

Privacy-Preserving Digital Twin for Elderly Care: A Literature Survey of Camera-Free Monitoring Using Ambient Sound and IoT Sensors

AgeSentinel – Intelligent Protection and Monitoring for Seniors

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Abstract: *The increasing number of older adults who prefer to remain in their own homes creates a need for continuous but privacy-preserving monitoring. Conventional elderly-care technologies often rely on cameras, wearable devices, or isolated emergency alarms, which can create privacy, usability, and coverage limitations. This literature survey examines existing approaches related to aging-in-place, activity recognition, smart-home monitoring, and privacy-preserving digital twins, with particular attention to the approach proposed in the AgeSentinel project. The reviewed project literature includes room-level motion sensing, wearable fall detection, voice-based caregiver check-ins, smart-speaker alarm detection, camera-free radar monitoring, and sensor-based assessment of aging-related changes. The comparison shows that existing solutions are often focused on specific events, require user participation, or lack context about ordinary daily routines. The proposed direction combines ambient sound events with door and appliance sensors to learn a personalized daily baseline while discarding raw audio. Machine-learning-based deviation detection can then identify meaningful changes such as prolonged silence or missed routines and generate alerts for family members. The survey identifies privacy, personalization, multi-resident operation, noise robustness, interpretability, and real-world validation as important areas for further investigation.*

Keywords: Digital Twin; Aging-in-Place; Elderly Care; Privacy-Preserving Monitoring; Ambient Sound; IoT Sensors; Activity Recognition; Anomaly Detection; Smart Home

I. INTRODUCTION

Aging-in-place refers to the ability of older adults to continue living in their preferred home environment rather than moving to institutional care. The AgeSentinel project presentation identifies aging-in-place as an important motivation for continuous monitoring and notes that emergencies or gradual changes in routine may go unnoticed when an older person lives alone. It also describes a digital twin as a live virtual model of the home and resident, providing a basis for representing routine behavior without requiring intrusive visual surveillance.

The central challenge is therefore not simply detecting a fall or an emergency. A useful monitoring system should understand what is normal for an individual and identify meaningful deviations from that normal pattern. The project proposes a camera-free approach based on ambient sound and simple IoT sensors. Events such as footsteps, kettle activity, television use, door activity, and periods of silence can provide contextual information about daily routines while avoiding storage of raw audio.

This literature survey follows the structure recommended in the accompanying literature-survey guide: relevant literature is organized and compared rather than summarized paper-by-paper; strengths and limitations are considered;



and a research gap is derived from the comparison. The scope is specifically limited to privacy-preserving elderly monitoring, activity recognition, smart-home sensing, and digital-twin-based aging-in-place.

II. LITERATURE REVIEW METHODOLOGY

The survey was constructed from the research references and comparison material included in the final project presentation. The literature-survey guide recommends identifying a focused topic, extracting the problem, method, findings, limitations, and research gap, and then grouping studies by common themes. Accordingly, the review considers the following dimensions: monitoring modality, type of activity or event detected, degree of user participation, privacy characteristics, routine-level context, and limitations.

The project presentation contains a direct comparison of five existing approaches and the proposed project. The supporting reference list also identifies work on activity recognition from streaming sensor data, intelligent assessment of aging changes, smart-home prediction of symptoms, and perceptions of aging-in-place. Because the supplied presentation does not provide complete bibliographic metadata for every cited source, the reference details in this paper are retained at the level provided in the presentation rather than being silently expanded or fabricated.

III. BACKGROUND AND NEED

The project presentation reports that one in six people aged 60 and above is expected by 2030, and it cites Singapore-specific figures showing a strong preference for aging in place and a measurable proportion of older residents living alone. These figures motivate technologies that support independent living while preserving dignity and privacy.

Three problems are emphasized. First, privacy concerns make cameras undesirable in private spaces. Second, reactive care may miss gradual changes, such as unusually long periods of silence or missed activities. Third, generic threshold rules may generate excessive alerts because normal behaviour differs between individuals. These observations motivate a personalized baseline rather than a one-size-fits-all monitoring rule.

