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Posture Estimation System using Quasi-millimeter wave Radar in Indoor Environments

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This study aims to develop a privacy-conscious, non-contact posture estimation system for indoor living environments, focusing on the estimation of human postural activities without relying on visual sensing. In recent years, advances in deep learning have significantly improved the accuracy of camera-based pose estimation techniques, enabling detailed recognition of human postures and motions. However, systems based on continuous image acquisition inevitably raise serious privacy concerns, as they capture visual appearance and personal information. These concerns have become a major obstacle to the practical deployment of camera-based systems in residential spaces, caregiving facilities, and monitoring applications where long-term operation is required. As a result, alternative sensing modalities that can achieve posture estimation while preserving user privacy are increasingly demanded. From this perspective, quasi-millimeter-wave radar operating in the 24 GHz band has attracted attention as a promising sensing technology. Such radar sensors are robust to low-light conditions and occlusion, and they do not acquire visual appearance information. These characteristics make them well suited for privacy-preserving sensing in indoor environments. Nevertheless, radar-based observations are fundamentally limited by low spatial resolution and are highly sensitive to environmental factors such as multipath reflections, noise, and sensor placement. Due to these constraints, stable posture estimation using signals from a single radar sensor is difficult, especially in real-world environments where conditions are not strictly controlled.

Based on this background, this study focuses on posture estimation using multiple quasi-millimeter-wave radar sensors and aims to construct a learning framework that can effectively integrate time-series observations from multiple sensors. The central research challenge addressed in this work is how to jointly model spatial relationships among sensors and temporal transitions of human postures in order to improve estimation robustness under noisy and data-limited conditions. In particular, this study investigates model structures that can simultaneously capture spatial dependency between sensors and temporal dependency associated with posture transitions. The overall framework of this study consists of two major phases: a hardware phase and a software phase.

In the hardware phase, multiple quasi-millimeter-wave radar sensors were deployed in a real indoor environment, and posture-related data were measured and collected. The target postural actions were selected to represent common activities in daily life: Standing Up, Sitting Down, Sleeping, Getting Up, and Falling. These actions were chosen to cover both static and dynamic posture changes that frequently occur in residential and caregiving scenarios. To account for variations in sensor geometry and subject orientation, the relative orientation of the subject with respect to the sensors was varied across four conditions: east, west, south, and north. For each orientation, measurements were repeated ten times, resulting in a diverse dataset that reflects realistic variations in posture, body orientation, and sensing conditions encountered in practical environments.

The radar sensors were configured with a sampling rate of 10 Hz. Each trial consisted of a 10-second time series, corresponding to 100 frames per sample. Using this setup, single-action datasets were constructed, and a total of 1,000 single-action samples were collected. This data collection strategy ensures sufficient temporal resolution to capture posture changes while maintaining consistency across trials. In addition to isolated actions, posture transitions play a crucial role in practical monitoring scenarios, such as daily activity observation and fall detection. To evaluate robustness against posture transitions, two types of sequential datasets were further constructed. The first type consists of paired-action sequences, referred to as *Two-Action Transition Sequences* (2P), in which two different postural actions are concatenated to explicitly model posture changes. The second type consists of long continuous sequences, referred to as *Multi-Action Continuous Sequences* (10P), composed of ten consecutive actions, representing extended activity streams. These datasets enable evaluation not only of classification accuracy for individual actions but also of recognition stability and temporal consistency in continuous time-series data that include posture transitions.

In the software phase, the collected time-series data were subjected to correction and preprocessing to account for sensor characteristics and measurement noise. Based on the processed data, learning models were constructed and evaluated. As a baseline model, a Spatial-Temporal Graph Convolutional Network (ST-GCN) was introduced. ST-GCN is capable of simultaneously learning spatial and temporal dependencies in time-series data by representing the input as a graph structure. In this study, each radar sensor is treated as a node, and the time-series signal obtained from each sensor is used as node features. This representation allows sensor groups to be modeled as graphs, enabling explicit learning of inter-sensor relationships as well as temporal posture transitions. However, in real-world environments, radar signals often fluctuate due to noise, reflections, and environmental changes. Under such conditions, especially when the amount of training data is limited, the estimation of inter-sensor relationships becomes unstable. To address this issue, this study first investigated an extension of

ST-GCN that incorporates a general spatial attention mechanism, referred to as ST-GCN/SA (Self-Attention). The goal of this approach is to adaptively weight sensor relationships based on learned attention scores. Nevertheless, self-attention relies heavily on global correlations across the entire dataset. As a result, under noisy conditions or limited data scenarios, the estimation of sensor relationships does not sufficiently converge, and the expected improvements in performance and stability are not fully achieved. Experimental results confirmed that ST-GCN/SA provides moderate improvements under intermediate data conditions but suffers from instability when training data are further reduced. To overcome these limitations, this study proposes an Anchor-Guided ST-GCN (ST-GCN/AG), which incorporates an anchor-guided mechanism based on node reliability. In the proposed method, node reliability is estimated at each frame, reflecting the stability and informativeness of sensor signals. Nodes with high reliability are selected as anchors, and spatial relationships among sensors are actively guided with respect to these anchors. By using anchors as reference points, the proposed method reduces uncertainty in spatial relationship estimation that cannot be sufficiently suppressed by self-attention alone. This design aims to stabilize learning and improve generalization performance, particularly under noisy and data-limited conditions.

To evaluate the effectiveness of the proposed approach, experiments were conducted using a fixed five-layer neural network architecture. The training data ratio was varied among 50%, 33%, and 25% to analyze the impact of limited data availability on performance. Classification accuracy was evaluated for single-action datasets as well as for posture transition datasets (2P and 10P). The experimental results show that ST-GCN/AG consistently outperforms both the baseline ST-GCN and the self-attention-based ST-GCN/SA across all training data conditions. Notably, under the limited data conditions of 33% and 25%, the performance degradation of ST-GCN/AG remains relatively small compared to the other methods. High stability is maintained for both isolated actions and posture transition sequences. In contrast, ST-GCN/SA demonstrates improved performance only under intermediate data conditions, while its classification accuracy for single actions decreases when the training data ratio is reduced further. These results indicate that self-attention alone is insufficient to ensure stable learning under severe data constraints. Overall, the experimental findings demonstrate that the proposed anchor-guided mechanism effectively suppresses uncertainty in inter-sensor relationship estimation and reduces dependency on training data volume. From these results, it is concluded that ST-GCN/AG offers a robust and effective solution for sensor-based posture estimation using quasi-millimeter-wave radar. The proposed method enables stable learning even under limited data conditions, which are common in real-world sensing scenarios. The contributions of this study are expected to support the development of privacy-preserving indoor monitoring systems, including applications in home environments and caregiving sup protection is essential.