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Research on the Application of Millimetre-Wave Radar Technology in Elderly Care

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Abstract. With the global aging population intensifying, millimetre-wave radar has emerged as an innovative technology for elderly care due to its non-contact, high-precision, and all-weather capabilities. This paper examines its applications in fall prevention, vital signs monitoring, and behaviour recognition, demonstrating the technology's potential for continuous, unobtrusive health monitoring of the elderly alongside timely alerts. However, practical implementation faces challenges including signal interference, insufficient data accuracy, and privacy breaches. Future research should prioritise enhancing anti-interference algorithms, integrating multiple sensors, designing lightweight hardware, and establishing data security mechanisms to improve system robustness and user trust. This study provides a reference for technological refinement and practical implementation of millimetre-wave radar in smart elderly care, contributing to the advancement of home-based care towards intelligent and human-centred solutions.

Keywords: millimetre-wave radar, elderly care, fall prevention, electronic information

1. Introduction

Amidst accelerating global aging, safeguarding the safety and health of the elderly has become a societal priority. Risks such as falls and sudden illnesses significantly impact quality of life. Traditional contact sensors offer poor comfort and raise privacy concerns, while camera-based monitoring suffers from light sensitivity and privacy infringements [1]. Millimetre-wave radar, a non-contact high-precision sensing technology, holds significant potential for elderly care due to its ability to penetrate obstructions, operate independently of lighting conditions, and accurately detect minute movements [2]. Recent applications have primarily focused on fall detection, vital sign monitoring, and behaviour recognition, yet most studies address single functions only, lacking systemic robustness, adaptability to complex environments, and data privacy protection [3].

This paper aims to systematically organise the key technological application framework of millimetre-wave radar in elderly care. It focuses on the implementation mechanisms and performance logic within core scenarios such as fall prevention monitoring, non-contact vital sign detection, and behaviour recognition. Through a combination of literature review and technical analysis, it delves into current technical challenges, including algorithmic susceptibility to interference, insufficient environmental adaptability, and ethical challenges concerning personal privacy. This research provides references for optimising millimetre-wave radar technical design in

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smart elderly care scenarios. It further proposes establishing a multi-technology integrated, intelligent elderly monitoring system to advance safer, privacy-friendly home-based elderly care models.

2. Literature review

2.1. Research progress in fall detection

Fall detection represents the most mature application of millimetre-wave radar in elderly care. Both domestic and international research predominantly employs micro-Doppler feature analysis combined with machine learning, though technical approaches vary. Domestic research predominantly focuses on refining algorithms for single radar perspectives. Li utilised point cloud data to extract human motion trajectory features, while Zhang explored indoor personnel tracking coupled with fall detection, demonstrating a shift from event detection towards continuous behavioural monitoring [4]. Overseas research places greater emphasis on multi-view fusion and enhancing system robustness. Feng et al. proposed a multi-view parameter fusion approach for fall detection, effectively reducing false alarm rates in complex environments [5]; Yael et al. employed micro-Doppler spectra to achieve non-intrusive recognition, safeguarding user privacy while maintaining detection accuracy [6]. Armeniakos et al. demonstrated the feasibility of distributed systems for large-scale monitoring through multi-radar node clustering, with international research leading in system scalability [7].

2.2. Non-contact vital sign monitoring

Regarding vital signs monitoring such as heartbeat and respiration, both domestic and international efforts focus on enhancing signal extraction accuracy and anti-interference capabilities. Domestic scholars Li and Liu applied deep learning to heart rate detection, employing data-driven approaches to improve noise resistance [8-9]; Su and Wang refined the FMCW radar system, advancing signal processing algorithms towards sleep health monitoring [10-11]. Hu and Sun extended this application to sleep apnoea warning systems, demonstrating potential for clinical translation [12-13]. Overseas research has delved deeper into multi-parameter synchronous monitoring and algorithmic universality. Shirazi et al. systematically reviewed machine learning applications in radar-based vital sign monitoring, highlighting deep learning's advantages for complex signal modelling [14]. Mahmoud and Lillian achieved synchronous monitoring of multiple individuals' vital signs using FMCW radar, demonstrating its integration potential in multi-user domestic settings [15]; Yong and Zhao utilised Doppler radar to validate the reliability of non-contact monitoring systems, advancing the technology towards practical implementation [16].

