Spectral Analysis Based Limb Movement Reconstruction Using Inertial Sensing Data

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1   Background

This brief paper illustrates the analysis of inertial sensing signals including linear acceleration and angular velocity for the reconstruction of movement trajectory of upper limbs, in order to assess the performance of stroke rehabilitation and build up an objective quantitative evaluation system. It is well noted that while using inertial sensing data, the motion-track reconstruction applies the Kalman filtering to process integrated time waveform [1–3]. This study consists of two parts. First, the method of track reconstruction of limb motion is built up through simulation. We present the new method to obtain angular displacement using spectral analysis by extracting the amplitude and phase of significant frequency components that correspond to limb movement. Then, the upper- and fore-arm positions corresponding to global coordinate system can be computed through the quaternion vector. Secondly, the proposed technique is verified using five designated upper-limb movements including upper limb rotating (1) upwards 90 deg and (2) transversely 90 deg from the forward-horizontal position, (3) forearm rotating axially 90 deg in the forward-horizontal position, (4) upper limb rotating 45 deg along the upward and transverse direction, and (5) both shoulder flexion and elbow flexion. The tasks of movement trajectory reconstruction are performed by both synthetic signals and acquired inertial sensing data from various limb movements. Here a triangle movement of upper limb is demonstrated as an example.

To help assess the rehabilitation performance of post-stroke patients the current proposed and implemented motion reconstruc-tion technique is although applied in rotating alike movement of upper limb. To reconstruct the motion trajectory of arbitrary but periodic limb movement is expected.

2   Methods

For the reconstruction of movement trajectory, measured inertial sensing data (angular velocity and linear acceleration) in the local coordinate system need to be transformed into their corresponding positions based on the global coordinate system. In the numerical computation the conventional method applied direct time-domain integration to obtain both angular and linear displacement, and further yields space trajectory. The study proposes and realizes a novel technique using spectral analysis to obtain angular displacement; subsequently, linear displacement can be evaluated through spectral analysis as well after a quaternion method is used for coordinate transformation.

The spectrum of time sequence data can be computed by (discrete) Fourier transform

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt \tag{1}$$

to obtain both the amplitude and the phase of each frequency component. For the sinusoids of an angular-velocity signal, the spectral components in its corresponding angular displacement signal can be definitely decided. Then, we apply inverse Fourier transform to have the time waveform of the angular-displacement signal. It should be noted that we can just select significant spectral components reflecting the movement and ignore other artifacts; therefore, the obtained waveform data are able to get rid of both noise influence and integration shift which are introduced by time integration.

Two methods of coordinate transformation from a local system to a global system are usually used; one is the Euler angle method and the other is the quaternion method. The latter is to compute the new coordinate using the old one rotating along a specific special axis. The four variables of a quaternion are defined as below [4,5]

$$\vec{q} = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \end{bmatrix}^T \tag{2}$$

where the quaternion is satisfied with the following constraint rather than remains four degrees of freedom,

$$q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1 \tag{3}$$

When rotation occurs, the change of quaternion can be expressed as

Fig. 1   Illustration of three inertial sensors mounted on the upper limb, conducting a triangle movement

$$\dot{\vec{q}} = \frac{1}{2} \vec{\omega} \otimes \vec{q} \qquad (4)$$

where $\dot{\vec{q}}$ denotes the time derivation of the quaternion, $\vec{\omega}$ is the angular-velocity vector along the local coordinate system, $\otimes$ indicates the multiplication of quaternion. Therefore, the matrix form of Eq. (4) can be expressed as

