Pattern Recognition ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Pattern Recognition

journal homepage: www.elsevier.com/locate/pr

Shape decomposition and classification by searching optimal part pruning sequence

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ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form
11 December 2015
Accepted 6 January 2016

Keywords:
Shape decomposition
Optimal pruning sequence
Dynamic programming
Shape classification

ABSTRACT

Representing shapes in terms of meaningful parts is a fundamental problem in shape analysis and part-based object representation. Decomposition methods typically utilize handcrafted geometric rules in a nondata-driven manner. However, these rules are insufficient to mimic human decomposition behavior, which limits the applications of decomposition in vision tasks. In this paper, we propose a novel shape analysis framework that integrates shape decomposition with shape classification in fundamental level. We first train probabilistic models for contours and part cuts involved in decomposition process. Next, we construct a data structure called "decomposition graph" whose nodes represent intermediate contours and whose edges represent part cut selections. The decomposition and classification results are obtained by efficiently searching the optimal path on decomposition graph with minimum energy. Experimental results show that such integrated framework improves the decomposition performance under various shape deformations and achieves competitive classification performance.

1. Introduction

Decomposing a shape into visually friendly and meaningful parts is a fundamental task for human vision [1,2]. Despite the mechanism for shape decomposition of human beings is still unclear, it is strongly suggested that human recognition of shapes is part-based [3]. In last two decades, computational methods that mimic human decomposition have been extensively studied. Various part-related factors and decomposition methods have been proposed and achieved impressive progress [4–18].

However, computational decomposition still remains a challenging problem. The counter-intuitive decomposition results are often encountered when dealing with certain situations, such as ambiguous part structures and abrupt boundary disturbances. One of the most important reasons is that the existing decomposition methods utilize handcrafted geometric rules to guide decomposition. These rules are summarized from psychological studies and implemented in a nondata-driven manner, which are insufficient to comprehensively describe the human decomposition behavior. In addition, the decomposition results, consisting of segmentation points and part cuts, are low-level features that are difficult to capture the characteristics of shapes. For these reasons, the computational decomposition results are not always in consistent with human decomposition. As shown in Fig. 1(a), although the part cuts on birds' neck and legs follow the geometric rules, the yielding part structure still conflicts to human perception. The current status of computational decomposition limits its application in visual tasks. For example, although part-based representation is deemed to play an important role in human shape recognition [3,19], it has seldom been used in computational shape classification. Recently, Macrini et al. [13,20] proposed methods that classify shapes according to matching scores of decomposition results. However, their classification and decomposition are in two separate stages where the learning techniques are not involved.

To improve the performance of computational decomposition and make it applicable to classification, in this paper, we integrate shape decomposition and classification in a unified framework. The integration is in fundamental level in that we use class information in decomposition and use part-based descriptor to construct classifier, benefiting both decomposition and classification tasks. Our objective is to maximize the joint posterior probability of decomposition and classification. By applying the chain rule and the sequential pruning, we expand the joint posterior probability into a set of probabilistic terms involving class label, part cuts and intermediate remained contours. Next, we learn computational models for these probabilistic terms from training data. Then, we show that our objective leads to a discrete optimization problem that can be efficiently solved via dynamic programming. The decomposition is represented by a sequence of

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http://dx.doi.org/10.1016/j.patcog.2016.01.005
0031-3203/

