Application of update lifting morphological wavelet and non-negative matrix factorization for wheeled and tracked vehicles classification

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Abstract. This paper presents an available scheme based on update lifting morphological wavelet (ULMW) and Non-negative matrix factorization (NMF) for wheeled and tracked vehicles classification. The ULMW algorithm which utilizes the update operator, means the morphological filter to replace the linear filter can preserve the impulsive shape details in seismic signal. Meanwhile the NMF method can reduce the computation cost. The traditional linear wavelet analysis and statistical analysis are compared with the presented scheme. Experimental results demonstrate that the presented scheme achieves a promising performance on extracting impulsive features of seismic signal and recognizing ground moving target.

1. Introduction

Seismic signal is widely used in ground target classification due to its inherent characteristics. With the development and maturity of the time frequency analysis theory, wavelet transform has been widely employed for processing seismic signals. However, the seismic signal has been found to demonstrate a complicated non-linear characteristic. Thus, the traditional wavelet analysis methods cannot effectively extract the non-linear features.

Morphological wavelet (MW) transform, proposed by Goutsias and Heijmans[1], is a direction in the study of nonlinear expansion of wavelet theory. As a kind of non-linear wavelet, MW inherits the morphological characteristics of mathematical morphology and multiresolution characteristics of wavelet, with good performance in detail retention and noise resistance.

The MW can effectively extract the non-linear features contained in the original signals, but the space dimension after processing is still very high. In order to reduce the computational complexity and avoid the ‘curse of dimensionality’, we must carry out the further feature extraction method. Non-negative matrix factorization (NMF) algorithm is a new technique by operating an iterative matrix factorization, proposed by Lee and Seung[2]. It factorizes the database into two nonnegative matrix factors. These constraints lead to a parts-based representation.

Motivated by this, this paper investigates the application of NMF to characterize the information obtained by ULMW transform of seismic signals. Experimental results reveal that the presented method achieves a promising performance for wheeled and tracked vehicles classification.
2. Update lifting morphological wavelet (ULMW)

2.1. Morphological wavelet

We can construct a class of nonlinear MW through replace the filters in the linear wavelet with nonlinear morphological filter. MW can divide into dual wavelet and non-dual wavelet. Assume the sets \( V_j \) and \( W_j \) denote the signal space and detail space at level \( j \), respectively. The signal analysis consists of signal analysis operators \( \psi_j^+ : V_j \rightarrow V_{j+1} \) and detail operators \( \psi_j^- : W_j \rightarrow W_{j+1} \). On the other hand, the signal synthetic reconstructs the signal through the synthetic operators \( \psi_j^+ : V_j \times W_j \rightarrow V_j \). The decomposition scheme must satisfy the complete representation of a signal, that is, the signal analysis operator \( \psi_j^+ (x,y) = \Psi_j^+ (x,y) = \phi, \quad if \ x \in V_j \)

\[
\phi = \psi_j^+ (x,y) = \psi_j^+ (x,y) = \phi, \quad if \ x \in V_j 
\]

The above formulate is the perfect reconstruction condition.

2.2. Update lifting scheme

The lifting scheme provides a practical and flexible method for the design of MW, and it can be ensured that the new wavelet transform is reversible[3]. The update method proposed by Goustias[4] utilizes the information in the detail signal to modify the scale signal to reduce the information contained in the scale signal.

Assume the addition operator \( \hat{+} \) and subtraction operator \( \hat{-} \) exists in the signal space \( V_i \), meet the following condition:

\[
(x_i \hat{+} x_2) \hat{-} x_2 = (x_i \hat{-} x_2) \hat{+} x_2 = x_i, \quad x_i, x_2 \in V_i 
\]

The scale signal modified by the update operator can be expressed as:

\[
x_i' = x_i \hat{-} \lambda (y_i), \quad y_i \in W_i 
\]

The update operator \( \lambda \) maps the elements from signal space \( V_i \) to detail space \( W_i \). Obviously, the input signal can be reconstructed by \( x_i \) and \( y_i \):

\[
x_0 = \psi_i (x_i, y_i) = \psi_i (x_i \hat{+} \lambda (y_i), y_i) \quad x_0 \in V_0 
\]