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_\theta & -\omega_r & -\omega_\varphi \\ \omega_\theta & 0 & \omega_\varphi & -\omega_r \\ \omega_r & -\omega_\varphi & 0 & \omega_\theta \\ \omega_\varphi & \omega_r & -\omega_\theta & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \qquad (5)$$
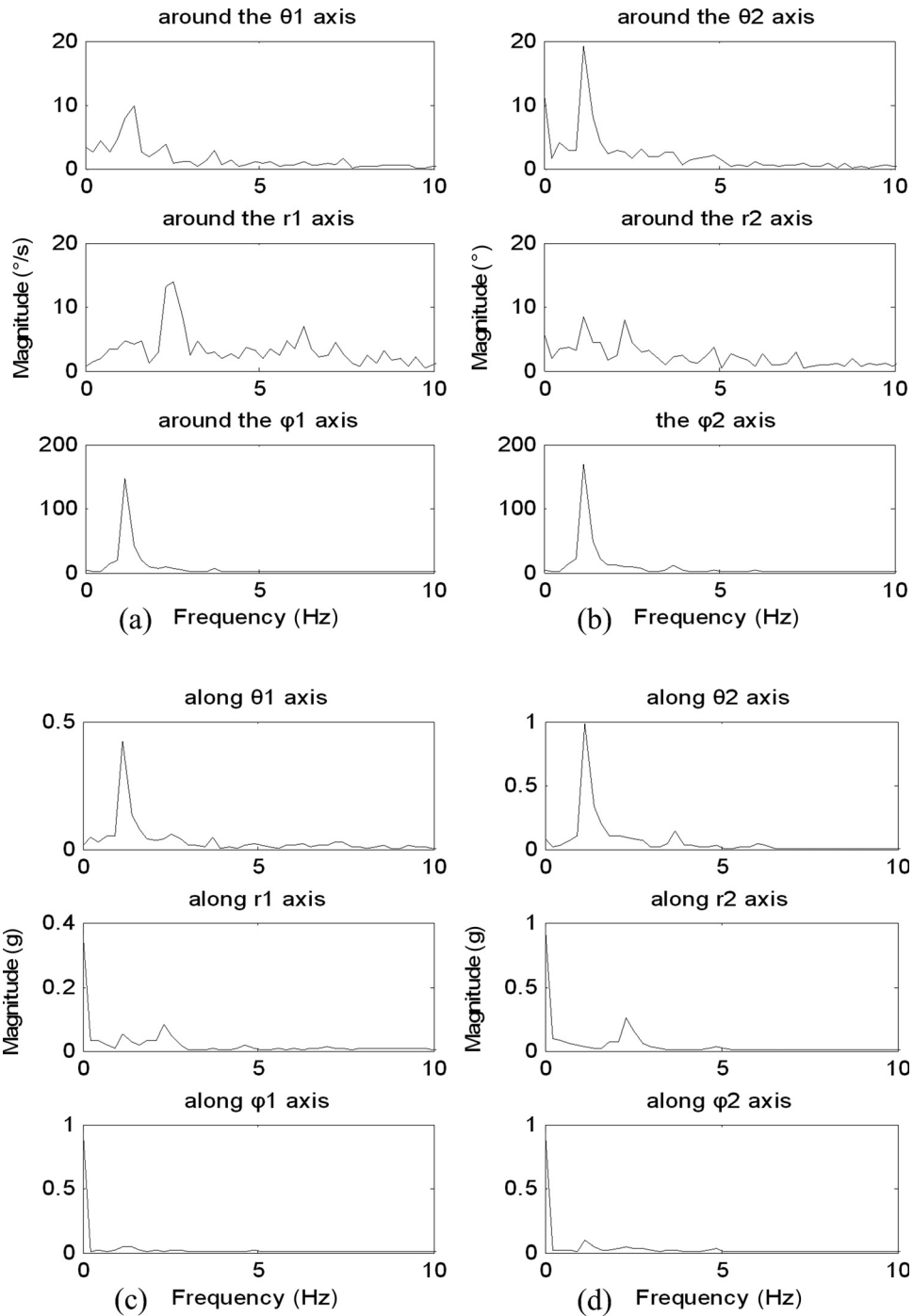

