execution [13].

Additionally, countries such as the United States, France, and Japan have invested substantial resources in developing multi-sensor fusion-based military defense systems, such as the U.S. "All Source Analysis System" (ASAS) and the "Land and Air Commanders' Tactical Intelligence Support System" (LENSCE). In recent years, China has also accelerated its research efforts, designating multi-sensor fusion as a key national defense technology project to develop comprehensive strategic defense systems, including maritime surveillance and integrated ground-air defense [14].

4.2 Breakthroughs in Medical Diagnostics

In the medical field, the application of multi-sensor information fusion technology provides robust support for studying human anatomy and diagnosing various diseases. For example, by integrating X-ray images, MRI scans, and ultrasound images, it becomes possible to more accurately identify diseased tissues, such as cancerous

regions, assisting doctors in making more precise diagnoses. This multi-data fusion approach enhances diagnostic efficiency, reduces the risk of misdiagnosis, and opens new directions for medical equipment development and disease research [15].

4.3 Intelligent Transportation and Security Assurance

Multi-sensor fusion technology also plays a vital role in intelligent transportation systems. For instance, by coordinating multiple radars and sensors, it is possible to identify aircraft types and flight conditions, thereby improving the efficiency and safety of air traffic management. In the realm of security assurance, integrating various biometric features such as fingerprints, facial recognition, iris patterns, and voice significantly enhances the accuracy of identity authentication, improving crime prevention and societal safety capabilities. Furthermore, in criminal investigations, microwave and infrared sensors are utilized to efficiently detect hidden drugs and weapons, providing strong support for investigative work.

4.4 Applications in Robotics

Robotics is one of the key application areas of multi-sensor fusion technology. Fusion technology enables robots to achieve three-dimensional target recognition, autonomous navigation, and task execution in complex environments. Sensor fusion is widely applied in industrial monitoring, underwater operations, and hazardous environment tasks, further advancing the application and development of robotics in specialized fields [13].

In summary, multi-sensor fusion technology significantly enhances the reliability, real-time performance, and adaptability of systems by integrating complementary information from various sensors. Its application spans multiple domains, including military, medical diagnostics, intelligent transportation, and security assurance. As technology continues to advance, multi-sensor fusion is evolving toward greater efficiency and intelligence, promising an even more critical role in future military and civilian sectors [16].

5 Outlook

Multi-sensor fusion technology demonstrates vast application prospects in fields such as military, healthcare, and transportation. Future research should focus on the collaborative optimization of algorithms and hardware. On one hand, developing high-performance sensors will enhance data quality and redundancy; on the other hand, artificial intelligence can be leveraged to optimize fusion algorithms, improving system adaptability and intelligence. Additionally, in terms of structural design, more flexible fusion architectures need to be explored to adapt to dynamic environments and address issues of information uncertainty and real-time performance. Research should also prioritize the construction of a unified theoretical framework to enhance the generality and applicability of the methods.

Through continuous innovation, multi-sensor fusion will provide technological support for the intelligent development of the information society, improving efficiency

and decision-making capabilities while driving technological advancements across various fields.

6 Conclusion

This paper analyzes the current state and methods of multi-sensor fusion technology, summarizing the characteristics, advantages, and disadvantages of fusion at the data, feature, and decision levels, and discussing the core challenges of current technologies. The study shows that multi-sensor fusion can enhance system robustness and efficiency, but further exploration is needed in areas such as unified theoretical frameworks, adaptive algorithms, and structural design for dynamic environments.

In the future, multi-sensor fusion should rely on the coordinated development of software and hardware. High-performance sensors and artificial intelligence technologies will drive more efficient and flexible fusion methods. Moreover, optimizing the balance between real-time performance and computational complexity and developing general-purpose algorithms will be important research directions in this field.

In summary, as a key technology, multi-sensor fusion plays a significant role in advancing the information society. Through continuous innovation, its application value will be further realized across multiple fields, providing strong support for addressing complex information processing challenges.

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