Correcting Smartphone Orientation for Accelerometer-Based Analysis

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***Abstract*—A method was developed for rotating a Smartphone accelerometer coordinate system from an offset to a predetermined three-dimensional position to improve accelerometer-based activity identification. A quaternion-based rotation matrix was constructed from an axis-angle pair, produced via algebraic manipulations of the gravity acceleration components in the device's body-fixed frame of reference with the desired position of the vector. The rotation matrix is constructed during quiet standing and then applied to all subsequent accelerometer readings thereafter, transforming their values in this new fixed frame. This method provides a consistent accelerometer orientation between people, thereby reducing Smartphone orientation variability that can adversely affect activity classification algorithms.**

Keywords—accelerometer, quaterion, rotation, calibration, orientation.

I. Introduction

A Wearable Mobility Monitoring System (WMMS) utilizes wearable sensors to predict static and dynamic movements and user activities [1]. One WMMS implementation uses Smartphone tri-axis accelerometer data to determine activity changes-of-state and classify mobility activities. This application runs on a Blackberry™ device located at the user's waist and, as the user performs daily activities (walking, standing, sitting, lying, etc.), the application recognizes movements based on accelerometer signal processing. Features are calculated within one second windows and then combined to determine the current mobility state. By comparing with the previous movement state, the WMMS can determine a change-of-state in user activity.

A common source of error with a waist-mounted Smartphone WMMS is the resting device angle due to waist girth, clothing, or the device's holster. Certain users require a standing offset calibration to orient the accelerometer axis to a world reference. Several activity classifications rely heavily on the standing state. For this class of users, inaccuracies in activity determination occur since the features and state evaluations are adversely affected by the orientation offset.

II. Calibration

We propose a calibration method that positions the accelerometer components to an orientation that conforms to a natural device stance for a mobility monitoring system. This method corrects accelerometer axis orientation by applying a quaternion rotation transformation to the device's raw data. This rotation compensates for user variability in device alignment when standing naturally. The standing position coordinate system for the WMMS Blackberry device is described in Fig. 1.

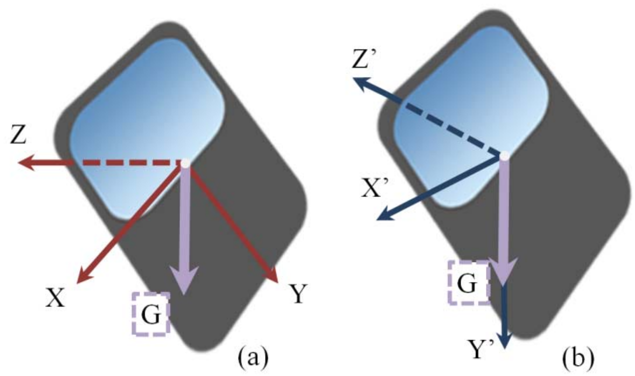

Figure 1 (a) The non-calibrated standing position (*XYZ*) is the device's position in the holster. The gravitational force vector (G) is split into components along *X*, *Y* and *Z*. (b) The virtual calibrated standing position (*X'Y'Z'*) after the transformation. The gravitational force vector (G) is now along the positive Y' axis, representing an upright device position.

III. Rotation Matrix

A rotation matrix describes a coordinate system orientation with respect to another orientation. A vector $\vec{V}$ in the initial reference frame F can be transformed into a vector $\vec{V}'$ in a rotated frame F' by multiplication of $\vec{V}$ with the rotation matrix between F and F' [2]. Rotation matrices are characterized as orthogonal, square, and invertible:

$$R^T = R^{-1},\ \det R = 1. \tag{1}$$

In three dimensions, rotations around the three principal axes produce a shift of any vector or point from the frame F to F' (Fig. 2).

The two static vectors $\vec{V}$ and $\vec{V}'$ can be used to describe the orientation adjustment between the current reference frame and desired frame, producing a rotation matrix R. Multiplying

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R by $\vec{V}$ produces $\vec{V}'$, while multiplying the transpose rotation matrix R^T with $\vec{V}'$, produces the initial vector $\vec{V}$.