Fig. 2 Spectra of (*a*) upper-arm and (*b*) fore-arm rotation angular velocity, and (*c*) upper-arm and (*d*) fore-arm linear acceleration, related to their local coordinate.
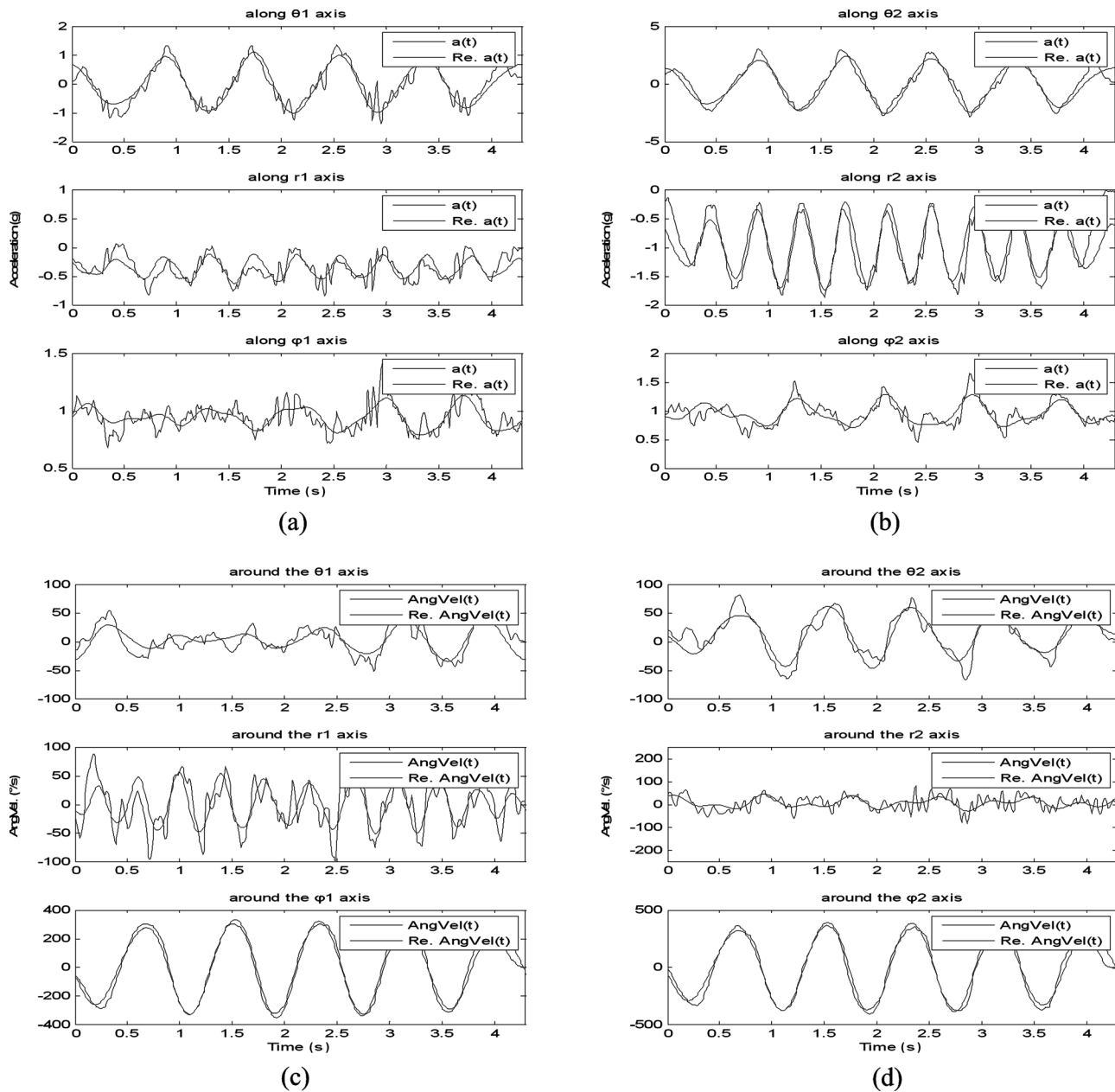
Fig. 3 Reconstructed (in blue) and original (in red) waveform of (*a*) upper-arm and (*b*) fore-arm rotation angular velocity, and (*c*) upper-arm and (*d*) fore-arm linear acceleration, related to local coordinate.

Likewise, through the spectral analysis of linear acceleration data measured on the local coordinates, we can compute their global linear displacement, and then reconstruct motion trajectory.

3 Results

To verify the effectiveness of the proposed method, as shown in Fig. 1 three inertial sensors (IMU-3000, InvenSense), each one sensing three orthogonal directions of angular velocity and linear acceleration, respectively, with a sampling frequency of 100 Hz, are mounted on the fore arm, upper arm and shoulder. Figure 2 shows the spectra of measured rotation angular velocity and linear acceleration on upper-arm and fore-arm, related to their local coordinate. Through the processing in frequency domain the

angular-velocity and linear-acceleration waveform neglecting artifacts can be reconstructed (Fig. 3). Then, the linear acceleration related to global coordinate can be evaluated using the quaternion method (Fig. 4). Here, as an example shown in Fig. 5, the reconstructed upper-limb movement is characterized by a larger triangle and a smaller triangle, respectively.