2.3. System integration and privacy protection

Following technological advancements, system-level integration and ethical considerations have emerged as research frontiers. Domestic efforts have explored hardware innovations: Wan Jifeng enhanced the angular resolution and multi-target tracking capabilities of MIMO millimetre-wave radar systems, providing hardware support for high-precision monitoring [17]. However, system miniaturisation, cost reduction, and the establishment of privacy standards remain underdeveloped. Internationally, attention to multimodal fusion and privacy protection mechanisms emerged earlier. Kaur et al. systematically reviewed fall detection technologies, clearly demonstrating millimetre-wave radar's privacy advantages over cameras ([18]). Furthermore, Yael et al. enhanced privacy

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security through non-imaging detection strategies, demonstrating consideration of ethical concerns during technological design [6].

In summary, current research centres on fall detection and vital signs monitoring, with technological pathways transitioning towards intelligent systems. Domestic approaches favour algorithm implementation tailored to specific application scenarios, whilst international efforts delve deeper into multimodal fusion, cluster deployment, and privacy protection. Common challenges include inadequate suppression of signal interference in complex environments and insufficient algorithmic generalisation and personalisation capabilities. Data security and ethical frameworks remain underdeveloped, with much research confined to laboratory settings lacking real-world validation. Future efforts should enhance system robustness, foster interdisciplinary collaboration, and improve real-world implementation capabilities, driving technology from merely functional towards trustworthy and scalable solutions.

3. Specific applications of millimetre-wave radar in elderly care

3.1. Fall prevention monitoring

Falls among the elderly can lead to severe injury or even death, particularly when balance is lost. Leveraging its non-contact, high-precision, and all-weather capabilities, millimetre-wave radar can effectively monitor elderly activity, pre-emptively identify fall risks, and trigger alerts. Fall prevention systems primarily rely on radar signal reflection characteristics, analysing behavioural and movement changes to assess fall probability. Key steps include:

(1) Signal Reflection and Analysis: Electromagnetic waves emitted by the millimetre-wave radar reflect off the human body. The receiver then analyses signal parameters such as time delay, frequency variation, and amplitude to determine the target's motion state. The relationship between reflection time tr and distance d is expressed as in Equation (1):

$$d=\frac{c\cdot t_r}{2} \tag{1}$$

Where c denotes the speed of light and tr represents the transmission time of the reflected wave. Continuous tracking of this parameter enables real-time determination of the elderly person's current location. (2) Gait Recognition and Variation: Changes in gait constitute a key indicator for fall prediction. By analysing reflected signals, millimetre-wave radar can continuously monitor the gait patterns of elderly individuals during walking. By measuring the gait cycle period Tcycle and step frequency fstep, the system can determine whether an elderly person's movement is normal. Should any abnormal gait patterns or step frequency variations exceeding a predetermined threshold be detected, this is classified as high-risk behaviour for falling, triggering an immediate alert. (3) Fall posture detection: When elderly individuals fall, their body posture typically exhibits specific characteristics. Millimetre-wave radar can monitor these postures in real time to determine whether a fall has occurred. Upon detecting abnormal postures, such as rapid changes in the horizontal plane, the radar employs the formula:

$$\Delta\theta=\frac{\Delta x}{\Delta t} \tag{2}$$

where $\Delta\theta$ denotes angular posture change, Δx represents positional change, and Δt indicates time interval, to analyse whether a fall has occurred.

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(4) Fall Detection Algorithm: Through data fusion and analysis, combined with machine learning and pattern recognition techniques, the millimetre-wave radar system can assess the dynamic behaviour of elderly individuals. After training the algorithm, the system can recognise transitions between different states—from standing to walking, and from walking to sitting—and react immediately upon detecting a fall, as illustrated in Figure 1.

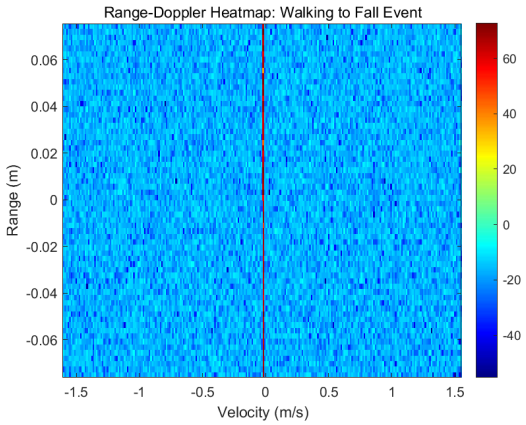


Figure 1. Range-doppler heatmap: walking to fall event

3.2. Non-contact vital signs monitoring

Non-contact vital signs monitoring constitutes a pivotal application of millimetre-wave radar in elderly care. It achieves real-time monitoring of vital signs—including heart rate and respiration—by analysing millimetre-wave signals reflected from the human body. As millimetre-wave radar penetrates clothing and other obstructions, it enables vital sign monitoring without physical contact. This approach offers greater comfort and safety for elderly individuals, particularly those with mobility impairments or cognitive impairments.