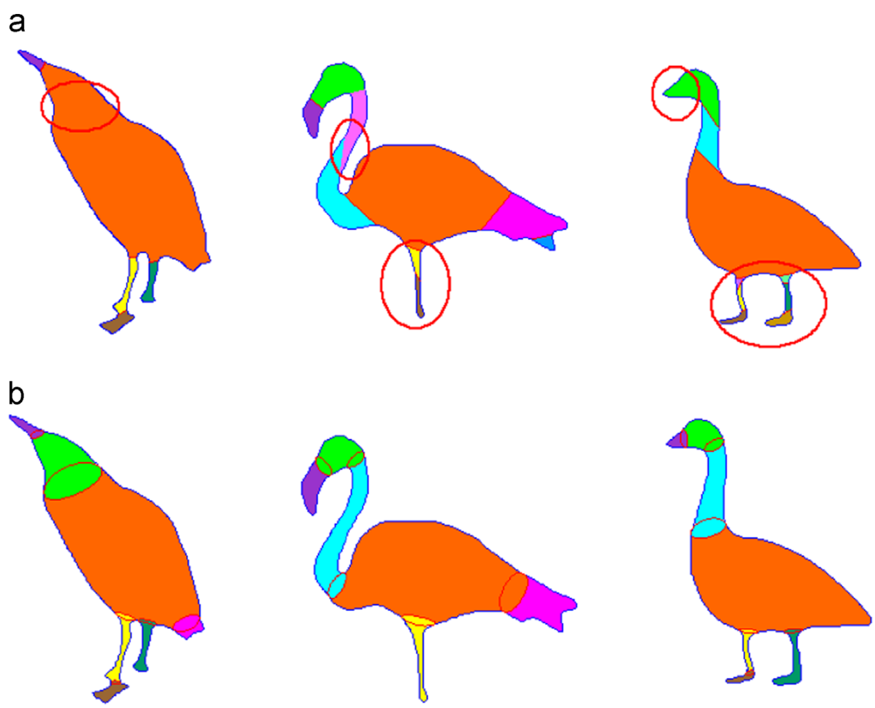

Fig. 1. Decomposition on category of birds: (a) is the result of [15]. The incorrect decompositions are marked in red ellipses and (b) shows the result of our approach. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

pruned parts(or part cuts). Fig. 1(b) shows our decomposition result on bird category. Comparing to [15], our method achieves higher decomposition accuracy and more robust part structure, thus it has more applied potential in further visual tasks.

Different from existing methods that perform decomposition by detecting geometric cues and implementing geometric rules, we decompose shapes in a data-driven manner. The probabilistic models learned from human decomposition results provide complementary information to geometric cues, improving the performance of disambiguating part structures. Instead of using part-based similarity score to construct shape classifier where the decomposition and recognition are irrelative and separated, we infer the decomposition and classification results simultaneously. This process is more consistent with human vision behavior, so as to improve the decomposition performance as well as facilitate the classification.

This paper makes the following contributions:

1. It proposes a novel shape analysis framework that integrates decomposition and classification in fundamental level. The inference of part structure is performed via searching for optimal part pruning sequence. It is a general framework that be independent of geometric cues, shape features and computational models.
2. It takes the effect of prior knowledge to decomposition into account. We learn probabilistic models from human-labeled shapes and human-decomposed parts, and use them to supervise the decomposition process. These models simulate the role of cognitive knowledge in human decomposition, so as to improve the consistency of computational decomposition to human decomposition.
3. It proposes an efficient algorithm to infer the decomposition and classification. By constructing the decomposition graph, the optimal part pruning sequence is transformed into a path on the graph with minimum energy where the dynamic programming can be applied. This algorithm is of polynomial complexity.

The rest of the paper is organized as follows. We review the related work in Section 2. Then, we introduce our main idea in Section 3. Section 4 describes the computation of probabilistic models. The inference algorithm for decomposition and classification is presented in Section 5. In Section 6, we evaluate our decomposition and classification performance on several benchmark datasets. Finally, we conclude our method in Section 7.

2. Related work

We give a brief review on two topics related to our work: (a) shape decomposition, and (b) shape classification.

2.1. Shape decomposition

Psychological researchers on human vision suggested that people understand shapes by representing them in terms of parts [1–3]. Hoffman and Richards [1] and Biederman [2] have argued that parts supply a first index to a possible object category or identity and that objects can thus be recognized on the basis of their parts. Compared with template descriptor, part-based descriptor has the following advantages. (1) As stated by Siddiqi et al., it is more suitable to deal with occlusions, movements, growth and deletion [21]. (2) As stated by Pinker, it is better at handling deformations for semi-rigid and non-rigid objects [22]. In a word, decomposing shape into parts is very natural and useful for human vision.

Aiming at obtaining decomposed parts being consistent with human vision, many computational decomposition methods have been proposed. Various part-related factors, such as curvature [1], cut length [23,24], convexity [8,25], and boundary points [7] have been investigated as visual cues for decomposition. However, the mainstream approaches prefer symmetry axis [4,6,10,11,13,20] because it combines the feature of boundary and region. Recently, researchers tried to simulate complex interactions among various part-related factors by modeling decompositions subject to