IV. COMPARATIVE SYNTHESIS

4.1 Existing Monitoring Approaches

Existing elderly-monitoring systems demonstrate several useful sensing strategies, but each emphasizes a particular type of information. Room motion sensing can notify caregivers that movement has or has not occurred, while wearable sensors can detect selected physical events such as hard falls. Smart-speaker systems can support check-ins or detect specific alarm events, and radar-based approaches can provide camera-free monitoring. However, these approaches do not necessarily construct a continuous, personalized representation of ordinary household routines.

Study / System	Approach	Main Finding / Limitation	Relevance to AgeSentinel
QuietCare (Intel-GE)	Room motion sensors alert family.	Room-level monitoring; does not provide audio cues.	Shows usefulness of passive room sensing, but leaves a gap in sound-based context.
Apple Watch (2018)	Wrist sensor detects hard falls.	Must be worn; can miss gradual decline.	Demonstrates wearable-event detection but depends on user compliance and focuses on specific events.
Alexa Together (2021)	Echo supports caregiver check-ins.	Relies on voice use and provides limited activity detail.	Provides remote support but does not build a detailed passive routine signature.
Alexa Guard (2019)	Echo detects events such as glass break and smoke alarms.	Focuses on alarm events rather than daily routines.	Useful for emergency awareness but not for



			personalized routine-deviation analysis.
Vayyar Care	Camera-free radar tracks falls.	Fall-focused; lacks door/appliance context.	Demonstrates privacy-preserving sensing, while highlighting the need for broader routine context.
AgeSentinel (proposed)	Ambient sound events + door/appliance sensors; personalized baseline and ML deviation detection.	Adds sound cues while discarding raw audio; requires learning period and robust handling of noise.	Targets routine-level, privacy-first monitoring rather than only isolated emergency events.

The comparison indicates a common pattern: existing systems can detect particular events or provide specific caregiver functions, but they do not all combine passive sensing, routine context, personalization, and privacy in one framework. The proposed project therefore treats the resident's normal daily pattern as the central reference point for anomaly detection.

4.3 Thematic Synthesis

Privacy-preserving sensing is the first major theme. Radar, motion sensors, and non-visual sensing demonstrate that monitoring can be performed without continuous camera footage. The proposed system extends this principle by extracting sound events and storing event labels instead of raw audio.

The second theme is event-specific versus routine-level monitoring. Wearables and alarm-detection systems are effective for particular events, but gradual behavioural change can occur without a single obvious emergency. A routine-oriented model can represent patterns over time and therefore identify deviations that isolated event detectors may not capture.

The third theme is personalization. The project presentation explicitly identifies alert fatigue as a problem with generic rules. A personal daily sound signature provides a resident-specific baseline, allowing the system to distinguish ordinary variation from potentially meaningful change.

The fourth theme is multimodal context. Sound alone may be ambiguous, while door and appliance sensors can add context. Combining these signals can help represent household activities more accurately than relying on a single sensor modality.

4.4. Related Research Areas

The final project presentation cites Krishnan and Cook's work on activity recognition from streaming sensor data [3], which is relevant to the use of continuous sensor streams for recognizing activities. Work by Kaye et al. on intelligent systems for assessing aging changes [4] supports the broader idea that computational monitoring can assist in understanding changes associated with aging. Aramendi et al. examine functional health decline using smart-home data [5], while Alberdi et al. investigate smart-home-based prediction of symptoms related to Alzheimer's disease [6]. Together, these references support the broader research direction of using passive home data to understand changes in an older person's condition or behaviour.

The presentation also cites Stones and Gullifer on older adults' perceptions of aging in place [7]. This is important because technical effectiveness alone does not determine whether a monitoring technology is acceptable. A privacy-preserving design can improve the alignment between monitoring capability and the resident's desire for dignity and independence.