(1) Respiration Detection: Millimetre-wave radar detects minute bodily movements by analysing variations in reflected signal frequency. The rise and fall of the chest during respiration constitutes the "minute movement" targeted by the radar. Human breathing induces slight displacement, altering the phase of the reflected signal emitted by the radar. Changes in the reflected signal's frequency are influenced by the Doppler effect. According to this principle, when the reflected signal frequency shifts, the velocity is calculated as:

$$v=\frac{f_r-f_0}{2f_0}c \tag{3}$$

Where fr is the received frequency, f0 is the transmitted frequency, and c is the speed of light. By analysing frequency variations, the system can determine an elderly individual's respiratory rate per breath and breathing depth. The system continuously monitors breathing patterns, triggering an alarm should it detect rapid breathing or respiratory arrest.

(2) Heartbeat Monitoring: Similar to respiration detection, heartbeats cause minute chest movements. The frequency of the radar-reflected signal also changes with each heartbeat. By analysing these frequency variations, the system detects heartbeat patterns to determine the elderly individual's heart rate and rhythm. The heartbeat cycle can be calculated using the following formula:

$$T_{heartbeat}=\frac{1}{f_{heartbeat}} \tag{4}$$

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Where Theartbeat represents the heartbeat period and fheartbeat denotes the heart rate. By continuously monitoring variations in heartbeat signals, the millimetre-wave radar system enables real-time heart rate monitoring for elderly individuals. It promptly alerts care personnel to abnormal heart rates, such as tachycardia or bradycardia.

(3) Signal Processing and Data Fusion: Millimetre-wave radar systems typically employ high-frequency signal processing techniques. Through methods such as filtering, denoising, and and time-domain analysis to extract useful information from reflected signals. By integrating machine learning algorithms with signal processing techniques, the radar system can distinguish signals generated by different physiological activities (such as respiration, heartbeat, movement, etc.), subsequently processing each distinct physiological signal separately. For instance, analysis based on amplitude variations and frequency fluctuations can precisely identify an elderly person's heartbeat and respiratory data from complex reflected signals.

3.3. Activity status and behaviour monitoring

When employed for monitoring elderly individuals' activity states and behaviour, millimetre-wave radar can instantly capture daily activities such as walking, standing, sitting, and sleeping. Moreover, it can assess health conditions based on activity patterns. By analysing variations in reflected signals, millimetre-wave radar effectively distinguishes behavioural patterns among the elderly.

(1) Human motion detection: Millimetre-wave radar determines movement velocity by measuring displacement of objects or human bodies, employing the Doppler effect. After electromagnetic waves emitted by the radar are reflected by the human body, the receiver analyses the resulting frequency shift to calculate the velocity v of the body:

$$v=\frac{f_r-f_0}{2f_0}c \tag{5}$$

Where fr denotes the received frequency, f0 denotes the transmitted frequency, and c denotes the speed of light. By analysing variations in speed across different time intervals, it is possible to determine whether an elderly individual is stationary, walking, or engaged in other activities.

(2) Behavioural Pattern Analysis: Continuous monitoring of millimetre-wave signals reveals the elderly person's activity patterns. If their behaviour repeats within a cycle, changes in this cycle can indicate their activity state. For instance, the standing cycle is denoted as Tstand,, whilst the walking cycle is Twalk. These periodic signals can undergo spectral analysis via Fourier transform:

$$X(f)=\int_{-\infty}^{\infty}x(t)e^{-j2\pi ft}dt \tag{6}$$

(3) Fall Detection and Abnormal Behaviour Recognition: Continuous monitoring of activity patterns identifies anomalous behaviour—such as abrupt stops or violent movements—which may indicate falls or health issues. By tracking the rate of change in activity patterns (ΔA), sudden alterations (e.g., abrupt shifts in position or posture) trigger immediate alerts. Here, Anew and Aold denote the current and previous activity states respectively, with Δt representing the time difference. Employing these methods enables millimetre-wave radar to accurately perceive elderly individuals' behaviour, swiftly identify anomalies, and trigger alerts. This enhances the safety and responsiveness of elderly care, as illustrated in Figure 2.

