In this paper, we propose a new supervised classification method based on a modified sparse model for action recognition. The main contributions are three-fold. First, a novel hierarchical descriptor is presented for action representation. To capture spatial information about neighboring interest points, a compound motion and appearance feature is proposed for the interest point at low level. Furthermore, at high level, a continuous motion-segment descriptor is presented to combine temporal ordering information of motion. Second, we propose a modified sparse model which incorporates the similarity constrained term and the dictionary incoherence term for classification. Our sparse model not only captures the correlations between similar samples by sharing dictionary, but also encourages dictionaries associated with different classes to be independent by the dictionary incoherence term. The proposed sparse model targets classification, rather than pure reconstruction. Third, in the sparse model, we adopt a specific dictionary for each action class. Moreover, a classification loss function is proposed to optimize the class-specific dictionaries. Experiments validate that the proposed framework obtains the performance comparable to the state-of-the-art.
explicitly associate each sample with a label in order to perform
the supervised training. How to learn a discriminative dictionary for both sparse data representation and classification is still an open problem.

In this paper, we solve the three problems aforementioned and present a novel framework for action recognition. Fig. 1 shows the flowchart of our framework. We make the following three contributions.

First, traditional interest-point-based representation only utilizes features of a single interest point, and fails to capture adequate spatial or temporal information. It is sensitive to the noise. We consider that spatial and temporal information is very important for action representation. So a novel hierarchical descriptor is presented. The proposed compound appearance and motion feature captures spatial information of neighboring interest points. Furthermore, we propose a continuous motion segment descriptor to represent human action by capturing the temporal ordering information in actions. Spatial and temporal context information is utilized for action representation.

Second, we propose a modified sparse model for classification. Different from traditional sparse representation whose only task is to minimize the reconstruction error, the proposed sparse model targets at classification. Given K action classes, we learn K class-specific dictionaries for representing the data, and then classify the test sample into the class whose dictionary generates the minimum reconstruction error. The similarity-constrained term is utilized to project each descriptor into its local coordinate system which captures the correlations between similar descriptors by sharing bases. The dictionary incoherence term ensures that samples from different classes are reconstructed by independent dictionaries. Our proposed sparse model ensures samples are best reconstructed by their own class specific dictionary.

Third, we introduce a classification loss function for the class-specific dictionary learning. The dictionaries are trained by minimizing the classification loss function. The test sample is classified into the class whose dictionary generates the minimum reconstruction error. The learned dictionaries are remarkably more discriminative.

The remainder of this paper is organized as follows. Section 2 gives a review of related approaches for action representation and sparse representation. Section 3 introduces the compound appearance and motion feature and the continuous motion segment descriptor. Section 4 presents a modified sparse model and a supervised class-specific dictionary learning method for classification. Section 5 demonstrates experimental results. Section 6 concludes this paper.

2. Related work

Over the last few years, many methods for action recognition have been presented and made impressive progress. Approaches can be categorized on the basis of action representation. There are appearance-based representation [13–15], shape-based representation [16–18], optical-flow-based representation [19–21], volume-based representation [22–24] and interest-point-based representation [1–3]. A number of approaches adopt the bag of space–time interest points [2] representation for human action recognition. This representation can be combined with either discriminative [1,25] classifiers, semi-latent topic models [26] or unsupervised generative [3,27] models. Such holistic representation of video sequences does not capture adequate time ordering and arrangement of features in the sequence. To represent actions accurately, some researchers have studied the use of temporal structures for recognizing human activities. Methods based on dynamical Bayesian networks and Markov models improve the performance but require either manual design by experts [28] or detailed training data that are expensive to collect [29]. Other work has aimed at constructing plausible temporal structures in the actions of different agents but does not consider the temporal composition within the movements of a single subject, due in part to their holistic representation. On the other hand, discriminative models of temporal context have also been applied to classification of simple motions in rather simplified environments [30,31].

