Biometric Technology Based on Wireless Sensing: Principles, Applications, and Challenges

Peican Su *

Information Science and Engineering, Shandong University, Qingdao, China

* Corresponding Author Email: 202300272220@sdu.edu.cn

Abstract. With the rapid advancement of computer technology, image processing, and artificial intelligence, biometric identification technology has seen widespread application, gradually permeating areas such as national security, public security, and home security. However, traditional biometric technologies exhibit certain limitations. In contrast, biometric identification based on wireless sensing offers distinct advantages, including non-contact operation and strong concealment, making it a promising alternative in various security applications. This paper provides a comprehensive overview of the history and current state of biometric technology, alongside the development background of wireless sensing technology. It details the principles of wireless sensing-based biometric identification, covering essential characteristics of wireless signals, and related technologies such as RFID, Wi-Fi, Bluetooth, and millimeter wave technology, as well as relevant signal processing algorithms. Furthermore, the paper analyzes the application of this technology in areas like human posture and motion recognition and physiological feature recognition, supported by practical case studies. Finally, it addresses the environmental dependencies, data privacy, and security concerns associated with this technology, while offering insights into future development directions.

Keywords: Biometrics, Signal Processing, Human Posture Recognition, Physiological Feature Recognition.

1. Introduction

Research Background: Biometric technology has undergone significant evolution since its inception in the 1960s, initially focusing on voice and fingerprint recognition. Over the decades, advancements in computer technology, image processing, and artificial intelligence have propelled biometric identification into a pivotal role across various sectors, including national security, public safety, finance, and telecommunications. As of 2020, the global biometrics market was valued at approximately $24 billion, with projections indicating it could reach $87.4 billion by 2028. Among the various biometric technologies, fingerprint and face recognition are the most widely adopted due to their convenience and cost-effectiveness. However, traditional biometric methods have certain limitations, such as the need for direct contact and potential privacy concerns, which have spurred interest in alternative approaches.

Development of Wireless Sensing Technology: The development of wireless sensing technology can be traced through several key stages. In the late 20th to early 21st century, the focus was primarily on basic theoretical research, exploring how wireless signals could be utilized for environmental perception. This foundational work set the stage for practical applications in the early 21st century, with the advent of popular wireless communication technologies like Wi-Fi and Bluetooth. During this period, researchers began applying these technologies to non-sensor scene perception. Since the 2010s, wireless sensing technology has matured, finding applications in intelligent transportation, smart homes, and medical monitoring. The integration of IoT and AI has further enhanced wireless perception capabilities. Recently, the development of 5G and the anticipation of 6G technologies have driven wireless sensing towards greater intelligence, integration, and precision, expanding its potential for advanced human-computer interaction and intelligent applications.

This Work: This paper explores the emerging field of biometric recognition technology based on wireless perception, which leverages ubiquitous wireless signals such as Wi-Fi, radar, 4G/5G, and RFID to sense and recognize human behavior and status. Compared to traditional biometric methods, wireless sensing-based biometrics offers significant advantages, including non-contact operation, convenience, concealment, the ability to capture multi-dimensional information, environmental adaptability, and the capability for remote recognition. This work provides a comprehensive analysis of wireless sensing biometric technology, discussing its principles, applications, and the challenges it faces. Additionally, the paper forecasts future development directions for this technology, highlighting its potential to revolutionize the field of biometric identification.

2. Principles of Wireless Sensing Biometric Technology

2.1. Basic Characteristics of Wireless Signal and Its Application in Biometrics

The basic characteristics of wireless signals: Wireless signals transmit information by transmitting and receiving radio waves. These signals interact with the surrounding environment during the propagation process, so that the position, motion state and various characteristics of objects, people or other objects in the environment can be inferred. Wireless sensing technology is based on these characteristics to achieve. s possible to calculate where the person is and how fast they are moving. The transmission characteristics of wireless signals vary with different frequency bands, so it is challenging to accurately perceive environmental information.

Application in biometrics: Intelligent health perception based on ubiquitous wireless technology is an important application field. This technology uses non-contact wireless sensing to remotely measure physiological signals reflected from the human body. This smart health-sensing technology can be used to collect basic physiological data such as respiration, heart rate, blood oxygen and blood pressure, as well as advanced behavioral data such as exercise, sleep and interaction. Among them, contactless sensing technology enables health data acquisition and monitoring through sensing devices deployed in the environment (such as cameras, radio frequency devices, etc.), providing a natural and friendly user experience.