V. RESEARCH GAPS IDENTIFIED

The literature comparison suggests that existing systems have addressed passive sensing, fall detection, caregiver communication, alarm detection, and camera-free monitoring. However, limited attention is given in the project's



reviewed set to combining ambient sound cues with door and appliance context to learn an individualized daily routine while retaining privacy through disposal of raw audio.

A second gap concerns gradual behavioural change. Several reviewed systems are oriented toward explicit events such as falls, alarms, or check-ins. A personalized baseline can instead support detection of deviations such as unusually long silence or missed routine activities.

A third gap is practical deployment. The project presentation identifies important limitations including noise that can confuse sound events, the assumption of one resident, the need for a learning period, lack of medical or fall diagnosis, and requirements for consent and data security. These limitations indicate that real-world validation, multi-resident operation, robust event recognition, and interpretable alerts remain open areas.

VI. AGESENTINEL: PROPOSED INTEGRATED FRAMEWORK

Based on the identified gap, AgeSentinel proposes a five-stage privacy-first workflow:

1. Sense: Collect ambient sound events together with door and appliance sensor data.
2. Process: Extract useful sound-event information and discard raw audio to reduce privacy exposure.
3. Signature: Learn the resident's normal daily pattern and establish a personalized baseline.
4. Detect: Use machine learning to score deviations from the learned baseline and identify significant changes.
5. Act: Present routines and anomalies on a dashboard and send an alert to family members when a significant change is detected.

The project presentation suggests sound classification using log-mel features with a small convolutional neural network and anomaly detection using an autoencoder or Isolation Forest over event counts. These are presented as possible implementation choices rather than completed experimental results. The system is intended to identify behavioural drift, not to diagnose disease or claim medical detection.

6.1. Expected Outcomes and Evaluation

The expected outcomes stated in the project presentation are: (1) a personal sound signature for each resident, (2) detection of long silence and missed routines, (3) alerts only for significant changes, and (4) a working routine dashboard. The presentation references Wang et al. (2025) as a benchmark, while explicitly stating that the project's own results are still to follow.

Once implemented, evaluation should distinguish event-recognition performance from anomaly-detection performance. Useful measures include sound-event classification accuracy, anomaly precision and recall, false alerts per week, and detection delay. These measures would provide a more meaningful evaluation than reporting a single overall accuracy value.

VII. ADVANTAGES AND LIMITATIONS

The main advantages identified by the project are privacy preservation through the absence of cameras, continuous monitoring, personalization through a resident-specific baseline, relatively low-cost hardware, and visualization of routine trends. These features directly address the privacy, reactive-care, and alert-fatigue problems defined in the project statement.

However, the approach also has limitations. Environmental noise can reduce sound-event recognition quality. The current design assumes a single resident and requires an initial learning period. It is not intended to replace medical diagnosis or dedicated fall detection. Consent, secure handling of event data, and appropriate alert policies are also essential for responsible deployment.

VIII. FUTURE SCOPE

Future research can extend the system to multi-resident homes, larger real-world pilots, improved sound-event robustness, and more interpretable machine-learning decisions. Additional work can investigate sensor fusion, privacy-



preserving on-device processing, adaptive baselines, and methods for reducing false alerts without discarding meaningful behavioural changes. These directions are consistent with the limitations and future-work points identified in the project presentation.

8.1 Privacy, Ethics, and User Acceptance

Privacy is not only a technical requirement but also an adoption requirement for elderly monitoring systems. Recent evidence shows that older adults and caregivers may value the safety benefits of smart-home monitoring while remaining concerned about data collection, data access, misuse, autonomy, and the feeling that the home is becoming a monitored space. A 2024 systematic review of smart-home health technologies reported privacy, cost, technical reliability, and usability as important barriers, while a review of adults aged 50 years and above found that privacy concerns were discussed in most of the included studies. These findings strengthen the AgeSentinel design principle of minimizing sensitive data and avoiding continuous visual surveillance.