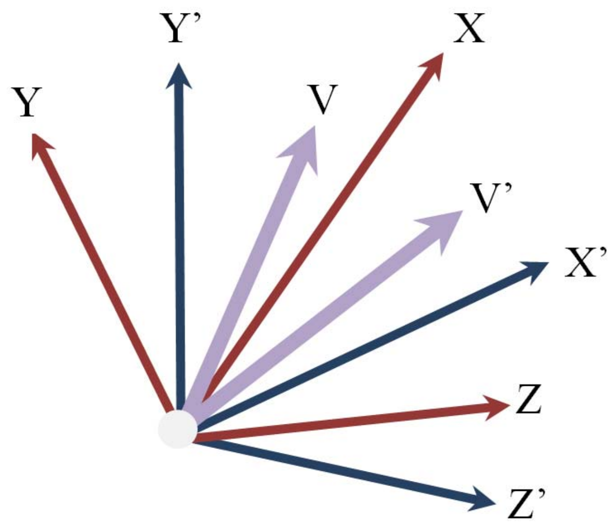

Figure 2 Vector $\vec{V}$ in reference frame F rotated to become vector $\vec{V'}$ in reference frame F'.

A rotation in three dimensions can be represented by a four-dimensional linear description of the rotation through quaternions. Using a four-dimensional quaternion space to represent a three-dimensional rotation is beneficial because non-linearity, singularities, and other difficulties with an Euler angle representation of rotation can be avoided. A quaternion rotation acts as a single rotation of angle α, around an axis in the direction of a normalized vector $\vec{A}$. This relationship is called the axis-angle representation of a rotation [3].

IV. Application

The calibration method involves constructing the quaternion rotation matrix, via the axis-angle representation. First, the axis vector is produced by taking the cross product of the initial orientation gravitational vector with the desired orientation gravitational vector. Then, the dot product is used to solve for the rotation angle α, which is then used with the axis vector as inputs to build the quaternion rotation matrix. Finally, all raw accelerometer data thereafter are multiplied by the rotation matrix to achieve the corrected orientation.

The gravitational force applied to the Smartphone accelerometer is used as the initial orientation vector. The desired device position is upright; therefore, the final orientation vector is gravity acting only in the *Y'* direction in the second reference frame, as seen in Fig. 1. We call the gravitational acceleration vector for the user's natural stance $\vec{V}_i$ and the desired gravitational vector, which passes only through the *Y'* axis, $\vec{V}_f$.

Considering the initial vector $\vec{V}_i$ and the desired vector $\vec{V}_f$,

$$\vec{V}_f = R\vec{V}_i,$$

$$\begin{Bmatrix} X' \\ Y' \\ Z' \end{Bmatrix} = R \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix}, \tag{2}$$

The rotation matrix from (1) is then applied to all accelerometer readings in real time using (2), thus correcting for the device slant or tilt.

The initial gravity vector $\vec{V}_i$ is a 10 second sampling of accelerometer data with the user naturally standing still. This is averaged to yield $\vec{V}_i = X\hat{\imath} + Y\hat{\jmath} + Z\hat{k}$ while the desired gravity vector is $\vec{V}_f = X'\hat{\imath} + Y'\hat{\jmath} + Z'\hat{k}$, where $\vec{V}_f = (0, 9.81, 0)$.