2.2. An Introduction to RFID, Wi-Fi, Bluetooth and Millimeter Wave Technologies

There are various types of wireless signals, and each signal has its specific characteristics and application scenarios. Here are some common types of wireless signals and their applications in the field of biometrics:

2.2.1. RFID.

The advantages of RFID include strong anti-interference, non-contact identification, and can work in harsh environments; Large data capacity, can be expanded according to demand; The recognition speed is fast, and the data reading is completed quickly.

Application: RFID technology can be used to track and identify individuals, such as patient tracking and item tracking in hospitals. Recently, a team also proposed a student identification system based on biometrics and RFID passive tags for safe attendance management [1]. Although RFID itself is not a biometric technology, it can be used in combination with biometric systems to improve the accuracy and convenience of identification.

2.2.2. WIFI.

Wi-Fi typically uses cordless bands of 2.4 GHz or 5 GHz, following the IEEE 802.11 standard. The advantage of Wi-Fi is convenience: devices can connect to the network anytime, anywhere. Flexibility: easy to install and extend the network; High Speed: Modern Wi-Fi standards provide high-speed data transmission; Compatibility: Most modern devices support Wi-Fi.

Application: Use Wi-Fi signals for biometric identification, which can identify a person's vital indicators, such as their heartbeat and respiration, by examining reflected signals. This technology can be used for contactless health monitoring or safety monitoring [2].

2.2.3. Bluetooth.

The low-cost near field wireless connection, a unique near field wireless technology link allowing fixed and mobile devices to build a communication environment, is the foundation of Bluetooth, an open global specification for wireless data and voice communication.

Applications: Bluetooth Low Energy (BLE) technology can be used to identify and track individuals at close range, combined with biosensors that can monitor biometrics such as heart rate and body temperature.

2.2.4. mmWave.

Beam narrowness: millimeter wave beam is very narrow and has good directivity, which makes it very useful in point-to-point communication; Small antenna size: Due to the short wavelength, millimeter wave antenna size can be made small, easy to integrate in small devices.

Applications: Millimeter wave technology can penetrate clothing and other non-conductive materials, and can be used for body scanning in airport security or non-contact heartbeat and breathing monitoring, human positioning and gesture recognition [3].

2.3. Signal Processing Algorithm of Wireless Sensing Technology

In the field of wireless sensing technology, some signal processing algorithms that have appeared or been widely concerned in recent years mainly include the following types. As show in the Table 1.

Table 1. Advantages and disadvantages of different signal processing techniques.

	Brief Introduction	Advantage	Disadvantage
Compressed Sensing	Also known as sparse sampling, is a signal processing theory that states that if a signal is sparse or can be represented as a sparse linear combination of a known dictionary, then that signal can be reconstructed by sampling rates well below those required by Nyquist's sampling theorem.	Sparse signals can be recovered from a small number of measurements, reducing the complexity of data acquisition and processing, and reducing hardware costs.	The performance and computational efficiency of the recovery algorithm are the research challenges due to the high signal sparsity requirement and the relatively high algorithm complexity.
Machine learning and deep learning algorithms	Machine learning is a technique that enables computer systems to use data to continuously improve their performance. Deep learning is a form of algorithm for learning that mimics how the human brain analyzes information by building several layers of neural networks.	It can deal with complex nonlinear problems, improve the accuracy of signal classification and recognition, and has strong adaptability.	The computational cost of model training and inference is high, necessitating a lot of training data, and there is a possibility of overfitting problems.
Federated Learning	Federated Learning is a machine learning approach that enables various devices or servers to work together in training models while keeping the data on-site, eliminating the need for centralized storage or processing of the data.	Protect user privacy, do not need to store data centrally, suitable for distributed network environment.	The communication cost is high, the model convergence speed may be slow, and there is potential privacy disclosure risk.
The fusion algorithm of wireless sensing and positioning	The fusion algorithm of wireless sensing and positioning combines a variety of wireless signal processing techniques to detect, track and locate the target object. These algorithms use the characteristics of the wireless	The combination of positioning information can provide more accurate perceptual results and enhance the practicality of the application.	The positioning accuracy is greatly affected by the environment, as the algorithm is complex and requires high hardware and processing power.

	signal to infer the location and behavior of the target.		
Nonlinear signal processing algorithms	Nonlinear signal processing algorithms are a series of techniques used to analyze and process signals with nonlinear characteristics.	It can deal with nonlinear problems which are difficult for traditional linear algorithms to deal with, and improve the adaptability of signal processing.	The algorithm design is complex and computatively heavy, which may require special hardware support.

