# Capacitive Sensing Based On-board Hand Gesture Recognition with TinyML

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## ABSTRACT

Although hand gesture recognition has been widely explored with sensing modalities like IMU, electromyography and camera, it is still a challenge of those modalities to provide a compact, power-efficient on-board inferencing solution. In this work, we present a capacitive-sensing wristband surrounded by four single-end electrodes for on-board hand gesture recognition. By deploying a single convolutional hidden layer as the classifier at the sensing edge, the wristband can recognize seven hand gestures from a single user with an accuracy of 96.4%.

## CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Gestural input**.

## KEYWORDS

human-computer interaction, capacitive sensing, hand gesture recognition, edge computing, TinyML

**ACM Reference Format:**
Sizhen Bian and Paul Lukowicz. 2021. Capacitive Sensing Based On-board Hand Gesture Recognition with TinyML. In *Adjunct Proceedings of the 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2021 ACM International Symposium on Wearable Computers (UbiComp-ISWC '21 Adjunct), September 21–26, 2021, Virtual, USA.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3460418.3479287

## 1 INTRODUCTION

Hand gesture recognition is one of the most widely explored interaction techniques for user intention interpreting. A power-efficient, on-board hand gesture recognition solution will enable a broad range of long-term applications, such as sign language recognition for deaf and speech-impaired community, device control for assistive input, games and virtual reality, etc. A typical example is that from 2021, Apple Watch supports a motion-controlled cursor for an assistive touch action, which relies on the built-in inertial sensors and accomplishes the primary "next" and "confirm" functionality. Besides inertial sensors, electromyography(EMG) and camera are the most widely explored sensing modalities for hand gesture recognition. EMG captures the electrical signals of skeletal muscles during a particular action with multiple skin-touched surface electrodes. However, the limitations like contact-demand, computing delay remain a challenge for EMG-based real-life applications. The vision-based approach also faces limitations like heavy computing load, lighting variation, occlusion affection, privacy issues, etc.


*UbiComp-ISWC '21 Adjunct, September 21–26, 2021, Virtual, USA*

ACM ISBN 978-1-4503-8461-2/21/09.
https://doi.org/10.1145/3460418.3479287

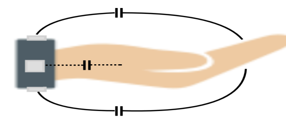


**Figure 1: Capacitance variation around the wrist**

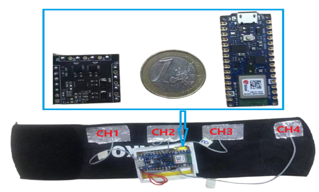



**Figure 2: Wrist-worn prototype with only four capacitive sensing electrodes working in single-end mode**

Although recent development on the far edge AI has enabled the deep neural network models to be deployed on weak devices by compressing the models with techniques like pruning and quantization, the on-board inference performance is still a challenge when balancing recognition accuracy, computation delay, and power consumption. To achieve the best in all those scores for hand gesture recognition, a fundamental approach is to find a more effective sensing modality delivering less data but with sufficient gesture information. Capacitive sensing [1, 2] has been verified with great effectiveness for activity recognition benefitting from the straightforward signal pattern of body motion. Here we explored the on-board hand gesture recognition with capacitive sensing. With a simple prototype, capacitive based design showed remarkable on-board recognition result with high accuracy, short inference delay, and very low power consumption. Capacitive based hand gesture recognition is not novel, a few previous works on capacitive-based hand gesture recognition [3, 4] have presented impressive off-line result. However, the previous supposed methods rely on luxury electrode pairs working in differential mode to sense the muscle deformation, which enables more gestures to be recognized, but results in the deployment complexity, since more electrodes will bring the electrode position into consideration (otherwise the accuracy drops greatly). Besides that, the inference was carried out

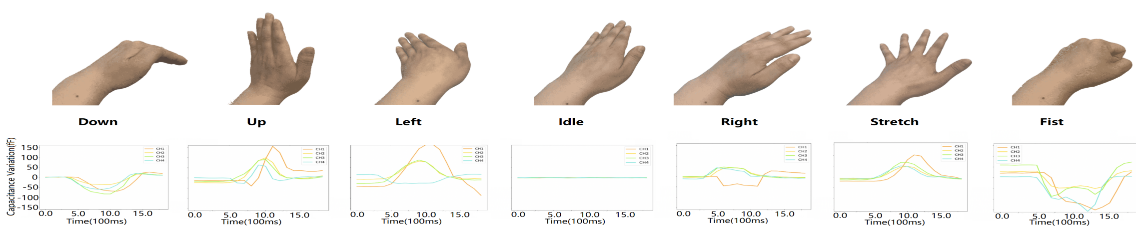
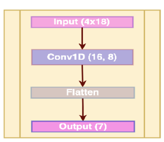