In recent years, sparse representation has received a lot of attention. It approximates the input signal in terms of a sparse linear combination of the given overcomplete bases in dictionary. Such sparse representations are usually derived by linear programming as an $L_1$ norm minimization problem. Many efficient algorithms have been proposed to capture sparse coding features in the past several years [12,32]. A number of algorithms have also been proposed to learn dictionaries for sparse representations of signals [32,33]. The sparse representation has been successfully applied to many problems, e.g., image restoration...
image denoising and also well applied to classification tasks [6]. Wright et al. [35] consider the recognition problem as one of finding a sparse representation of the test image in terms of the training set as a whole, up to some sparse errors due to occlusion. The algorithm achieves impressive results on public datasets, but fails to handle practical face variations such as alignment and pose. Others try to train a compact dictionary for sparse coding, and the sparse representations of the signals are used as image features trained latter with some classifiers [36].

3. Action representation

Traditional interest-point-based representation only describes features of a single interest point, and fails to capture adequate spatial or temporal information. So it is easily influenced by noise. A novel hierarchical descriptor for action representation is introduced in this section. We present a compound appearance and motion feature, and then design a continuous motion segment descriptor based on our compound features. The compound feature considers the relationship between neighboring interest points, and describes an area around the central interest point, not a single interest point. It captures the spatial information, and it is not sensitive to noise. Furthermore, the continuous motion segment descriptor describes the time ordering information in motion. Different from previous descriptors, our proposed hierarchical descriptor incorporates more spatial and temporal information. So it is more discriminative for action representation and improves the performance of our framework.

3.1. Compound appearance and motion feature

We perform space–time interest point detection and their associated local feature extraction. To detect interest points, the method in [2] is adopted, which is a space–time extension of the Harris operator. A multi-scale approach is adopted. For the initial features, we use the histograms-of-optical-flow (HOF) and histograms-of-oriented-gradients (HOG), which characterize the motion and appearance within a volume surrounding the interest point.

We specifically introduce the compound feature, which incorporates neighborhood information around the central interest point. For a given space–time point, its N closest interest points are collected, where the distance is measured by the normalized Euclidean distance on its 3D position coordinates:

\[ D_p(q_i) = \left( \sum_{i=1}^{3} \frac{1}{\sigma_i} (p(i) - q(i))^2 \right)^{1/2} \]

where \( p=(x_1, y_1, t_1) \) and \( q=(x_2, y_2, t_2) \) record the spatial position and the frame number of two interest points respectively, \( p(i) \) is the \( i \)th dimension of vector \( p \), and \( \sigma_i \) is a weight that scales the x, y or t dimension.

Let \( q(p) = [q_1, \ldots, q_N] \) denote the \( N \) nearest neighboring interest points for the central interest point \( p \). The compound feature of the central point \( p \) is formed from the features of the nearest neighboring points. The contribution that a neighboring point makes to the central interest point is adaptive to the distance between the central point and the neighboring point. Therefore, the compound feature of the interest point \( p \) is defined as follows:

\[ F_p = f_p + \sum_{j=1}^{N-1} \omega_j f_{q_j} \]

\[ \omega_j = \frac{1}{D_p(q_j)} \]

where \( F_p \) is the compound feature of the interest point \( p \), \( f_p \) is the HOG and HOF features of interest point \( p \), and \( f_{q_j} \) is the HOG and HOF features of the \( j \)th nearest interest point to the central interest point, \( \omega_j \) is a parameter, and \( D_p(q_j) \) is the distance between the central point and the \( j \)th nearest neighboring interest point. The neighborhood formation is shown in Fig. 2. Spatio-temporal words are built by applying k-means clustering to compound features of interest points. Each interest point is assigned to a closest spatio-temporal word. Compared with features of single interest point, the compound features adopt information of neighboring points. So they describe features of a larger area and they are more robust for action representation.

3.2. Continuous motion segment descriptor

Based on spatio-temporal words extracted from compound appearance and motion features, a continuous motion segment descriptor is proposed as shown in Fig. 3(a). The process includes three steps. First, we compute the histogram of spatio-temporal
words over a temporal span to represent a motion segment feature $f$, similar to the traditional bag-of-features approach. Second, we concatenate several continuous segment features as our continuous motion segment descriptor $F$ to capture temporal context information, particularly the time ordering information in the motion. The concatenation of continuous segment features can represent a continuous motion process which is discriminative. Third, we assign a label to each continuous motion segment descriptor $F$ by applying k-means clustering to all the continuous motion segment descriptors extracted from the video. We accumulate the occurrences of each label in the video, so each video is represented by a histogram vector. For example, we represent continuous $m$ frames as a motion segment and concatenate $n$ continuous motion segments as our descriptor. So the continuous motion segment descriptor is extracted from continuous $m\cdot n$ frames. From every continuous $m\cdot n$ frames in the video, we extract a continuous motion segment descriptor. Also there is not any manual annotation. Fig. 3(b) illustrates the action representation process of each action video.