3. Applications of Biometric Technology

3.1. Human Posture and Movement Recognition

Attitude recognition technology based on Wi-Fi and millimeter wave.

The wireless signals used for human posture recognition mainly include WIFI signals, millimeter-wave radar signals, ultra-wideband signals and Bluetooth signals. Millimeter wave radar signal and ultra-wideband signal, although the recognition accuracy is high, but the cost is also high, the application is limited. The accuracy and coverage of Bluetooth signals are relatively low, so they are rarely used. The following is mainly to analyze a method of human posture recognition using WIFI signals.

Their team used nine WiFi antenna pairs, one as the transmitting end and one as the receiving end, to record WiFi signals at 30 frequency points in the 2.4GHz band. At the same time, Mask R-CNN and OpenPose were used to segment the human body and estimate the pose of the synchronously collected RGB video as the annotation data. The WiFi signal and video annotation data are input into the deep learning model as CSI tensors for training. The model includes a U-Net network for human body segmentation, and two U-Net networks for joint joint heat maps (JHMs) and joint joint heat maps (PAFs). The following is the general process of the experiment. As show in the figure 1.

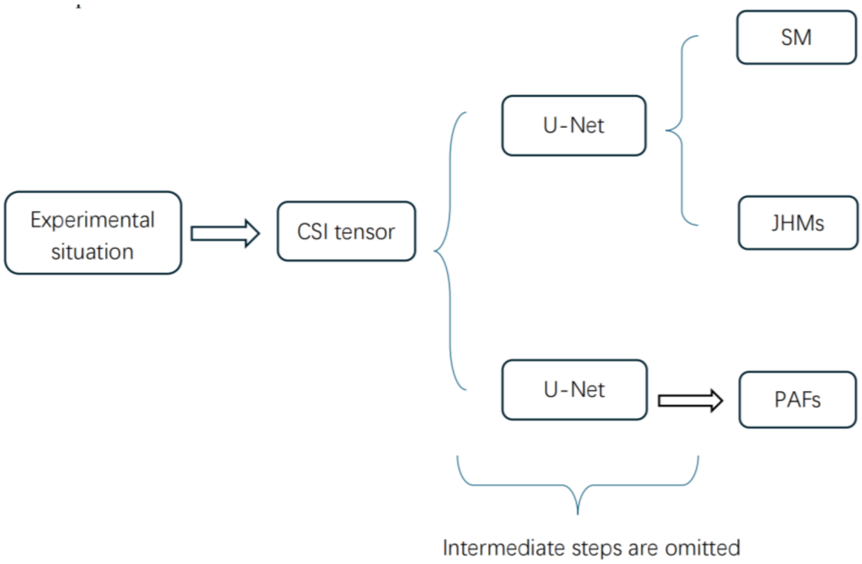

Figure 1. General process of the experiment (SM: Segmentation Mask, JHMs: Joint Heatmaps , PAFs: Part Affinity Fields) (Photo credit: Original).

$$\mathcal{L} = \lambda_1 L_{\mathrm{SM}} + \lambda_2 L_{\mathrm{JHM}} + \lambda_3 L_{\mathrm{PAF}} \quad (1)$$

The scalar weights λ 1 , λ 2, λ 3 are used to balance out the three losses: SM, JHMs, PAFs.

Finally, the OpenPose API was used to correlate the output JHMs and PAFs to obtain the final human pose estimation result.

In summary, the experiment uses WiFi signals as inputs to achieve human body segmentation and pose estimation through deep learning models, and proposes some technological innovations to solve the challenge of reconstructing spatial information from WiFi signals.

The distributed WIFI antenna is used to collect WIFI signal data, and the 3D posture of human body is estimated by analyzing the amplitude and phase changes of WIFI signal [4, 5].

By using standard 802.11n WIFI signal, the characteristics of WIFI signal are analyzed by machine learning algorithm, and the attitude recognition of a single person or several people is realized [6-9].