8.2 Sensor Architecture and Digital-Twin Design

The supplied Wang et al. study provides a useful implementation reference for privacy-preserving digital twins. Its prototype combines motion, temperature and humidity, light, noise, and low-resolution thermal sensors rather than cameras or microphones. The system uses ZigBee-connected sensor modules, a Raspberry Pi-based data hub, cloud processing, and a database for time-stamped sensor features. The study was deployed in two homes for two months and demonstrated that heterogeneous sensor streams can be converted into a virtual representation of activities and environmental conditions. This supports the broader AgeSentinel concept of combining multiple low-intrusion signals rather than relying on a single sensor.

8.3 Evidence from Activity Recognition and Health Monitoring

The Wang et al. study also demonstrates the value of combining low-level sensing with higher-level activity inference. Its thermal-sensor CNN achieved 95.12% and 99.32% test accuracy for high- and low-resolution adult posture data, respectively, while performance on the elderly posture dataset was 84.10% and 88.20%. Its rule-based activity recognition achieved 73.9% on the adult ADL dataset and 78.2% on the elderly ADL dataset. These results are relevant to AgeSentinel because they show that performance can decrease when a model moves from controlled adult data to elderly real-world data. Therefore, AgeSentinel should report separate results for event recognition and routine-anomaly detection and should validate models in realistic homes rather than relying only on laboratory accuracy.

8.4 Recent Literature on Smart-Home Elderly Care

Recent literature supports the general direction of AgeSentinel while also revealing that the field remains heterogeneous. A 2024 systematic review of smart-home technologies for older adults reported benefits in safety and health monitoring but identified privacy, autonomy, cost, and interface complexity as continuing barriers. Another systematic review published in 2025 found evidence that smart-home technologies can support independence, daily monitoring, functional improvement, emotional support, and caregiver assistance. A 2024 systematic review of aging-in-place technologies identified a broad range of non-mobile environmental and individual-monitoring technologies, indicating that multimodal sensing is becoming an important research direction. Together, these studies suggest that future systems should not be evaluated only by classification accuracy; they should also be evaluated for usability, privacy, false-alert burden, reliability, and sustained real-world adoption.

8.5 Implications for AgeSentinel

The additional literature suggests several refinements to the proposed AgeSentinel framework. First, raw audio should remain outside long-term storage whenever possible, with local feature extraction or event classification preferred. Second, the system should maintain a resident-specific baseline because normal routines differ substantially between



people. Third, sensor fusion should be used to reduce ambiguity; for example, a sound event can be interpreted together with door activity, appliance state, time of day, and recent routine history. Fourth, alerts should include interpretable reasons such as missed breakfast activity, unusually long inactivity, or an abnormal change in the resident's routine. Finally, deployment should include explicit consent, secure communication, access control, data minimization, and a mechanism for caregivers or residents to correct false alarms.

IX. CONCLUSION

This literature survey reviewed privacy-preserving approaches for elderly monitoring and positioned AgeSentinel within that research landscape. Existing approaches demonstrate the value of passive sensing, wearable detection, smart-speaker support, and camera-free monitoring, but the reviewed systems often focus on specific events or provide limited context about an individual's ordinary routine. The proposed AgeSentinel framework addresses this gap by combining ambient sound events with door and appliance sensing, learning a personalized daily signature, and detecting significant deviations while avoiding storage of raw audio.

The central research direction is therefore privacy-first and personalized monitoring rather than surveillance. The approach has clear potential for aging-in-place support, but its effectiveness must be established through prototype evaluation and real-world validation. Noise robustness, multi-resident operation, interpretability, security, consent, and false-alert control should remain key research priorities.

Expanded literature note: The new discussion incorporates evidence from the supplied Wang et al. (2025) paper and recent peer-reviewed literature. Web-researched sources are listed as references [8]–[15]. Claims about AgeSentinel itself remain framed as proposed design or expected outcomes, not completed experimental results.

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