Applying Hilbert-Huang Transform to Extract Essential Patterns from Hand Accelerometer Data

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Abstract Hand Accelerometers are widely used to detect human motion patterns in real-time. It is essential to reliably identify which type of activity is performed by human subjects. This rests on having accurate template of each activity. Many human activities are represented as a set of multiple time-series data from such sensors, which are mostly non-stationary and non-linear in nature. This requires a method which can effectively extract patterns from non-stationary and non-linear data. To achieve such a goal, we propose the method to apply Hilbert-Huang Transform which is known to be an effective way of extracting non-stationary and non-linear components from time-series data. It is applied on samples of accelerometer data to determine its effectiveness.

Key Words : Hilbert-Huang Transformation, Accelerometer, Hand Motion
occur on short time scale. By removing it, we can arrive at a pattern on proper time scale which can show essential characteristic of a given activity. The trouble is that the time-series data are mostly non-stationary and non-linear, and decomposing time-series data into components of predetermined set of frequency(period) could lead to inaccurate result. A method which perform decomposition into non-stationary and non-linear components of various time-scale is needed. Hilbert–Huang Transform (HHT) is ideally suited to performing such a transform. Time-series data can be broken down into components of multiple time scale, and choose a component on a proper time scale [11,12].

Time-series usually contains some type of fluctuation over time, which appears to occur at certain frequencies. Unfortunately, it rarely has precise periods. In addition, its perceived frequency could change over time. Human physical activities are no exception. Human hand motion while performing certain activities such as walking, eating a particular type of food, or brushing teeth all show contains oscillatory pattern with dynamically changing frequency and amplitude.

Fast Fourier Transform (FFT) and Wavelet Transform have wide-spread application in many fields [8,9,15]. While they can be effective in solving certain problems, they do have some limitation. They are essentially static in that they start with predetermined basis of frequencies. In case of FFT, time-series is represented as a static periodic function over the entire range of interest. To remedy this limitation, Windowed FFT was introduced with varying level of success. Still it is not suitable for representing non-linear and non-stationary time-series.

Wavelet Transform is designed to tackle this problem. It can produce three dimensional charts which can show change of frequency amplitude distribution over time. However, it still requires the use of predetermined basis. Wavelet Transform can handle non-stationary time-series but not non-linear one. In contrast, HHT has adaptive basis. The basis is not predetermined. It is derived from the data while HHT is performed. It is especially effective in catching instantaneous frequencies and amplitudes [8,9]. It is well-suited to identifying profiles of aforementioned human physical activities.

Previously, HHT has been applied to a wide range of problems with great success. It is used for analyzing heart beats or EEG signals while a subject is performing a particular cognitive task [23]. It is applied to analyze wave signals propagating through structures such as vibration and detect anomalies such as cracks [18]. Image processing is another area of application in which it was used for filtering and feature detection [24]. On a more macro scale, it has been applied to extracting periodic modes of epidemic outbreak time-series, and analyzing time-series data from weekly mortgage rates [25,26]. Another area where HHT has been extensively used is structural engineering [18]. While they all employed HHT, the manner of application may vary. In some cases, it is used to remove noisy components, usually signals in high frequency range [16]. In other cases, it is used to identify particular pattern which can characterize an onset of significant event such as heart attacks or structural failure [17,18].

A prior research on the application of HHT to analyzing human hand motion is the application of HHT to aiding minimally invasive surgery. The procedure requires surgeons to manipulate specialized tools in uncomfortable posture for extended duration. Over time, it will introduce hand muscle fatigue, generating hand–tremors which will affect accuracy of the procedure. Computer software is attached to analyze signals from hand motions. Then it identifies the high frequency components which are the result of hand tremor, which are filtered out and the resulting signal, now with hand–tremor removed, is sent to a slave manipulator inside a body of patient undergoing surgery. This is a way to self-correct signals so that the surgery maintains its accuracy.

In this paper, we used hand motion data from tri-axial
accelerometer and apply Empirical Mode Decomposition to them. It will produce components on different time scale.

We will analyze which ones can be suitable for identifying a particular type of activity.

II. Hilbert–Huang Transform

The Hilbert–Huang transform (HHT) ([10], [11],[12], [13], [14]) is a method which is superior to any comparable techniques when it comes to non–stationary and non–linear time–series data. It first split the original time–series into multiple oscillatory components, which are called Intrinsic Mode Functions (IMF). This process is called Empirical Mode Decomposition (EMD.) This is essentially a process of decomposing time–series data into components in separate frequency bands. The bands are not static but dynamic. Furthermore, it can show change of instantaneous frequencies. It can catch intra–wave frequency modulation, which other techniques like FFT or Wavelet Transform tend to destroy. Highly complex non–linear systems exhibit such a pattern. HHT is a proper tool to analyze data from such a system.

As has been mentioned in the previous section, the basis of HHT is not determined in advance. It will be derived through the process of Empirical Mode Decomposition(EMD.) EMD is essentially an iterative process which isolates components in different time–scales in stages. Each stage employs a sifting process which is to produce proper oscillatory component without containing components which is on larger time scale. Each component isolated via this process is an Intrinsic Mode Function. IMF is isolated starting with the highest frequency (smallest time-scale.) Isolated IMF is subtracted from the current time-series, producing new time-series with lower frequencies. This process continues, producing IMF’s of lower and lower frequency (larger time-scale) until a terminating condition is met, at which point EMD ends.
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Fig. 2 (a) a Sample curve f(x) (b) Power Spectrum of f(x) (c) IMF curves derived from f(x) via EMD (d) Power Spectrum of each IMF curve.

\[ X_i = \sum_{k=1}^{n} c_k(t) + r_n(t) \]

\( X_i \) is now decomposed into \( n \) IMF’s. Figure 1 shows how two envelope curves, \( u_i(t) \), \( l_i(t) \) and its mean curve \( m_i(t) \) are derived. The sample result of EMD is shown in Figure 2.