The compound appearance and motion feature captures the spatial information of neighboring interest points and our continuous motion segment descriptor makes use of the time ordering information in motion. Incorporating spatial and temporal context information makes our descriptor more discriminative.

4. Sparse representation and dictionary learning

Sparse representation has been successfully applied to solve some problems in computer vision, such as image restoration, image denoising, texture synthesis and texture classification. In this section, we propose a modified sparse representation for action recognition.

Sparse representation means to represent a signal as a linear combination of a few bases of a given dictionary. Mathematically, given a signal $x \in \mathbb{R}^n$ and a dictionary $D \in \mathbb{R}^{k \times n}$, the sparse representation problem is stated as \( \min_{a} \|a\|_0 \text{ s.t. } x = Da \), where \( \|a\|_0 \) is the $L_0$ pseudo-norm of the coefficient vector $a \in \mathbb{R}^n$, the number of non-zero elements. As minimizing $L_0$ is NP-hard, a common approximation is to replace it with the $L_1$-norm. In the noisy case, the equality constraint must be relaxed as well. An alternative then is to solve the unconstrained problem

\[
\min_{a} \|x-Da\|_2^2 + \lambda \|a\|_1
\]

where $\lambda$ is a parameter that balances the tradeoff between the reconstruction error and the sparsity.

The only target of traditional sparse representation is to minimize the reconstruction error, rather than consider classification. As an improvement, each sample is locally approximated by a linear combination of its nearby samples, and the linear weights become its local coordinate coding in LCC [51] and LLC [12]. This method turns a difficult high dimensional nonlinear learning problem into a simple linear learning problem. We consider that the samples in different action classes have different features, so we adopt the class-specific dictionary. In our method, the dictionary incoherence term encourages dictionaries associated to different classes to be independent. Similar samples use similar bases and samples belonging to different classes use absolutely different bases. The reconstruction error is minimized when samples are sparsely represented by the bases in their own dictionaries. We incorporate the similarity constrained term and the dictionary incoherence term. Our proposed sparse representation algorithm is more effective for classification.

For dictionary learning, we propose a classification loss function. The target is to improve the class specific dictionaries to better reconstruct samples of their own classes than that of other classes. To minimize the classification loss function, we optimize the class specific dictionaries for more effective classification. The optimization is carried out using an iterative approach that is composed of two steps: the sparse representation step on a fixed $D$ and the dictionary update step on fixed $a$.

4.1. Sparse representation and classification

Let $x'_i, i = 1, \ldots, K, j = 1, \ldots, m_i$ denotes a video representation in class $i$ as described in Section 3 and $B_i$ is the corresponding dictionary trained for class $i$. The proposed similarity-constrained and dictionary-incoherence sparse model (SDSM) is computed as

\[
\min_{|a_i|} \sum_{j=1}^{m_i} \sum_{i=1}^{K} \|x'_i - B_i a_i^j\|_2^2 + \lambda \|d_i\|_1 + \eta \sum_{p \neq q} \|B_p^j B_q^j\|_2^2
\]

where “.” denotes the element-wise multiplication, and the notation $d_i^j$ is the sparse code corresponding to the video descriptor $j \in [1, m_i]$ in class $i$. $\|B_p B_q\|_F$ denotes the dictionary incoherence term. $\|d_i\|_1$ is the similarity constrained term, and $d_i^j$ is the similarity adapter that gives different freedom for each basis vector proportional to its similarity to the input signal $x'_i$. Specifically

\[
d_i^j = \exp\left(\frac{\text{dist}(x'_i, B_i)}{\sigma}\right)
\]

As in [12], $\text{dist}(x'_i, B_i) = [\text{dist}(x'_i, b_1), \ldots, \text{dist}(x'_i, b_n)]^T$, and $\text{dist}(x'_i, b_n)$ is the Euclidean distance between $x'_i$ and $b_n$. $\sigma$ is used for adjusting the weight decay speed for the similarity adapter. Usually, we further normalize $d_i^j$ to be between (0, 1] by subtracting $\max(\text{dist}(x'_i, B_i))$ from $\text{dist}(x'_i, B_i)$.