To construct the set of quaternions that yield the required rotation, we must first produce an axis-angle pair. The axis vector $\vec{A}$ can be found from the cross-product between the initial and final gravity vector:

$$\vec{A} = \vec{V}_i \times \vec{V}_f = (-9.81Z)\hat{\imath} + (9.81X)\hat{k}. \tag{3}$$

The axis vector $\vec{A}$ from (3) can then be normalized by dividing by the magnitude of $\vec{A}$:

$$\vec{A}_{norm} = -\left(\frac{Z}{\sqrt{X^2+Z^2}}\right)\hat{\imath} + \left(\frac{X}{\sqrt{X^2+Z^2}}\right)\hat{k}. \tag{4}$$

The angle between vectors can be expressed as the cosine angle from the dot product. Using initial vector $\vec{V}_i$ and end vector $\vec{V}_f$, we obtain:

$$\vec{V}_i \cdot \vec{V}_f = \|\vec{V}_i\|\|\vec{V}_f\|\cos(\alpha),$$

$$\vec{V}_i \cdot \vec{V}_f = XX' + YY' + ZZ'.$$

Since *X'* and *Z'* = 0, and the magnitude of $\vec{V}_f$ equals Y', the equation becomes:

$$\alpha = \arccos\left(\frac{Y}{\|\vec{V}_i\|}\right). \tag{5}$$

Our axis-angle pair described in (4) and (5) can now be used in the quaternion rotation equations, as described in [5]:

$$q_0 = \cos(\alpha/2),$$

$$q_1 = \sin(\alpha/2)\, A_{norm,x},$$

$$q_2 = \sin(\alpha/2)\, A_{norm,y},$$

$$q_3 = \sin(\alpha/2)\, A_{norm,z}.$$

$$R(q_0, q_1, q_2, q_3) = R = \begin{bmatrix} 1-2(q_2^2+q_3^2) & 2(q_1q_2-q_0q_3) & 2(q_0q_2+q_1q_3) \\ 2(q_1q_2+q_0q_3) & 1-2(q_1^2+q_3^2) & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_0q_1+q_2q_3) & 1-2(q_1^2+q_2^2) \end{bmatrix}. \tag{6}$$

Applying (6) into (2) allows for the rotation of the raw acceleration components as desired.

V. Experiments

A. Validating the Rotation Matrix

A controlled experiment was conducted to verify the method for correcting accelerometer data orientation for a Smartphone WMMS. A Blackberry device was securely attached to a rotating mechanical arm that spun 360° clockwise (Fig. 3). Four trials were conducted, each with specific Smartphone orientations similar to how the device may rest on the user's hips. Each trial included 20 seconds of sampling without mechanical arm movement, followed by 20 arm revolutions at a constant angular velocity. Accelerometer data were recorded using the TOHRC Data Logger application (available via Blackberry App World) at a variable sample rate between 17-20 Hz.

The testing protocol was repeated with an XSens MTi sensor in the upright orientation as a comparator to the Smartphone accelerometer output. Accelerations were recorded at 100 Hz.

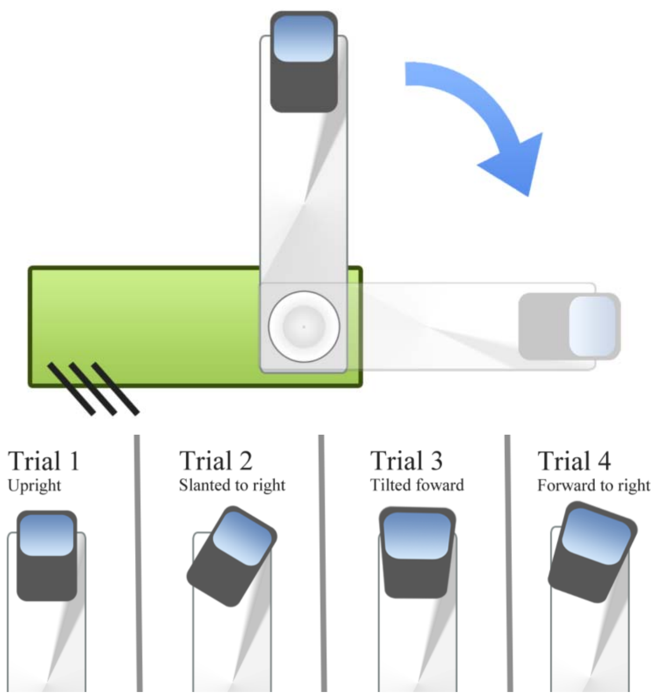

Figure 3 Device experimental setup.

