Efficient Indoor Human Sensing and Continuous Tracking

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The proliferation of indoor location-based systems (LBSs) has been notably accelerated by the successful integration of Internet of Things technologies, advancements in wireless network technology, and the unprecedented impact of the COVID-19 pandemic. Indoor LBS encompass a spectrum of hardware and software technologies, rendering them adaptable and applicable across diverse industrial sectors.

While hardware technologies based on electromagnetic waves, such as Wi-Fi or Bluetooth, dominate the landscape, they predominantly cater to device-based applications, thereby potentially marginalizing the elderly demographic. Indeed, this demographic cohort exhibits a reduced inclination towards mobile device utilization and diminished adeptness in sustained daily engagement with such technology. Furthermore, these technologies primarily serve sales and marketing sectors, focusing on functions like customer preference tracking, inventory management, and supply chain optimization. Conversely, device-free localization assumes a pivotal role in facilitating ambient-assisted living within intelligent infrastructures, encompassing functionalities such as intrusion detection, fall detection, and occupancy monitoring to promote energy efficiency and illumination management. Furthermore, certain applications such as fall detection and emergency response for elderly or vulnerable individuals, navigation guidance for the visually impaired, and security and access control necessitate high accuracy. These specific fields constitute the focus of our investigation.

This thesis endeavors to implement a proficient device-free indoor location-based system, with focus on accuracy and resource efficiency. The main contributions are:

- Design and characterization of a novel front-end based on slope modulation for long-range load-mode capacitive sensors that rejects sensor drift and increases sensing range and stability.
- Investigation into advanced neural network architectures conducive to continuous indoor human tracking.

- Setting up a neural network optimization methodology, integrating multi-step knowledge distillation and neural architecture search techniques for continuous indoor human tracking.

Capacitive sensors, falling within the electric field sensing domain, present themselves as promising candidates for the implementation of an efficient device-free localization system. This is due to their attributes of being cost effective, energy efficient, easy to deploy, privacy conscious and unobtrusive. Of the capacitive sensor operating modes, the load mode allows the use of a single sensing plate, making the system architecture lighter and more manageable. Nevertheless, over long distances (e.g., more than 10 times the plate diameter), the measurement field becomes highly susceptible to environmental noise, thereby compromising stability and accuracy. Electric charge variations in their environment cause variable electric fields that can induce a slow, quasi-constant drift current that can alter sensor readings even when their capacitance does not change. To address this challenge, we introduce a novel slope modulation interface. This interface functions on the galvanostatic charge-discharge principle of plate capacitance, akin to period modulation interfaces. However, it utilizes distinct measurements and employs data post-processing techniques to mitigate environmental noise, thereby extending the monitoring range and improving measurement stability. The technique uses a constant current generator driven by a square wave to charge and discharge the transducer plate with a fixed period. Subsequently, the average slope of two consecutive charge-discharge ramps of the triangular waveform of the plate voltage is measured to determine both the transducer capacitance and reject drift (low frequency) noise.

To evaluate the effectiveness of the method, is compared and examined the slope modulator front-end against the constant-current and RC period modulator analytically. Following this, the circuit is simulated and results validated using implementations of the front-ends and a noise generator. The findings are highly encouraging; specifically, the slope modulator exhibits an inversely proportional noise attenuation relative to frequency, rejecting mostly the range of very low frequencies characteristic of quasi-constant drifts. Inversely, the period modulators exhibit a flattening behavior in noise rejection below a specific frequency, where constant drift currents become dominant. Additionally, the slope modulator achieves noise rejection while preserving high sensitivity, detecting people at distances up to 230 cm. Comparatively, period modulator interfaces can sense people up to 130 cm beyond which the noise increases significantly, surpassing signal levels around 250 cm.

In LBS context, sensor measurements are typically post-processed with general techniques such as outlier removal, frequency filtering and averaging, and then using specialized processing often based on machine learning techniques. The latter are increasingly used because their ability to process effectively noisy and non-linear responses, while also offering scalability and robustness. Tariq, Lazarescu, and Lavagno [1] employ digital filters in conjunction with neural neural networks (NNs) to mitigate noise and extract position and motion dynamics. Their design space exploration encompasses various popular NN architectures, including multilayer perceptron, 1D convolutional neural network (1DCNN), and long short-term memory. Their findings indicate that 1DCNN achieves superior accuracy, whereas long short-term memory excels in capturing natural movement dynamics.

However, the pooling operations employed in convolutional neural networks is acknowledged in literature that can lead to the loss of significant relational information, while the recursive nature of long short-term memory networks may introduce time-consuming complexities. In light of these considerations, we opt to investigate two enhanced network architectures, namely, the capsule network and temporal convolutional network, both of which avoid the use of pooling and recursion. Through hyperparameter optimization, the capsule network network achieves comparable accuracy to top-performing 1DCNN, utilizing only 78.7 % of the computational resources, while the temporal convolutional network, albeit with a slight decrease of accuracy, uses merely 26.7 % of the 1DCNN computational resources.

Among the most sought-after characteristics of device-free localization systems are low cost, low power consumption, ease of deployment and management, and unobtrusiveness. However, their effectiveness may often require resources beyond what can be offered by the typically restricted IoT devices. In this regard, we propose a novel method based on KD and neural architecture search aimed at optimizing the resource requirements of NN models. The KD technique involves the transfer of knowledge from a large NN (referred to as the teacher) to a smaller NN (referred to as the student). While this technique has been extensively studied in the context of classification problems, there is a paucity of research addressing its application to regression tasks and specifically to indoor continuous human tracking. The neural architecture search optimizes NN and KD parameters for teachers and students.

To evaluate the efficacy of the optimization method, we utilize the enhanced models (temporal convolutional network and capsule network), along with several LBSs employing diverse sensing principles and data formats, each subject to varying levels of noise, including capacitive, infrared radiation, and radar-based systems. We start with the capacitive environment, considered as the most complex scenario, and iterate through multiple steps, experimenting with different teacher-student configurations in each step of KD.

The results indicate that employing a teacher of the same type as the student in the initial KD stage, followed by a teacher of a different type in the subsequent stage, offers varied perspectives on the features, thereby aiding the student in enhancing accuracy and generalizability. Subsequently, the effectiveness of the optimal workflow is validated through distinct experiments conducted across the capacitive environment and other LBSs. These experiments, conducted under similar yet distinct conditions on different days, confirm the robustness of the proposed methodology.

The experimental outcomes demonstrate that the proposed method frequently reduces the size of NNs significantly, while concurrently improving their accuracy and generalizability in comparison to both state-of-the-art models and the original teacher NNs. Notably, NNs optimized via two-stage KD process tend to demonstrate enhanced generalization, showcasing an average mean squared error improvement of 9.57 % for capacitive,14.4 % for infrared, and 4.86 % for radar LBS. This improvement is accompanied by an average reduction in resource utilization of 59.9 %, 56.4 %, and 61.28 % respectively. These findings underscore the effectiveness of the mixed two-step KD approach implemented within the proposed framework.