The SDSM reconstruction error is

\[
\tilde{R}(x'_i, B_i) = \min_{d_i^j} \|x'_i - B_i d_i^j\|_2^2 + \lambda \|d_i^j\|_1 + \eta \sum_{p \neq q} \|B_p^j B_q^j\|_2^2
\]

For classification, once the dictionaries have been learned, the class $i_0$ for a given new sample $x$ is found by solving $i_0 = \arg\min_{i=1, \ldots, K} \tilde{R}(x, B_i)$.

Fig. 4 shows the comparison between standard sparse coding (SC), locality-constrained linear coding (LLC) and our SDSM. For SC, the bases are selected from all the samples. LLC only selects bases similar to input. LLC code captures the correlations between similar inputs. SDSM not only has the properties of LLC, but also considers dictionary incoherence. The proposed sparse model selects samples that can best represent their own action class as...
the bases of their class-specific dictionary. It does not select samples similar to other classes as bases. In the training samples, we compute the distance between the histogram representation of a video and the center of each action class. In practice, there may be complex background in some action videos. So the bases selected by SDSM can better represent their own action class than that of other classes, as the bases of their class-specific dictionary, which are more close to the center of their own action class than in SDSM discards the noise samples and selects the samples, selected samples belonging to other classes are similar to the other classes. We call these action videos "noise". For this reason, the bases of their class-specific dictionary. It does not select samples similar to other classes as bases. In the training samples. The selection of the bases by LLC may be complex background in some action videos. So the bases selected by SDSM can better represent their own action class and be more discriminative for classification than that selected by LLC.

4.2. Supervised class-specific dictionary learning

To learn a discriminative sparse model instead of pure reconstruction, we propose a supervised method to learn the dictionaries \( \{B_i\}_{i=1}^{K} \) of sparse representation. To evaluate the effect of dictionaries for classification, we propose a classification loss function:

\[
E(B^{(t)}_{i=1}) = \sum_{i=1}^{m} \sum_{k \neq i} \left( \hat{R}(x_{i}^{t}, B_i) - \sum_{i} \hat{R}(x_{i}^{t}, B_i) \right)
\]

(8)

Minimizing \( E(B^{(t)}_{i=1}) \) over \( B_i \), the learned class specific dictionaries will better reconstruct samples of their own classes than dictionaries of other classes, and therefore, be more discriminative for classification. The dictionaries optimization is carried out using an iterative approach that is composed of two steps: the sparse coding step on a fixed \( \{B_i\}_{i=1}^{K} \) according to our SDSM model and the dictionary update step on fixed \( a^{t}_i \). We elaborate the class specific dictionary update step on fixed \( a^{t}_i \) as follows:

\[
\frac{\partial E}{\partial B_{i}} = \sum_{i=1}^{m} \sum_{j=1}^{k} \frac{\partial \hat{R}(x_{i}^{t}, B_i)}{\partial B_{i}} \sum_{k \neq i} \hat{R}(x_{i}^{t}, B_i)
\]

(9)

where \( B = B_1, B_2, \ldots, B_K \)

\[
\frac{\partial \hat{R}(x_{i}^{t}, B)}{\partial B_{mn}} = \lim_{\Delta B_{mn} \to 0} \frac{\hat{R}(x_{i}^{t}, B + \Delta B_{mn}) - \hat{R}(x_{i}^{t}, B)}{\Delta B_{mn}}
\]

(10)

\[
\frac{\partial \hat{R}(x_{i}^{t}, B)}{\partial B_{mn}} = \lim_{\Delta B_{mn} \to 0} \frac{\hat{R}(x_{i}^{t}, B + \Delta B_{mn}) - \hat{R}(x_{i}^{t}, B)}{\Delta B_{mn}} 
\]