4 Interpretation

Using the proposed technique through spectral analysis, to reconstruct the trajectory of arbitrary but periodic movement is expected. The results show that the technique can reduce noise, get rid of bias signal, and reconstruct trajectory well. But, the limitations and problems need to be coped with. First, the technique is used for periodic although arbitrary movement due to
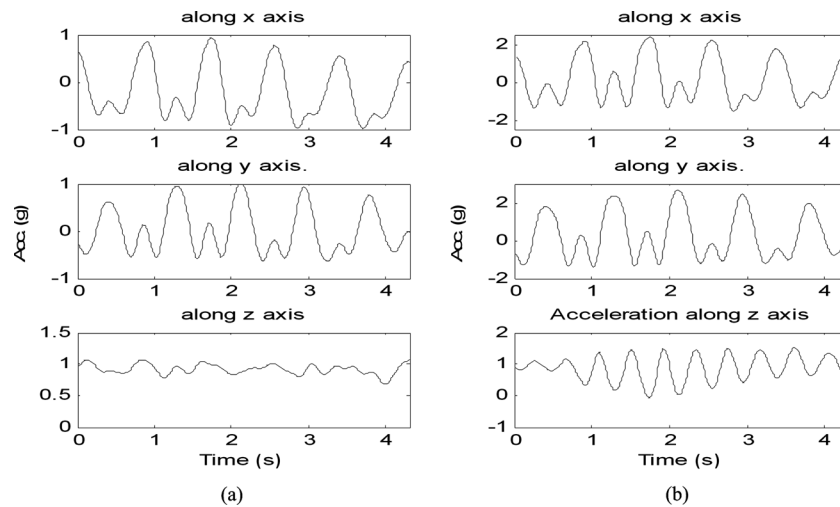
Fig. 4 Evaluated (*a*) upper-arm and (*b*) fore-arm linear acceleration, related to global coordinate
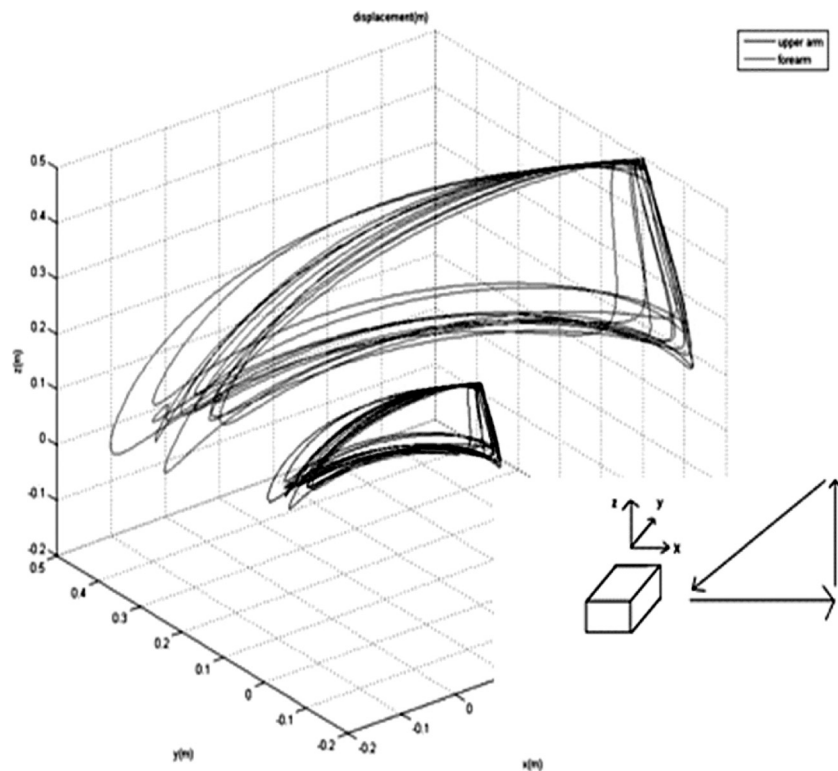

Fig. 5 Reconstructed movement of fore arm (larger triangle) and upper arm (smaller triangle), where the lower-right sketch shows the designated movement

using Fourier transform. Second, to choose appropriate spectral components accompanied with a more complicated movement is crucial to the reconstruction.

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