Thus, the update lifting scheme can be defined as:

\[
\psi_i (x) = \psi (x \hat{+} \lambda (y), y) \quad x \in V_i 
\]

\[
\psi_i (x, y) = \psi (x \hat{+} \lambda (y), y) \quad x, y \in V_i 
\]
Derived from max-lifting and min-lifting schemes, we utilize the morphological operator
\((-0 \lor y(n-1) \lor y(n)) + (0 \land y(n-1) \land y(n))\) as the update operator to enhance the impulsive
components in the seismic signal. Then the signal coefficients and detail coefficients after update
lifting can be represented as:

\[ y(n') = y(n) \]

\[ x(n') = x(n) + (0 \lor y'(n-1) \lor y'(n)) - (0 \land y(n-1) \land y(n)) \quad (11) \]

Corresponding, we can reconstruct \(x(n)\) by:

\[ x(n) = x(n') - (0 \lor y'(n-1) \lor y'(n)) + (0 \land y(n-1) \land y(n)) \quad (12) \]

3. **Non-negative matrix factorization (NMF)**

Given a non-negative matrix \(V\), find non-negative matrix factors \(W\) and \(H\) such that:

\[ V_{ij} \approx (WH)_{ij} = \sum_{a=1}^{r} W_{ia} H_{aj} \quad (13) \]

Where \(r\) is the number of base vectors which is usually chosen as small as possible for dimension
reduction, and each column of matrix \(W\) represents a basis vector while each column of \(H\) means the
weights used to approximate the corresponding column in \(V\) using the bases from \(W\).

To find an approximate factorization \(V \approx WH\), we employ the Kullback-Laebler divergence as the
cost function to quantify the quality of the approximation:

\[ F(V \parallel WH) = \sum_{i=1}^{n} \sum_{j=1}^{m} \left( V_{ij} \log \frac{V_{ij}}{(WH)_{ij}} - V_{ij} + (WH)_{ij} \right) \quad (14) \]

Which subject to \(W, H \geq 0\)

Then an iterative algorithm to reach a local maximum of this objective function is given:

\[ H_{uai} \leftarrow H_{uai} \frac{\sum W_{uai} V_{ia} / (WH)_{uai}}{\sum W_{uai}} \quad (15) \]

\[ W_{uai} \leftarrow W_{uai} \frac{\sum H_{uai} V_{ia} / (WH)_{uai}}{\sum H_{uai}} \quad (16) \]

\[ W_{ia} = \frac{W_{uai}}{\sum W_{uai}} \quad (17) \]

4. **Result and discussion**

4.1. **Experiment equipment**

In field experiments, one tactical wheeled vehicle (a kind of wheeled vehicle) and one main battle tank
(a kind of tracked vehicle) were used as the experimental object. The specific vehicle parameters are
shown in Table 1. Moreover, a kind of vibration sensor (CDJ-Z2.5), was employed to measure the
Rayleigh component of seismic signals. Forty samples are collected for each type of target. Thus,
totally 80 samples are collected.
Table 1 Vehicle parameters of wheeled vehicle and tracked vehicle

| Vehicle parameters                    | Wheeled vehicle | Tracked vehicle |
|---------------------------------------|-----------------|-----------------|
| Weight                                | 50000(kg)       | 25000(kg)       |
| Length                                | 10.6(m)         | 6.63(m)         |
| Width                                 | 3.4(m)          | 2.8(m)          |
| Height                                | 2.3(m)          | 2.8(m)          |
| Mass of wheel                         | 310(kg)         | 280(kg)         |
| Number of wheels                      | 14              | 8               |
| Suspension spring stiffness           | 4.2×10^5(Nm^-1) | 3.8×10^5(Nm^-1) |
| Suspension damping                    | 1.2×10^4(Nsm^-1)| 1.2×10^4(Nsm^-1)|
| Track/tread pitch                     | 0.18(m)         | 0.03(m)         |
| Wheelbases                            | 0.67(m)         | 1.8(m)          |

4.2. Feature extraction based on NMF

We find that the effective characteristic frequency is mainly focus below 200Hz. When the third level approximation coefficient based on ULMW algorithm is transformed into frequency domain by fast Fourier transform (FFT), the frequency domain 0~200Hz is selected as the analysis scope, and then a sample set \( X_{200×80} \) can be acquired. Choose 20 samples of each target as the training samples, so that we can obtain a training sample set \( X_{200×40} \). Part of the training sample set, ten samples of each target, are given in Figure.1.