(11)

where \( B_{mn} \) is the element of matrix \( B \). Therefore, the problem is reduced to compute the gradients of the sparse representation vector \( a^{t}_i \) with respect to the dictionaries \( \{B_i\}_{i=1}^{K} \). In order to establish the relationship between a sparse code \( a^{t}_i \) and \( B_i \), we first find the fixed point equations by computing the gradient with respect to \( a^{t}_i \) on Eq. (7) at its minimum \( \hat{\alpha} \):

\[
\frac{\partial \hat{R}(x_{i}^{t} - B_{i} a^{t}_i)}{\partial a^{t}_i} = -\lambda \frac{\partial \hat{R}(x_{i}^{t} - B_{i} a^{t}_i)}{\partial a^{t}_i}
\]

leading to

\[
2(B_{i}^{T} B_{i} a^{t} - B_{i}^{T} x_{i}^{t})|_{a^{t} = \hat{\alpha}} = -\lambda a^{t}_i \text{sign}(a^{t}_i)|_{a^{t} = \hat{\alpha}}
\]

(13)

where \( \text{sign}(a^{t}_i) \) is a vector function on each element of vector \( a^{t}_i \).

In Eq. (13), \( a^{t}_i \) is not linked with \( B_i \) explicitly. To calculate the gradient of \( a^{t}_i \) with respect to \( B_i \), we take derivative of \( B_i \) on both sides of Eq. (13):

\[
\frac{\partial (2(B_{i}^{T} B_{i} a^{t} - B_{i}^{T} x_{i}^{t}))}{\partial B_{mn}} = \frac{\partial (-\lambda a^{t}_i \text{sign}(a^{t}_i))}{\partial B_{mn}}
\]

(14)

The "sign" function on the right side does not continue at zero. However, since the left side of Eq. (14) cannot be infinite, \( \frac{\partial (-\lambda a^{t}_i \text{sign}(a^{t}_i))}{\partial B_{mn}} = 0 \).

\[
\frac{\partial (2(B_{i}^{T} B_{i} a^{t} - B_{i}^{T} x_{i}^{t}))}{\partial B_{mn}} = 0
\]

(15)

\[
\frac{\partial a^{t}_i}{\partial B_{mn}} = (B_{i}^{T} B_{i})^{-1} \left( \frac{\partial B_{i}^{T} B_{i} a^{t}_i}{\partial B_{mn}} - \frac{\partial B_{i}^{T} a^{t}_i}{\partial B_{mn}} \right)
\]

(16)

Substituting Eq. (16) into (11), \( \hat{\alpha} R(x_{i}^{t}, B_{i}) / \partial B_{mn} \) is solved. Then based on Eq. (9), we get the gradient of classification loss \( E \) with respect to dictionaries \( B_1, B_2, \ldots, B_K \) for the class specific dictionary update.

4.3. The process of SDSM classification

For each class, we first obtain bases of the dictionary \( B_i \) by k-means clustering to all the training samples of class \( i \) for initialization. Second, we select bases from the initialization of dictionary \( B_i \) through the proposed sparse model. To regard the similarity constrained term, we only keep the set of bases with large weights. To regard the incoherence of different dictionaries, we discard the bases which are far from the center of the bases in their own action class. All the bases kept form the class-specific dictionary \( B_i \). By the same way, we obtain all the class specific dictionaries. Third, dictionaries are updated by looping through all the training samples. The classification loss function is minimized by gradient descent method. Finally, for classification, the test sample is classified into the class whose dictionary generates the minimum reconstruction error. The process of SDSM classification is illustrated in Algorithm 1.

Algorithm 1. SDSM classification

Input: \( B_{mn} \in \mathbb{R}^{D \times H}, \ B_{mn} \in \{B_1, B_2, \ldots, B_K\} \)

Output: test video \( x_{io} \in \text{class} i_0 \)

Dictionary learning:

\( B \leftarrow B_{init} \)

for \( i = 1 \) to \( K \) do

for \( j = 1 \) to \( m_i \) do

\( a^{t}_i \leftarrow H \times 1 \) zero vector.

for \( m = 1 \) to \( H \) do

\( d_{mn} \leftarrow \exp^{-1}(-||x_{i}^{t} - B_{mn}||^2/\sigma) \)

end

\( d_{mn} \leftarrow \text{normalize}(d_{mn}) \)

\( d_{mn} \leftarrow \text{arg} \min_{a} ||x_{i}^{t} - B_{mn}a||^2 + \lambda ||a||^2 \)

end

\( i_0 \leftarrow \text{p} \left( |d_{mn}(p)| > 0.01 \right), B_{init} \leftarrow B_{i_0}, \text{id} \)

end
5. Experiments

We evaluate our approach on three benchmark datasets for human action recognition: the KTH actions dataset [49], the Weizmann action recognition dataset [50], and the UCF Sports dataset [43]. All the video clips contain primarily a single action of interest. Examples of the datasets are shown in Fig. 6.