Figure 2(a),(b) shows a sample curve(top) and its power spectrum(bottom). EMD produces IMF’s in Figure 2(c). Figure 2(d) shows power spectrum of each IMF. Each IMF has a power spectrum concentrated around a single major frequency unlike the original curve with more spread-out power spectrum. Original time-series is decomposed into IMF’s in different frequency bands, which are not known in advance but rather found during EMD. Since each IMF is not a simple periodic curve, its power spectrum can be complicated. Some have sharp peaks clearly showing dominant frequencies, while others have more spread-out distribution. Since EMD relies on envelope curve of peaks, it does not perform well if there are no available peaks. IMF’s on either end of time-series tend to be inaccurate, frequently showing significant deviation from original time-series data. So segments of IMF on both ends should be discarded.

III. Experiments

We used data from Activities of Daily Living (ADLs) Recognition at UCI Machine Learning Repository. Tri-axial accelerometers are attached to a wrist of human subjects [21,22]. Figure 3 shows one
Fig. 4. (a) X-axis values from a tri-axial accelerometer during "Brushing Teeth" activity (b) 8 IMF curves derived via EMD. IMF’s are arranged according to their time-scale (top-left is the shortest, and the bottom-right is the longest.)

Three sets of time series data are generated for each trial. Some of collected time series data were chosen. For time-series corresponding to each axis, HHT was applied and IMF’s were derived via EMD. Each IMF represents pattern on a particular time-scale. IMF’s are subtracted from original time-series in succession, removing component of shorter time-scale (fast changing component) one at a time, until the resulting time-series data turns out to be the one which best represents essential pattern of original time-series data. It is a process of choosing a right time scale where essential pattern can be found. To put it formally, we are trying to find the best LIMF1 where LIMF = X (IMF1 + … + IMFn) where Xi represents original time-series.
Fig. 5. LIMF Curves from x–axis Values of “Brushing Teeth” Activity
IV. Result

Figure 4 shows the result of Empirical Mode Decomposition (EMD) performed on time-series data from x-axis measurement of "brushing teeth" activity. The top graph is the original time-series data and 8 IMF’s are shown. As can be seen here, time-series is broken into multiple components of varying time-scale. These are pieces of original time-series. Since we are trying to find overall pattern which can represent the time-series best, an individual piece may not be a suitable candidate. Instead, we are peeling off each IMF one at a time starting with $\text{LIMF}_1$. This would remove noisy or non-essential components from the time-series. Conventional filtering can be used for the same purpose, but it may not be as effective because it lacks a kind of good adaptive feature HHT can provide. LIMF’s obtained by removing IMF one by one are shown in Figure 5. Starting from the top which is the original time-series, the figure shows the result of removing each IMF one at a time. After performing the removal process 4 or 5 times, we have the result which may best capture overall pattern of the original time-series. If we proceed further, the resulting time-series is on the time-scale too long to contain useful information. Performing the same operation for time-series data from y,z-axis, we have a result shown in Figure 6. It has $\text{IMF}_4$ and $\text{IMF}_5$ for all three axis. $\text{IMF}_4$ may have more details but too many peaks and valleys. $\text{IMF}_5$ may be more suitable. The same operation can be done for other data. The rule of thumb to pick the right LIMF is to find a number by dividing the number of IMF’s by 2 and pick LIMF corresponding to the number. That is, pick $\text{LIMF}_{\lfloor n/2 \rfloor}$ where $[n/2] = \lfloor n/2 \rfloor$ or $[n/2]$. Figure 7,8,9,10 shows additional result for various activities. Most of LIMF’s shown here capture essential pattern of activities, except brushing teeth. Its high frequency IMF’s do reflect significant pattern of activities, and it may not have to be discarded. This requires further analysis on Instantaneous Frequency(IF) of the activity.
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Fig. 7. Eating Meat-1 (a) time-series data from x,y,z direction (x: black, y: red, z:blue) (b) 5th LIMF (c) 6th LIMF

Fig. 8. Eating Meat-2 (a) time-series data from x,y,z direction (x: black, y: red, z:blue) (b) 5th LIMF (c) 6th LIMF

그림 8. 육류 섭취시 움직임-2 (a) x,y,z 축 방향 시계열 데이터 측정치(x:검은 색, y:빨간 색, z:파란 색) (b) 5번째 LIMF (c) 6번째 LIMF
Fig. 9. Lying Down to Bed (a) time-series data from x,y,z direction (x: black, y: red, z: blue) (b) 2nd LIMF (c) 3rd LIMF

Fig. 10. Brushing Teeth (a) time-series data from x,y,z direction (x: black, y: red, z: blue) (b) 4th LIMF (c) 5th LIMF
V. Conclusion

The application of HHT to derive a series of LIMF's to find the essential pattern which best captures the essential feature of time-series has been investigated. It turns out that this method is good at capturing non-stationary and non-linear feature of time-series. The resulting time-series can be used as a good template for identifying the type of activities a human subject is engaged in. However, depending on the activities, we cannot pinpoint the right IMF to characterize the type of activity. For example, brushing teeth contains significant component of high frequency activity and it is not noise. It constitutes one of important features. For this paper, we only used IMF's derived via EMD. We left out Instantaneous Frequency (IF) and Instantaneous Amplitude (IA,) which make the other half of HHT.

To address the problem with activity like brushing teeth, we need to use IF and IA plot. HHT can be used in a nested fashion. EMD can be applied to IF and IA plot, generating new IMF's for each, which can be used to address the problem, a topic our future research could explore.

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