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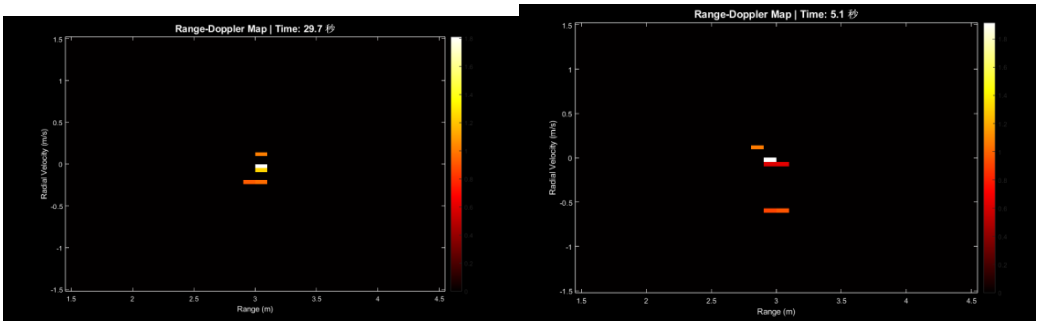


Figure 2. Distance-doppler plot

Under normal circumstances, algorithms can determine whether an elderly person has left their bed without authorisation or if an emergency has occurred, thereby triggering an alert.

4. Challenges in the application of millimetre-wave radar technology

4.1. Technical limitations and environmental adaptability challenges

Millimetre-wave radar still encounters technical bottlenecks in real-world applications. Within complex indoor environments, diverse walls, furniture, and building structures introduce multipath effects. This impacts fall detection accuracy and vital sign acquisition, particularly as physiological phenomena like breathing and heartbeat are minute, measuring merely millimetres in scale, are highly susceptible to human micro-movements or ambient environmental noise, resulting in low signal-to-noise ratios. Existing algorithm designs are often formulated under idealised conditions, making accurate detection challenging in real-world scenarios involving obstructions, multiple users coexisting, or excessive distances. Enhancing the system's interference resistance in non-ideal environments remains a significant challenge.

4.2. Data privacy and ethical compliance risks

Millimetre-wave radar continuously collects behavioural and physiological data from elderly individuals, posing privacy leakage risks. While it does not generate images, movement characteristics may be exploited for identity recognition or inferring health conditions. Currently, most systems lack encryption for transmission, access controls, or data anonymisation, posing risks of misuse. Furthermore, there are no unified standards regarding ethical issues such as informed consent from the elderly or data ownership. Establishing secure, compliant data management mechanisms while maintaining monitoring effectiveness is a prerequisite for the technology to gain societal acceptance and widespread adoption.

5. Conclusion

This paper reviews the application of millimetre-wave radar in elderly care, highlighting its technical advantages in fall prevention, vital signs monitoring, and behavioural recognition. Research indicates this technology offers non-contact, all-weather, and high-precision capabilities, enabling continuous, unobtrusive monitoring of elderly health conditions. This enhances home safety and improves care efficiency. Compared to wearable devices or cameras, it requires no wearable devices, is unaffected by lighting conditions, and facilitates privacy protection. By analysing reflected signals and micro-Doppler characteristics, the system can instantly detect fall

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risks, monitor vital signs such as respiration and heart rate, and identify abnormal behaviour, providing timely alerts for care personnel.

This study constitutes a review and did not involve experimental testing. Coverage of actual products and real-world scenarios remains limited; future evaluations should incorporate field-tested data.

Current technology faces challenges: firstly, signal interference and difficulty extracting physiological signals in complex environments; secondly, long-term data collection risks privacy breaches and lacks ethical frameworks. Future efforts should focus on enhancing anti-interference algorithms, multi-sensor fusion, lightweight hardware, and data security mechanisms. With advances in artificial intelligence and edge computing, millimetre-wave radar may become the primary sensing method for smart elderly care, shifting the care model from "passive response" to "proactive prevention."

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