5.1. Parameters

We extract sparse Harris 3D points on the KTH and Weizmann datasets, and perform dense and multi-scale interest point extraction on the UCF Sports dataset. For the compound appearance and motion feature, we collect 6 nearest neighboring interest points. It describes a larger area than single interest point. Obviously, the compound appearance and motion feature is more robust for action representation. The recognition rate is raised to 94.17% when we collect six nearest neighboring interest points. It describes a larger area than single interest point.

For example, the recognition accuracies for some actions are high up to 97%, such as “box” and “hand clap”. Fig. 7 illustrates that the proposed compound appearance and motion feature improves the performance of our framework. Traditional interest point based methods only utilize features of single interest point. It can only describe a very small area. So the accuracy can easily be influenced by noise. The recognition rate is only 92.86%. However, the proposed compound feature makes full use of the information of neighboring interest points. It describes a larger area than single interest point. Obviously, the compound appearance and motion feature is more robust for action representation. The recognition rate is raised to 94.17% when we collect six nearest neighboring interest points to generate the compound feature. Table 2 shows the contribution of the proposed hierarchical descriptor. Each of samples in each action class as the bases in the class-specific dictionary. On the UCF Sports dataset, the number of videos in each action class is different. So the number of bases in each class-specific dictionary is different. Because the dataset is not very large, the number of bases in each class-specific dictionary is near to the number of training samples in corresponding action class.

5.2. Experiments on the KTH dataset

The KTH action dataset contains six types of human actions: boxing, hand waving, hand clapping, walking, jogging, and running. For example, the recognition accuracies for some actions are high up to 97%, such as “box” and “hand clap”.

Table 1 shows the average confusion matrix across all scenarios. It is seen that our approach works excellently on most actions. For example, the recognition accuracies for some actions are high up to 97%, such as “box” and “hand clap”. Fig. 7 illustrates that the proposed compound appearance and motion feature improves the performance of our framework. Traditional interest point based methods only utilize features of single interest point. It can only describe a very small area. So the accuracy can easily be influenced by noise. The recognition rate is only 92.86%. However, the proposed compound feature makes full use of the information of neighboring interest points. It describes a larger area than single interest point. Obviously, the compound appearance and motion feature is more robust for action representation. The recognition rate is raised to 94.17% when we collect six nearest neighboring interest points to generate the compound feature. Table 2 shows the contribution of the proposed hierarchical descriptor. Each of samples in each action class as the bases in the class-specific dictionary. On the UCF Sports dataset, the number of videos in each action class is different. So the number of bases in each class-specific dictionary is different. Because the dataset is not very large, the number of bases in each class-specific dictionary is near to the number of training samples in corresponding action class.

Table 2 Contribution of proposed features.

<table>
<thead>
<tr>
<th>Action feature</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional single interest feature</td>
<td>92.18</td>
</tr>
<tr>
<td>(A) Compound feature</td>
<td>93.19</td>
</tr>
<tr>
<td>(B) Continuous motion segment feature</td>
<td>92.69</td>
</tr>
<tr>
<td>A + B</td>
<td>94.17</td>
</tr>
</tbody>
</table>
the proposed features offers more discriminative power than traditional single interest point feature, and in combination our hierarchical descriptor provides a richer representation than any single proposed feature. The hierarchical descriptor achieves the highest recognition rate. The compound feature incorporates neighborhood spatial information and our continuous motion segment descriptor captures the action temporal ordering information. Experimental results validate that the proposed hierarchical descriptor is effective for capturing the spatial and temporal information which is important for action representation.