For trial 1, the device was positioned upright on the rotating arm. This reflects the natural standing position for the average user, where the gravity vector passes only through the accelerometer's Y axis. Trials 2-4 represent offsets that can occur when the device is positioned on the user's pelvis, as shown in Fig. 3.

All Blackberry accelerometer data were imported into Microsoft Excel for analysis. A 10 second sample of static data was used to produce the $\vec{V_i}$ vector, and an individual rotation matrix from (6) was generated for each trial. The raw accelerometer readings were then converted to $\vec{V_f}$ through equation (2).

Accelerometer data from trials 1, 2, 3 and 4 (Fig. 3) should correlate with one another after the rotation matrix is applied. This is a result of the shift to a world-coordinate system for the upright position.

B. Testing Rotation Matrix on Subject Data

A transtibial amputee subject was recruited through the Ottawa Hospital Rehabilitation Center to perform the circuit described in [6]. While the subject followed the predetermined path, accelerometer data were collected using the WMMS Blackberry app. The accelerometer raw data file was then extracted from the device and evaluated with the WMMS algorithm separately on a PC in MATLAB software.

The MATLAB program, called the 'WMMS Tool', was developed to explore rotation matrix effects on the circuit data. Features, state variables, and the expected states were calculated from both the raw accelerometer data and the associated rotated data set. The program allows for toggling between views of the raw and rotated data, providing a visual depiction of how the rotation matrix affects the acceleration component signals.

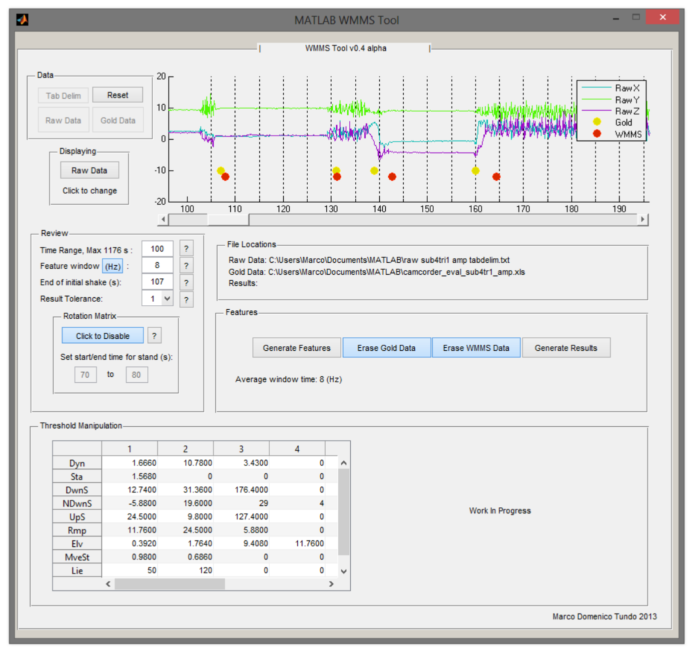

Figure 4 Screenshot of the WMMS Tool.

Figure 4 is a screenshot of the graphical user interface for the WMMS Tool. Accelerometer data features, as described in [6], were calculated using eight samples and the $\vec{V_i}$ vector for the subject's rotation matrix was sampled between 70 and 80 seconds of the raw accelerometer data, where the subject was stationary.

VI. Results

A. Mechanical Arm

Gravitational, normal, and tangential forces were applied to the Smartphone as the mechanical arm rotated. The different phone orientations produced different sets of *X*, *Y* and *Z* data. Table 1 shows the static 10 second sampling averages used to construct their respective rotation matrices. *Y'* values did not reach the full 9.81m/s^2, possibly due to consumer grade Smartphone accelerometer inaccuracy.