In general, the WiFi-based attitude recognition technology is an emerging research field. Compared with the traditional camera-based method, it has the advantages of low cost and good privacy, and has great application prospects in the future. These studies have laid a foundation for the further development of WiFi-based human posture perception technology.

3.2. Recognition of Physiological Characteristics

Heartbeat and breathing monitoring based on wireless signals mainly uses Doppler radar signals, WiFi signals, ultra-wideband (UWB) signals, in comparison, Doppler radar signals provide the highest detection accuracy, but the cost and environmental dependence is high. WiFi signals use existing equipment, the cost advantage is obvious, but the accuracy and robustness is weak. UWB signal is between the two in terms of accuracy and anti-interference, which is a more balanced choice. The following describes a UWB signal and millimeter wave signal related applications

A method of detecting human respiratory waveform during sleep based on pulsed ultra-wideband (IR-UWB) was proposed [10]. This enables real-time output of the respiratory waveform and high-precision estimation of the respiratory rate. As show in the figure 2.

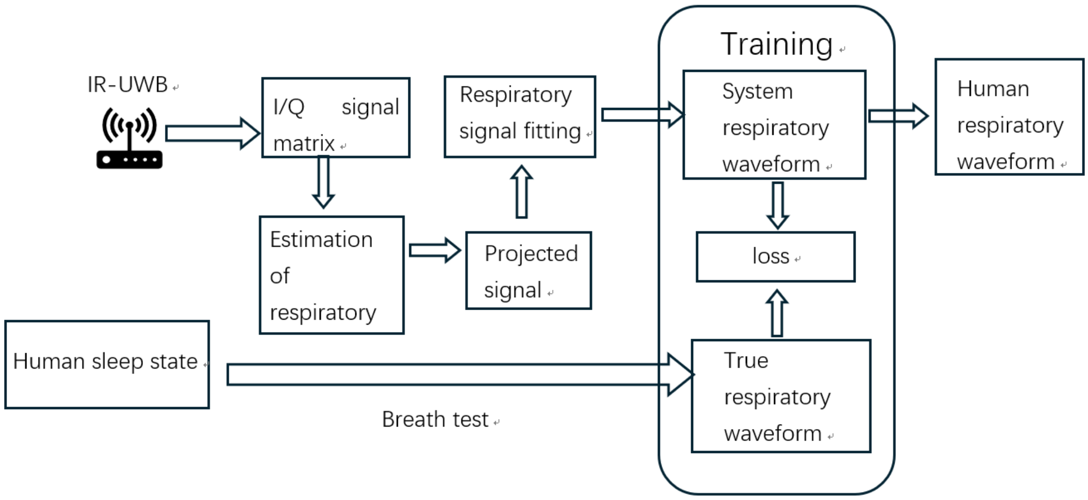

Figure 2. Frme diagram of human respiratory waveform detection method in sleep state based on IR-UWB (Photo credit: Original).

Compared with other breathing sensing methods based on RF signals, IR-UWB technology has better distributed and non-contact characteristics, which can realize the perception of human breathing and heartbeat activity in any radar field of view, providing a more flexible and convenient solution for applications such as sleep monitoring.

In addition, the real-time non-contact electrocardiogram (ECG) monitoring technology based on millimeter wave radar is an important progress in the field of wireless human perception. Professor Chen Yan and Researcher Sun Qibin from Academician Wu Manqing's team at the University of Science and Technology of China have made breakthrough achievements in this field [11]. The technology they developed allows the non-contact measurement of the mechanical activity of the heart on the body surface through millimeter-wave radar and the recovery of the ECG waveform.

This method not only improves the comfort of monitoring, but also maintains high precision and medical value, which is of great significance for the daily monitoring and diagnosis of arrhythmia, myocardial infarction and other diseases.

The key advantage of this technology is that it breaks through the limitations of conventional electrocardiograms, which require contact electrodes to capture the electrical activity of the heart. Using mmwave radar, ECG monitoring can be done without the need to wear electrodes or remove clothing, which is particularly valuable for daily health monitoring because it can provide a non-inductive way of monitoring, allowing for continuous monitoring over long periods of time, reducing discomfort caused by monitoring equipment.

Flexible and dry capacitive electrodes are used in contactless wearable wireless ECG systems developed by research for long-term cardiovascular health monitoring. This indicates that the application of wireless sensing technology in electrocardiogram monitoring is gradually maturing, and has the potential to play an important role in the future medical and health field.