To prove the effectiveness of the proposed sparse model and the class specific dictionary learning algorithm for classification, we make comparisons with other classifiers. The results are shown in Table 3. The performance of SVM is better than that of sparse representation without dictionary learning (WDL), and our sparse model with supervised dictionary learning (SDL) algorithm achieves the best performance. The result of WDL is comparable with that of SVM which is a powerful classifier. It proves that the proposed sparse model based on class specific dictionaries is discriminative for classification. The accuracy of SDL is higher than that of WDL and SVM. It validates that our proposed dictionary learning method is effective for boosting the recognition rate. We also compare the accuracy of our sparse model with that without the dictionary incoherence term (WDI). When we remove the dictionary incoherence term, the accuracy of WDI is lower than that of SDL. It validates that the dictionary incoherence term can improve the accuracy. Comparing the results when different lambda is chosen in the sparse model, the performance is robust as shown in Fig. 8. Experiments show that our method achieves the state-of-the-art result on the KTH dataset as shown in Table 4.

### 5.3. Experiments on the Weizmann dataset

In order to further validate the performance of our algorithm, we also conducted experiments on the Weizmann dataset. The Weizmann action dataset contains 10 actions (bend, jumping, jack, jump forward, jump in place, jump sideways, skip, run, walk, wave with two hands, and wave with one hand) performed by 9 different subjects. This dataset contains videos with static cameras and simple background, but it provides a good test environment to evaluate the performance of the algorithm when the number of categories is larger compared with the KTH dataset (a total of six categories). In each run, eight actors’ videos are used as the training set and the remaining one person’s videos as the testing set. So the results are the average of nine times runs.

Table 5 shows the average confusion matrix. The recognition accuracies for some actions are high up to 100%. Table 6 illustrates the comparisons of two proposed features and their combination. Each feature offers discriminative power, and in combination our hierarchical descriptor provides a richer representation that can boost recognition rate. Similar to the performance on KTH dataset, our SDL method outperforms SVM and WDL as shown in Table 7. When we remove the dictionary incoherence term, the accuracy of WDI remains the same as that of SDL. Videos on the Weizmann dataset have little noise with static cameras and simple background. So the recognition rate is higher than that of KTH, but there are still some confused actions with small difference. Experiments show that our framework leads to the results comparable to the state-of-the-art performance as shown in Table 8.

### 5.4. Experiments on the UCF sports dataset

The authors of [43] have collected a large set of action clips from various broadcast sport videos. The actions in this dataset include diving, golf swinging, kicking, lifting, horseback riding, running, skating, swinging a baseball bat, and pole vaulting. The pole vaulting sequences were removed from the original database due to copyright concerns. The videos on UCF sports dataset are captured from much more camera views. Different from the datasets above, the UCF Sports is a challenging dataset for action recognition. The actions are featured in a wide range of scenes.

<table>
<thead>
<tr>
<th>Action feature</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional single interest feature</td>
<td>94.5</td>
</tr>
<tr>
<td>(A) Compound feature</td>
<td>95.6</td>
</tr>
<tr>
<td>(B) Continuous motion segment feature</td>
<td>94.5</td>
</tr>
<tr>
<td>A + B</td>
<td>96.7</td>
</tr>
</tbody>
</table>

### Table 6

<table>
<thead>
<tr>
<th>Year</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>91.80</td>
</tr>
<tr>
<td>2009</td>
<td>93.17</td>
</tr>
<tr>
<td>2009</td>
<td>93.80</td>
</tr>
<tr>
<td>2009</td>
<td>94.50</td>
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<td>2010</td>
<td>94.22</td>
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<tr>
<td>2010</td>
<td>94.53</td>
</tr>
<tr>
<td>2011</td>
<td>93.90</td>
</tr>
<tr>
<td>2011</td>
<td>93.60</td>
</tr>
<tr>
<td>2011</td>
<td>94.17</td>
</tr>
</tbody>
</table>
and viewpoints. The dataset is tested in a leave-one-out manner, cycling each example in as a test video one at a time.

