Machine Learning Techniques for Device Free Indoor Person Tracking

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Low-cost, low-maintenance, and accurate indoor localization of persons is important for several applications, such as health care, safety monitoring, and resource usage optimization. For example, assisted living applications can lower assistance costs and improve quality of life, which are increasingly important as the projected ratio between working-age and elderly people keeps on increasing.

Several smart home application can also benefit from indoor localization. For instance, room occupancy information, alongside other factors, can help reducing energy consumption by controlling the ambient temperature, lighting, and water consumption. Health care applications, such as those monitoring the human activity for extended periods, can detect behavioral changes (e.g., gait changes), which can help recognizing the early onset of diseases, e.g., Parkinson's. Moreover, presence monitoring systems can also detect unauthorized intrusions, e.g., through the house windows, which can be a sign of burglary attempt.

Many localization techniques have been researched over the years. However, no *silver bullet* solution emerged mainly because of the complexity of person localization in indoor environments. A large variety of solutions, such as ultra-wide band or Wi-Fi techniques, assume that the person carries a device to be visible to the localization system. However, always wearing or carrying a device is not realistic for all indoor conditions and activities, reducing the acceptance of such systems. Other solutions are privacy-invasive, such as image-based systems, or may require significant infrastructure changes, such as changing floors. Systems based on infrared (IR) radiation, e.g., using passive infrared detectors (PIRs) or thermopiles, can be significantly affected by various environmental heat sources.

Capacitive sensors provide unique advantages, such as simple installation, privacy, and low cost. The capacitive sensors can be used in transmit mode, shunt mode, or load mode. The transmit and shunt modes use two electrodes: the oscillator electrode and the ground electrode. The capacitive sensors operating in load mode use a single oscillator electrode, while the human body and the environment act as ground. While two-plate capacitive sensors operating in transmit and shunt modes can be more accurate, single-plate sensors working in load mode are more attractive because of their simpler installation.

Capacitive sensors in load mode have been used to localize and identify persons indoors, but their sensitivity decreases steeply with the distance. Long-range sensing, at distances of 10 to 15 times the plate diagonal, is highly susceptible to several environmental factors, such as electromagnetic and electrostatic noise, humidity, or temperature. Hence, the whole sensor data processing chain is crucial to achieving good localization accuracy and stability in variable environmental conditions. In this work, we investigate how machine learning techniques can help mitigating the effects of environmental electromagnetic noise and provide accurate person localization.

Human tracking in indoor environments can be divided in two main groups. The first one classifies the position of a person in a set of predefined locations. Such information can be useful particularly in smart homes to control energy consumption, to analyze the time spent at various locations, and so on. The second one, more complex, continuously tracks the position of a person inside a home. Such information can be useful for assisted living applications, for example, to analyze the gait and behavior deviations which can indicate possible health deterioration.

To determine the suitability of load-mode capacitive sensors for person localization, we designed a $3\,\mathrm{m} \times 3\,\mathrm{m}$ *virtual* room divided in 16 equidistant locations on a 60 cm grid. In the middle of each wall of the room, we installed a long-range capacitive sensor, at a height of 115 cm from the floor, four sensors in total. We collected the experimental data through an extensive campaign of experiments, labeled them with the person's position within the room, and then used them to train and test a large set of machine learning (ML) classifiers to infer the location of the person in the room as follows:

1. Collection of time-stamped measurements from the four capacitive sensors in the room labeled with the actual position of the person;

2. Processing the sensor data, both for conditioning and for person localization using different ML classification algorithms from the Weka collection;

3. Analyzing the performance of the ML classification algorithms in terms of localization accuracy, average distance error, precision, and recall;

4. Analyzing the effect of the training data size on the localization performance of the algorithms.

We analyze the performance of most ML classification algorithms from the Weka collection for testing machine learning algorithms, with a particular focus on the best performing: k-NN, Bayes Net, Support Vector Machine (SVM), Random Forest, as well as boosting techniques, such as LogitBoost and AdaBoostM1. The best algorithms can provide good localization results even with limited sensor data preprocessing for noise filtering, and we also analyze the effects of the size of the training data on the localization results for different algorithms.

The ML classifiers achieved 93 % accuracy. Random Forest performed the best overall, while AdaBoostM1 used on top of the C4.5 required much less time for inference at the cost of a small accuracy loss.

After exploring the effectiveness of capacitive sensors for classifying the location of a person indoors, we addressed the more complex problem of the inference of the trajectory of a person moving freely inside the same experimental room, using a time- and location X/Y-labeled sequence of continuous data instead of unordered sets of discrete locations. For this, we increased the sampling rate of the capacitive sensors to 3 Hz to better capture the free movement of a person. To record the ground truth of the person's movements and label the data from four capacitive sensors, we used an accurate ultrasound reference system from Marvelmind, which required the person to carry a tag during the experiments.

With the collected data, we explored how advanced data processing can improve the capacitive sensor accuracy and reconstruct the trajectory of a person's movements. As before, we used relatively simple capacitive sensors, which are known to be very susceptible to environmental noise, to better compare the effectiveness of the various data processing chains on the overall accuracy.

We used several signal filtering combinations for preprocessing and then we optimized different neural network (NN) types e.g., (1) autoregressive feedforward, (2) 1D convolutional NN (CNN), and (3) long short-term memory (LSTM), through design space exploration (DSE). For NN training, validation, and testing, we used capacitive sensor data collected while a person moved freely in the $3\,\mathrm{m} \times 3\,\mathrm{m}$ experimental room, and we compared the inferred position and trajectory with the reference location acquired using the reference Marvelmind ultrasound localization system.

we report in the thesis the main results on trajectory reconstruction based on data collected from capacitive sensors, which are:

- neural network-based signal processing techniques for indoor person localization and tracking using small capacitive sensors operating in load mode at long ranges (10 to 15 times their plate diagonal);
- noise attenuation using various kinds of digital filters and neural networks for location and trajectory inference;
- comparative analysis of NN-based location and movement dynamics inference accuracy from noisy sensor data.

We achieved a 25.1 cm localization root-mean-square error (RMSE) using the capacitive sensors, which is very good for such small, noisy, low-power, low-cost, privacy-aware sensors.

We also evaluated the effectiveness of my methods to reconstruct human trajectory using similar NNs but based on experimental data from $4\,\text{pixels} \times 4\,\text{pixels}$ thermopile infrared sensor. This analysis has two main goals: first to see the effectiveness of the ML methods developed in this thesis for other types of sensors, and second because the capacitive and thermopile sensors have several complementary advantages. In this case, we achieved a much lower localization RMSE of 9.6 cm.