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uWave: Accelerometer-based personalized gesture recognition and its applications

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ABSTRACT

The proliferation of accelerometers on consumer electronics has brought an opportunity for interaction based on gestures. We present uWave, an efficient recognition algorithm for such interaction using a single three-axis accelerometer. uWave requires a single training sample for each gesture pattern and allows users to employ personalized gestures. We evaluate uWave using a large gesture library with over 4000 samples for eight gesture patterns collected from eight users over one month. uWave achieves 98.6% accuracy, competitive with statistical methods that require significantly more training samples. We also present applications of uWave in gesture-based user authentication and interaction with 3D mobile user interfaces. In particular, we report a series of user studies that evaluates the feasibility and usability of lightweight user authentication. Our evaluation shows both the strength and limitations of gesture-based user authentication.

1. Introduction

Gestures[1] have recently become attractive for spontaneous interaction with consumer electronics and mobile devices in the context of pervasive computing [1–3]. However, there are multiple technical challenges to gesture-based interaction. First, unlike many pattern recognition problems, e.g. speech recognition, gesture recognition lacks a standardized or widely accepted "vocabulary". It is often desirable and necessary for users to create their own gestures, or personalized gestures. With personalized gestures, it is difficult to collect a large set of training samples necessary for established statistical methods, e.g., Hidden Markov Model (HMM) [4–6]. Secondly, spontaneous interaction requires immediate engagement, i.e., the overhead of setting up the recognition instrumentation should be minimal. More importantly, the targeted platforms for personalized gesture recognition are usually highly constrained in cost and system resources, including battery, computing power, and interface hardware, e.g. buttons. As a result, computer vision [1,2] or "glove" [3] based solutions are unsuitable.

In this work, we present uWave to address these challenges and focus on gestures without regard to finger movement, such as sign languages. Our goal is to support efficient personalized gesture recognition on a wide range of devices, in particular, on resource-constrained systems. Unlike statistical methods [4], uWave only requires a single training sample to start; unlike computer vision-based methods [5], uWave only employs a three-axis accelerometer that has already appeared in numerous consumer electronics, e.g. Nintendo Wii remote, and mobile device, e.g. Apple iPhone. uWave matches the accelerometer readings for an unknown gesture with those for a vocabulary of known gestures, or *templates*, based on dynamic time warping (DTW) [6]. uWave is efficient and thus amenable to implementation on resource-constrained platforms. We

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[1] We use "gestures" to refer to free-space hand movements that physically manipulate the interaction device. Such movements include not only gestures as we commonly know; but also any physical manipulations like shaking and tapping of the device.

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have implemented multiple prototypes of uWave on various platforms, including Smartphones, microcontroller, and the Nintendo Wii remote hardware [7]. Our measurement shows that uWave recognizes a gesture from an eight-gesture vocabulary in 2 ms on a modern laptop, 4 ms on a Pocket PC, and 300 ms on a 16-bit microcontroller, without any complicated optimization.

We evaluate uWave with a gesture vocabulary identified by a VTT research [4] for which we have collected a library of 4480 gestures for eight gesture patterns from eight participants over multiple weeks. The evaluation shows that uWave achieves accuracy of 98.6% and 93.5% with and without template adaptation, respectively, for user-dependent gesture recognition. The accuracy is the best for accelerometer-based user-dependent gesture recognition. Moreover, our evaluation data set is also the largest and most extensive in published studies, to the best of our knowledge.

We also evaluate the application of uWave in user authentication through a series of comprehensive user studies involving 25 participants over one month. Our user studies address two types of user authentication: non-critical authentication for a user to retrieve privacy-insensitive data and critical authentication for protection of privacy-sensitive data. For non-critical authentication, we demonstrate that uWave achieves average 98% accuracy with simple gesture selection constraints; a follow-up survey shows that the usability of uWave for non-critical authentication is comparable to the use of textual ID-based authentication. For critical authentication, we find 3% equal rate of false negatives, i.e. rejecting authentic users' gestures, and false positives, i.e. accepting attackers' gestures, or *equal error rate*, can be achieved without visual disclosure, meaning the attacker does not see the owner's password gesture performance. Visual disclosure increases the equal error rate to 10%. Therefore gesture-based authentication can be used only when strict security is either not necessary or can be achieved through combination of gesture-based authentication and traditional methods. Our evaluation highlights the need to conceal the gesture performance. Our analysis also shows the potential to achieve a lower equal error rate through recognizers that adapts to the users.

In summary, we make the following contributions.

- We present uWave, an efficient gesture recognition method based on a single accelerometer using dynamic time warping (DTW). uWave requires a single training sample per vocabulary gesture.
- We show that there are considerable variations in gestures collected over a long time and in gestures collected from multiple users; we highlight the importance of adaptive and user-dependent recognition.
- We report an extensive evaluation of uWave with over 4000 gesture samples of eight gesture patterns collected from eight users over multiple weeks for a predefined vocabulary of eight gesture patterns.
- We present two applications of uWave: gesture-based user authentication and gesture-based manipulation of three-dimensional user interfaces on mobile phones. The use of uWave in user authentication is extensively evaluated through a series of user studies.

The strength of uWave in user-dependent gesture recognition makes it ideal for personalized gesture-based interaction. With uWave, users can create simple personal gestures for frequent interaction. Its simplicity, efficiency, and minimal hardware requirement of a single accelerometer make uWave have the potential to enable personalized gesture-based interaction with a broad range of devices.

The rest of the paper is organized as follows. We discuss related work in Section 2 and then present the technical details of uWave in Section 3. We next describe a prototype implementation of uWave using the Wii remote in Section 4. We report an evaluation of uWave through a large database for a predefined gesture vocabulary of eight simple gestures in Section 5. We present the application of uWave to interaction with mobile phones and gesture-based user authentication in Sections 6 and 7 respectively. We discuss the limitations of uWave and acceleration-based gesture recognition in general in Section 8 and conclude in Section 9.

2. Related work

2.1. Gesture recognition

Gesture recognition has been extensively investigated [1,2]. The majority of the past work has focused on detecting the contour of hand movement. Computer vision techniques in different forms have been extensively explored in this direction [5]. As a recent example, the Wii remote has a "camera" (IR sensor) inside the remote and detects motion by tracking the relative movement of IR transmitters mounted on the display. It basically translates a "gesture" into "handwriting", lending itself to a rich set of handwriting recognition techniques. Vision-based methods, however, are fundamentally limited by their hardware requirements (i.e. cameras or transmitters) and high computation load. Similarly, "smart glove" based solutions [3,8,9] can recognize very fine gestures, e.g., the finger movement and conformation but require the user to wear a glove tagged with multiple sensors to capture finger and hand motions in fine granularity. As a result, they are unfit for spontaneous interaction due to the high overhead of engagement.

As ultra low-power low-cost accelerometers appear on consumer electronics and mobile devices, many have recently investigated gesture recognition based on the time series of acceleration, often with additional information from a gyroscope or compass. Signal processing and ad hoc recognition methods were explored in [10,11]. LiveMove Pro [12] from Ailive provides a gesture recognition library based on the accelerometer in the Wii remote. Unlike uWave, LiveMove Pro targets user-independent gesture recognition with a predefined gesture vocabulary and requires 5 to 10 training samples for each