Table 9 shows the average confusion matrix across all scenarios. Table 10 illustrates the comparison of two proposed features and their combination. As the experimental results on the datasets above, the two proposed features are both discriminative and in combination our hierarchical descriptor provides a richer representation based on compound features and continuous motion segments. Our descriptor incorporates spatial and temporal information which represents actions more accurately. We find a separating surface to put all the videos belonging to the same action class captured from different camera views in the same class in SVM. So WDL and SDL both achieve better performance than SVM on this dataset. The performance of WDI is lower than that of SDL. It validates that the dictionary incoherence term can improve the accuracy. The overall mean accuracy we obtain on this dataset is 86.6%, which is comparable to the state-of-the-art performance as shown in Table 12. Even in the challenging and realistic action dataset, our method also performs reliable recognition rate. It further indicates that the proposed hierarchical descriptor is discriminative and our sparse model is effective for classification.

6. Conclusions

In this paper, we have presented a novel method for action representation based on compound features and continuous motion segments. Our descriptor incorporates spatial and temporal information which represents actions more accurately.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Effectiveness of supervised dictionary learning.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach</td>
<td>Year</td>
</tr>
<tr>
<td>SVM</td>
<td>1.00</td>
</tr>
<tr>
<td>WDL</td>
<td>1.00</td>
</tr>
<tr>
<td>SDL</td>
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</table>

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Comparison with previous work on the Weizmann dataset.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach</td>
<td>Year</td>
</tr>
<tr>
<td>Klaser et al. [46]</td>
<td>2008</td>
</tr>
<tr>
<td>Fathi and Mori [47]</td>
<td>2008</td>
</tr>
<tr>
<td>Bregonzio et al. [38]</td>
<td>2009</td>
</tr>
<tr>
<td>Ali and Shah [21]</td>
<td>2010</td>
</tr>
<tr>
<td>Seo and Milanfar [48]</td>
<td>2010</td>
</tr>
<tr>
<td>Our method</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 9</th>
<th>Confusion matrix on the UCF Sports dataset.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>Diving</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Diving</td>
<td>1.00</td>
</tr>
<tr>
<td>Golf Swing</td>
<td>0.00</td>
</tr>
<tr>
<td>Kick</td>
<td>0.05</td>
</tr>
<tr>
<td>Lift</td>
<td>0.00</td>
</tr>
<tr>
<td>Ride Horse</td>
<td>0.00</td>
</tr>
<tr>
<td>Run</td>
<td>0.00</td>
</tr>
<tr>
<td>Skateboard</td>
<td>0.00</td>
</tr>
<tr>
<td>Swing</td>
<td>0.00</td>
</tr>
<tr>
<td>Walk</td>
<td>0.00</td>
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</tbody>
</table>

Fig. 9. The test sample is best reconstructed by samples in the same action class from similar camera view.

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Contribution of proposed features.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action feature</td>
<td>Accuracy (%)</td>
</tr>
<tr>
<td>Traditional single interest feature</td>
<td>79.3</td>
</tr>
<tr>
<td>(A) Compound feature</td>
<td>81.3</td>
</tr>
<tr>
<td>(B) Continuous motion segment feature</td>
<td>82.7</td>
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<tr>
<td>A + B</td>
<td>86.6</td>
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<table>
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<tr>
<th>Table 11</th>
<th>Effectiveness of supervised dictionary learning.</th>
</tr>
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<td>Approach</td>
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<tr>
<td>WDL</td>
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<tr>
<th>Table 12</th>
<th>Comparison with previous work on the UCF Sports dataset.</th>
</tr>
</thead>
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<tr>
<td>Approach</td>
<td>Year</td>
</tr>
<tr>
<td>Rodriguez et al. [43]</td>
<td>2008</td>
</tr>
<tr>
<td>Yeffet and Wolf [44]</td>
<td>2009</td>
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<tr>
<td>Wang et al. [45]</td>
<td>2009</td>
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<tr>
<td>Yao et al. [52]</td>
<td>2010</td>
</tr>
<tr>
<td>Kovashka and Grauman [53]</td>
<td>2010</td>
</tr>
<tr>
<td>Le et al. [42]</td>
<td>2011</td>
</tr>
<tr>
<td>Our method</td>
<td></td>
</tr>
</tbody>
</table>
have also introduced a supervised classification based on class specific sparse representation and dictionary learning. We have proposed a classification loss function for the class specific dictionary learning as well. Our framework achieves comparable performance on the datasets above. The experiments have validated that our proposed hierarchical descriptor is discriminative, and the proposed sparse model incorporating supervised dictionary learning is effective for classification.

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