**Figure 3: Seven hand gestures with the capacitive variation signals**




| | DOWN | FIST | IDLE | LEFT | RIGHT | STRETCH | UP |
|---|---|---|---|---|---|---|---|
| DOWN | 95.8 % | 4.2 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| FIST | 11.1 % | 88.9 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| IDLE | 0 % | 0 % | 96.4 % | 0 % | 0 % | 0 % | 3.6 % |
| LEFT | 0 % | 0 % | 0 % | 100 % | 0 % | 0 % | 0 % |
| RIGHT | 0 % | 0 % | 0 % | 0 % | 100 % | 0 % | 0 % |
| STRETCH | 0 % | 0 % | 0 % | 0 % | 0 % | 95.2 % | 4.8 % |
| UP | 0 % | 0 % | 0 % | 0 % | 0 % | 5.9 % | 94.1 % |
| F1 SCORE | 0.96 | 0.89 | 0.98 | 1.00 | 1.00 | 0.95 | 0.91 |

**Figure 4: On-board neural network architecture and the confusion matrix of hand gesture recognition with accuracy of 96.4%**

off-line by transmitting the sensor data to a stronger computing platform with bluetooth (which is the main power consumption source). As far as the authors know, there is no work describing the hand gesture recognition solution with the inference at the sensing edge locally.

## 2 PROPOSED SYSTEM AND PRELIMINARY RESULT

This work presents a preliminary result on an on-board-inference hand gesture recognition system with capacitive sensing. The physical background is that the hand actions will change the capacitance between the wrist-worn electrodes and surrounding(mainly the hand-to-electrode distance, in a level of sub-pF), as Figure 1 depicts. By deploying four independent electrodes around the wrist, different orientations of hand gestures could produce varied patterns of capacitive signals. The capacitive sensing module is based on FDC2214 from TI, which employs an L-C tank as a sensor. The working principle is that the change in capacitance of the L-C tank can be observed as a shift in the resonant frequency. The device outputs a digital value that is proportional to frequency, which can be converted to an equivalent capacitance. The signal processing module is the Arduino nano sense platform with a 64 MHz Cortex-M4 chip, which owns an FPU, 1 MB flash, 256 KB RAM. The chip is suitable for running compressed neural network models without the need of quantization thanks to the FPU. Figure 2 and 3 depict the wrist-worn prototype and the instances of four-channel capacitive signals with seven hand gestures.

To save the computing load, we sampled the four-channel signals with 10 Hz. We randomly collected around 400 instances of each gesture for the training data set and around 100 instances of each gesture for testing from a single user. Each instance has a time window of 1.8s. Benefitting from the obvious capacitance variation patterns of different gestures, we used a single 1D convolutional layer with 16 neurons and kernel size of 8 as the classifier, followed by a flatten layer, and got an accuracy of 96.4 %, as Figure 4 depicts. After converting and interpreting the model with TensorFlow lite, we got an on-board model with a size of 29.6 Kbytes(float32 mode without quantization). The on-board inference time is around 12 ms. The consumed power for the on-board gesture recognition is 26.4mW (8mA x 3.3V) without optimizing(currently we are giving full speed and full current to the sensing module, the power can be significantly optimised by supplying each channel with a threshold current while keeping the sensing sensitivity).

## 3 FUTURE WORK

In this work, we first designed an wrist-worn prototype to recognize seven hand gestures by perceiving the capacitance variation during the hand actions from four independent electrodes. Secondly, we used a single convolutional layer model to recognize the gestures and got an impressive result. We finally deployed the model on the board, enabled the prototype to perform on-board hand gesture recognition tasks. The future work will be firstly collecting more data from multiple users to verify the generalization of the on-board sensing modality. Secondly, the power efficiency will be focused on to further decrease the working current to the level of $uA$. A few practical use cases (like smart home control, augmented reality interaction) will be carried out to verify the long-term reliability of the prototype in real environment.

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