TABLE I. STATIC SAMPLING BEFORE AND AFTER TRANSFORMATION

	Raw Accelerometer Averages (m/s^2)				***Rotated Accelerometer Averages (m/s^2)***		
Trial	***X***	***Y***	***Z***		***X'***	***Y'***	***Z'***
1	-0.0100	9.7417	0.2092		0.0000	9.7440	0.0000
2	-6.1710	7.4321	0.1844		0.0000	9.6618	0.0000
3	-0.1760	9.1883	-3.2015		0.0000	9.7317	0.0000
4	-7.4938	5.6328	-1.9727		0.0000	9.580	0.0000

For trial 1, the quaternion rotation matrix fixed the slight offset on the *X* and *Z* axes caused by experimental setup (Table 1). The accelerometer reference frame was corrected, and the gravitational, tangential, and normal forces were applied only on the *XY* plane; consequently, the orthogonal *Z* component did not experience any forces, but did experience vibrational noise, with an average value of 0.151m/s^2 and standard deviation of 0.627m/s^2.

Trial 2 experienced a slant to the right, which resulted in acceleration due to gravity along the X component (Table 1). The result of applying the rotation matrix was as expected since the *Y* component comprised the full magnitude of acceleration due to gravity before movement and the sinusoidal nature of the *X* and *Y* accelerations due to the spinning arm reflected that of trial 1. The *Z* axis for trial 2 also experienced similar noise to trial 1, with an average value of 0.131m/s^2 and standard deviation of 0.255m/s^2.

Trial 3's forward tilt caused the *Z* component to take some of the gravitational component of acceleration (Table 1). As a result, the arm's spinning motion caused *Z* to fluctuate as the arm rotated. The *Z* acceleration's sinusoidal nature was greatly reduced once the rotation matrix was applied. Much like the other trials, the *Z* component experienced vibrational noise that averaged 0.066m/s^2 with a standard deviation of 0.480m/s^2. The larger standard deviation in *Z* for this trial was expected, since the rotation matrix was unable to fully negate the cyclic nature of the gravitational component along *Z*.

For trial 4, a forward and slanted position was applied, splitting the gravitational vector along all components. Rotating the reference frame fixed the offset; however, much like the other trials, *Z* experienced substantial noise, with an average of 0.034m/s^2 and standard deviation of 1.118m/s^2.

The quaternion rotation performed as expected in all trials, by rotating the *XYZ* into *X'Y'Z'* to achieve the upright slant required for the WMMS. Correlation results between data sets are shown in Table II.

The Blackberry device did not have a constant sampling rate, therefore each data set was interpolated from 10s (the start of the non-static data set) to 67.55s, in 0.05 second intervals (20Hz) to match time intervals prior to correlation. Furthermore, the start of the non-static data set was shifted within a range of -0.5s to +0.5s to synchronize the trial starting positions.

TABLE II. CORRELATIONS BETWEEN ACCELEROMETER DATA

	Rotated X	***Rotated Y***	***Rotated Z***
Trial 1 & 2	0.947	0.968	0.164
Trial 1 & 3	0.944	0.969	0.119
Trial 1 & 4	0.922	0.960	0.147
Trial 2 & 3	0.979	0.992	-0.018
Trial 2 & 4	0.977	0.995	0.142
Trial 3 & 4	0.979	0.992	-0.018

The *X* and *Y* values demonstrated strong correlations between the rotated data sets, with an average difference to perfect correlation of 4.2% and 2.1%, respectively. Experimental errors were a result of small vibrations in the rotating arm. The *Z* axis, which had very low accelerometer readings, was most affected by the vibration artifacts, resulting in poor correlations (Table 2). However, correlation values between all trials of the rotated *Z* component were close to zero, thus demonstrating uncorrelated noise.

The noise was further investigated with the XSens sensor on the rotating arm. *Z* component data averaged 0.059m/s^2, standard deviation 0.298m/s^2. These values were similar to those generated from the Smartphone, further confirming the random vibrational noise caused by the rotating arm.