Due to the fact that the PCA result shows, we set the parameter the base vector rank \( r \) to be 35. In the training process, the absolute values of the eigenvects corresponding to the first 35 eigenvalues are set to be the initialization basis matrix \( W \). Then by mapping training sample set \( X_{200×40} \) to the basis matrix \( W \), the absolute values of the mapping coefficients can be taken as the initialization coefficient matrix \( H \). After training, we can obtain the basis matrix \( W_{200×35} \) and the feature matrix \( H_{35×40} \). Figure.2 demonstrates the feature matrices corresponding to the twenty samples listed in Figure.1. It can be found that the feature matrices can distinguish the wheeled and tracked vehicles very effectively.

For the rest test samples, we can obtain the feature matrix by the following formula:

\[
H_{\text{test}} = W^T X_{\text{test}}
\]  

(18)

We denote the feature subset obtained by ULWM and NMF as \( F_{\text{ULWM-NMF}} \).

For comparison, we also calculate the feature subset generated by LW using NMF which can be denoted as \( F_{\text{LW-NMF}} \).

![Figure 1. Frequency spectrum (0-200HZ) of two targets obtained by ULWM: (a) wheeled vehicle; (b) tracked vehicle](image-url)
4.3. Feature extraction based on statistical analysis
To compare with the method presented in this paper, we employed statistical analysis which is widely used for ground target classification to extract features of seismic signals, and totally ten statistical parameters are calculated for each layer wavelet coefficient of three levels LW decomposition. In this way, 40 features can be obtained for each sample. The feature set exacted by linear wavelet and statistical analysis is denoted as $F_{\text{LW-SA}}$. The feature set exacted by ULWM and statistical analysis is denoted as $F_{\text{ULWM-SA}}$.

4.4. Experiment evaluating of four feature extraction method
In this subsection, we conduct an experiment evaluating the classification capacity of the four feature subsets $F_{\text{ULWM-NMF}}$, $F_{\text{LW-NMF}}$, $F_{\text{LW-SA}}$ and $F_{\text{ULWM-SA}}$. Three popular classifier, means the K nearest neighbor classifier (KNNC), the Naïve Bayes classifier (NBC) and the support vector machine (SVM) are employed to implement the classification task.

The best classification accuracy and the mean classification accuracy of four feature extraction techniques are summarized in Table 2.

| Feature extraction method | KNNC | NBC | SVM |
|---------------------------|------|-----|-----|
| Mean accuracy             | Best accuracy | Mean accuracy | Best accuracy | Mean accuracy | Best accuracy |
| $F_{\text{ULWM-NMF}}$    | 0.9825 | 1   | 0.9775 | 1   | 0.98 | 1   |
| $F_{\text{LW-NMF}}$      | 0.97  | 1   | 0.965  | 1   | 0.9675 | 1   |
| $F_{\text{LW-SA}}$       | 0.9025 | 0.975 | 0.895  | 0.95 | 0.8975 | 0.975 |
| $F_{\text{ULWM-SA}}$     | 0.9675 | 1   | 0.96   | 1   | 0.9625 | 1   |

The comparison results demonstrate that the proposed technique based on ULWM algorithm has obtained significant achievements in classification accuracy than traditional linear wavelet analysis. Moreover, the feature extraction method NMF gives better performance than statistical analysis.

5. Conclusion
This investigation has presented an available scheme based on update lifting morphological wavelet (ULMW) and non-negative matrix factorization (NMF) for wheeled and tracked vehicles classification. The idea under the ULMW is that by utilizing the update operator, means the morphological filter to
preserve the impulsive details and thus better impulsive extraction results can be obtained. Then the feature extraction technique NMF is employed to extract informative features. Experimental results have revealed that the presented scheme achieves the best performance on extracting impulsive features and recognizing targets.

This research has demonstrated clearly that the ULMW algorithm and the NMF technique has great potential to be an effective and efficient tool for wheeled and tracked vehicles classification. It also can be used for recognizing other ground moving target which will produce impulsive features.

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