3.3. Case Studies in Practical Applications

3.3.1. Home security monitoring.

Wireless sensing technology can be used to build remote home security monitoring and alarm systems. Such systems usually consist of wireless sensor networks (WSN) and GSM technology. Sensor networks can include a variety of sensors, such as motion sensors, smoke sensors, door and window sensors, etc., to monitor the safety of the home [12- 14]. In addition, wireless perception technology can also be combined with artificial intelligence technology to improve the intelligence level of home security monitoring systems [15]. For example, the system can use wireless signal strength (RSSI) to monitor and analyze activities in the home and automatically identify suspicious behavior [16]. At the same time, biometrics such as fingerprint recognition can also be integrated into home security systems to improve security.

In general, wireless sensing technology provides a flexible, intelligent and efficient solution for home security monitoring system [17].

3.3.2. Public safety and medical health monitoring.

These technologies can be used to monitor and prevent various public safety incidents, such as fires and traffic accidents [18, 19].

In terms of medical health monitoring, wireless sensing technology can be used to remotely monitor patients' physiological indicators, such as heart rate and blood oxygen saturation [20, 21]. These technologies can help people with chronic diseases receive treatment at home and improve their quality of life.

In general, wireless perception technology has a wide range of application prospects in the field of public safety and medical health monitoring, which can improve monitoring efficiency and improve the quality of public life. However, it is also necessary to pay attention to related security and privacy issues in the application process [22, 23].

4. Challenges and Future Outlook

The core of this technology is to use the radio frequency signal that already exists in the environment to perceive people's actions and behaviors, so as to realize the perception of the environment. This technology has the characteristics of sensorless, wireless, contactless, provides a new way to perceive the physical world, and has shown practical application potential in smart home, security monitoring, health monitoring and other fields.

However, this technology also faces some challenges and limitations. It mainly includes.

4.1. Environmental Dependence and interference of Wireless Sensing Technology

The signal features are related to the background environment, which leads to the perception result dependent on the deployment environment, poor generalization ability and high learning and training cost. Different use environments, different users, and even different locations and orientations of the same user may reduce the perceived accuracy [24]. In addition, wireless signals are susceptible to interference, which can affect perceived quality.

4.2. Data Privacy and Security Challenges

When wireless sensor networks collect, transmit and process massive data, there is a risk of privacy disclosure. This data may contain sensitive information that, if accessed or disclosed without authorization, could pose a threat to personal privacy

In addition to privacy breaches, wireless sensor networks also face the problem of data integrity breaches. This means that the data may be tampered with or damaged during transmission, affecting the accuracy and reliability of the data.

Identification can be achieved using the physiological or behavioral characteristics of the human body using biometric technology, and it is widely used in security, business and other fields. Future directions include improving the accuracy, speed, and security of identification, as well as the development of multimodal biometrics, which combines multiple biometrics to improve the accuracy and reliability of authentication.

Security monitoring: Used for identity verification and monitoring in scenarios such as border control and airport security screening.

Smart home: Through biometric technology to achieve the identity of family members and personalized services.

Exercise fitness: Monitor the physiological state of the exercisers, provide personalized exercise recommendations and effect assessment.

5. Conclusion

Biometric recognition technology based on wireless sensing represents a promising new frontier in the field of identity authentication, health monitoring, and security surveillance. By overcoming the inherent limitations of traditional biometric methods, such as the need for physical contact and limited adaptability to varying environments, wireless sensing biometrics offers innovative solutions that enhance convenience, concealment, and multi-dimensional information gathering. This paper has provided a comprehensive overview of the principles underlying wireless sensing biometric technology, its current applications, and the challenges it faces. The discussion has highlighted the significant advantages this technology brings to various fields, while also addressing concerns related to environmental dependency, interference, and data privacy.

Looking ahead, the future of wireless sensing biometric recognition is bright, with immense potential driven by ongoing advancements in deep learning, signal processing, and the accumulation of high-quality datasets. As these technologies evolve and application scenarios continue to expand, wireless sensing biometrics is expected to overcome its current challenges, leading to broader and more secure implementations. With its ability to provide non-contact, accurate, and reliable identification, this technology is poised to bring significant convenience and improvements to human society, contributing to enhanced security, health monitoring, and overall well-being. The continued research and development in this field will undoubtedly shape the future landscape of biometric identification.

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