B. Subject Data

The subject demonstrated a need for realignment of the phone's orientation since the phone had a tilt of 0.327 radians between $\vec{V_i}$ and $\vec{V_f}$ from the 70 to 80 second mark during the standing part of the circuit. The rotation matrix was then calculated during this interval and applied to all subsequent data. Both the rotated and non-rotated data were then evaluated with the WMMS algorithm.

The sensitivity and specificity of state determination at every feature interval were calculated for this subject and are shown in Table III.

TABLE III. SENSITIVITIES AND SPEFICITIES FOR STATE PREDICTION

	SE	***SP***		***SE***	***SP***
	Non-Rotated			***Rotated***	
Stand	11.2%	81%		11.2%	85.1%
Sit	0%	92.4%		47.8%	90.2%
Lie	0%	98.5%		0%	99.1%
Walk	51.8%	13.7%		51.8%	12.8%

The sensitivities (SE) and specificities (SP) are based on expected actions in accordance to gold standard timing data from a separate camcorder video that was recorded while the subject performed the predetermined circuit. Generated acceleration data features, such as minima, maxima, standard deviations, ranges, in 8Hz windows were evaluated with the WMMS algorithm, which predicted the resulting mobility state. This state was compared with the gold-standard state obtained from the camcorder recording of the subject during their trial.

The stand sensitivity remained at a low 11.2%, which was expected to increase with the application of the rotation matrix. However, the sitting prediction sensitivity increased from 0% to 47.8%. The specificity of the prediction remained generally unchanged.

This subject's accelerometer data was sufficiently variable that the WMMS had a difficult time in making accurate predictions. A closer look at the subject's data in the WMMS Tool demonstrated a wide discrepancy in phone alignments while the user was standing. The wide variability of the subject's standing acceleration data is shown in Table IV.

TABLE IV. SUBJECT ACCELERATIONS WHILE STANDING

	Raw Accelerometer (m/s^2)				***Rotated Accelerometer (m/s^2)***		
Time (s)	***X***	***Y***	***Z***		***X'***	***Y'***	***Z'***
80.98	2.51	9.35	1.91		0.05	9.87	-0.09
115.60	0.911	9.85	1.28		-1.60	9.81	-0.76
325.88	2.48	8.45	3.44		0.21	9.32	1.58
1102.45	8.24	5.95	2.31		4.34	7.92	2.55
1144.99	4.11	8.04	3.71		1.88	9.40	1.89

The selected time periods in Table IV show that throughout the circuit, the phone orientation as the user is standing is inconsistent. This alone accounted for a large source of the error in WMMS predictions. The rotation matrix aided in correcting in misalignment for a specific interval in time, but did not account for deviations in alignment throughout the entire trial as the rotation matrix was only calculated once and then applied to the remainder of the data. For this subject, several recalculations of the rotation matrix would likely have improved some of the WMMS predictions.

A real-time rotation matrix can be implemented, but requires stable standing intervals during the circuit such that a subsequent calculation of rotation matrix and further realignment can be applied. In a real-life scenario where the WMMS is running in real-time on the Smartphone, a dynamic, frequently-updated rotation matrix would be possible to implement, once identification of standing intervals is performed.

VII. CONCLUSION

A quaternion based rotation matrix was applied to a fixed standing Smartphone position, and all accelerations thereafter were calibrated to this new virtual device orientation. Controlled experimental accelerations were applied on the device in four separate orientations. Their components were then transformed to an upright three-dimensional reference stance, resulting in strong correlations between all trials undergoing the same applied forces.

Applications involving mobility and movement experiments will benefit by using this method since a device's accelerometer components can be orientated in any direction around its origin, allowing for full control of the accelerometer Cartesian mapping.

A rotation matrix was then applied to a single subject who demonstrated a need for the realignment of the Smartphone for their trial. The rotation matrix aided in increasing sensitivity for sitting, but all other predictions remained similar to the original WMMS prediction. High-variability standing subject data suggested that future work should include more frequent rotation matrix updates as standing subject intervals are identified in real-time.

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