Variability in foot-worn sensor placement for activity recognition

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Abstract

On-shoe acceleration and orientation sensors have revealed as a potentially powerful means for capturing aspects of human gait. The placement of sensors however has been done intuitively and mostly without quantitative evaluation of sensor positioning. Based on recorded signals of the five placement options sole, heel, toe-cap, instep and ankle we built SVM classifiers using orientation-based features and evaluate their performance on three activity classes level walking, going upstairs and going downstairs. Finally we present an approach to a placement-invariant classification model and discuss the benefit for a bipedal sensing setup.

Keywords. *Sensor Placement, Gait Recognition, Activity Recognition*

1. Introduction

Using wireless on-shoe sensor systems for human gait monitoring is an often practiced approach in wearable computing systems. The applications range from low-cost, commercial pedometers to infrastructure-less positioning and location tracking [1] [2].

Especially in the medical domain a lot of research has focused on capturing characteristics of gait-dysfunctional patients for clinical locomotion analysis. With the GaitShoe project Bamberg et al. [3] developed a system that strives to be able to fully capture a foot's motion using accelerometers, gyroscopes as well as FSR (force sensitive resistors) and bend sensors. The approach suits well for medial gait diagnosis measuring gait kinematics and kinetics. However for recognizing simple modes of locomotion the mounting of the GaitShoe parts consisting of insoles and adapters is time intense and the shape restricts the use within a variety of shoes. A less costly solution for medical locomotion analysis based on the foot-to-ground angle was proposed in [4]. A 2-axis accelerometer and one gyroscope mounted at the fifth metatarsal were used to capture acceleration and rotation updates in the bodies sagittal plane. Based on these features the ground inclination and foot angle were determined in stance and stride phase of a walk cycle. But due to the sensor's axis constraints the mounting position is limited to a single XY-plane and therefore the algorithmic robustness with respect to placement variability was not evaluated further.

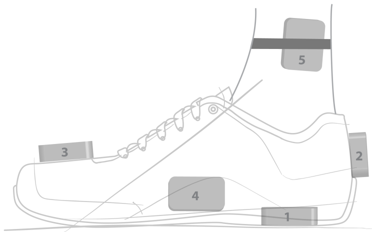

Figure 1. Sketch of sensor mounting options: sole(1), heel(2), toe-cap(3), instep(4) and ankle(5).

In contrary sourceless inertial measurement units (IMU) use accelerometers, gyroscopes and additional magnetometer information to determine absolute orientation in the world coordinate frame. Using global orientation-based features from sensors attached to rigid objects ensures insensitivity to motion related displacement and permits capturing signal characteristics independent of the initial mounting position and orientation. Especially in foot-worn activity recognition systems this helps developing stick-on solutions allowing the user to reattach sensors while switching shoes. Due to a limited choice of mounting on various shoe types the position and orientation may vary strongly requiring a generalizable approach for robust classification.

2. Methodology

2.1. Modeling placement invariance

For studying the variability of foot-mounted sensors we defined a 10 min round trip beginning with a ground level walk over several floors connected by numerous return stair segments. The test subject was a 26-year old male wearing a pair of Crocs shoes. On each shoe five Intersense Wireless Inertia Cube 3 sensors were used for data recording (see

Table 1. 10-fold cross validation accuracies of each sensor's dataset (diagonal) and the performance of the trained models when tested against each other.

	Test set				
Training set	Sole	Heel	Toe-cap	Instep	Ankle
Sole(1)	*99.9*	90.5	76.0	86.3	61.7
Heel(2)	97.3	*99.6*	94.0	89.2	61.7
Toe Tip(3)	91.6	90.2	*99.6*	89.1	61.7
Instep(4)	94.6	94.2	92.6	*99.6*	61.7
Ankle(5)	61.7	61.7	61.7	61.7	*88.1*

Figure 1). The first sensor was embedded in the shoe sole. The heel, instep and toe-cap sensors were attached to the shoe surface with respect to an unaffected gait. The fifth sensor was placed on the lower leg above the ankle. All sensors are powered by 9 volt batteries that were attached to the shoe's upper. The complete dataset of three runs consists of 36000 samples of five Euler orientation triplets recorded simultaneously at 20Hz with two wireless USB receivers connected to a laptop.

With a sensor's orientation initially axis-aligned to the world coordinate frame the characteristics of a gait signal incorporating a stance and stride phase is best captured by the Euler pitch component that gives the angle of inclination in the foot's sagittal plane. Using matrix notation the sensor orientation offset in initial resting phase R_o and during the trail $R_{(t)}$ can be determined. From that we can compute the relative rotation leading to a sensor orientation. For computing the unknown transformation matrix R_i we use the following equation:

$$R_{(t)} = R_i * R_o \longrightarrow R_i = R_{(t)}/R_o = R_{(t)} * R_o^{-1}$$

2.2. Results

For classification, the synchronous data of all sensor were labeled manually according to the three activity classes level walking, going upstairs and going downstairs. The ground truth was established by visual inspection of the sole signal. Step-wise feature extraction over the quantized signal in time domain is done using a 25-sample sliding window at the data recorded at 20Hz. All single-foot model accuracies on the the classes level walking, going upstairs and downstairs are significantly over 90% (see Table 1).

The heel model has a 99.6% accuracy in 10-fold cross validation and shows a average of 95.0% tested against orientation signals 1-4. As expected, the ankle sensor has limited potential for classifying locomotion characteristics. The models cross validation results with an accuracy of 88.1% fall off compared to the other signals and only reflects the 62.7% base line of identifying all samples as level walking.

These exceptional robust results of all sensor options except the ankle entitles us to further investigate on sensor placement invariance for developing a bipedal activity recognition unit. In such a setup we can use the correlation of two sensor signals to identify gait characteristics. Instead of computing only three gait classes we can extend the basic activity set for example to left and right turnings and lateral movements.

Even higher-level activities can be deduced from foot characteristics. For example in postures like lying, sitting and standing we find varying orientation and relation depending on the user and his activity context. Relaxing in a chair with legs outstretched results in a different feet position than sitting on a desk writing a note with the body usually leaned forward. Recognition can be achieved by analyzing variations in the two-foot sensor signals. During a long, repetitive walk cycle these signals are phase-shifted but similar in frequency and envelope characteristics. The signals of non-walking activities on the contrary may yield other relational patterns.

3. Conclusion

Although the insole option is considered to be most comfortable, the heel and toe-tip seem to be the most compelling ones for developing a foot-based activity recognition unit considering requirements like easy mounting and unobtrusiveness. With the 3-class activity set of level walking, going upstairs and going downstairs the trained SVM models deliver high accuracies of over 99.0% for sole, heel, toe-cap and instep sensor placement options. Our algorithm for placement invariance guarantees robustness for the classification of arbitrarily mounted IMUs.

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