Applied Soft Computing 69 (2018) 368–380

Contents lists available at ScienceDirect

Applied Soft Computing

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

Syntactic-geometric-fuzzy hierarchical classifier of contours with application to analysis of bone contours in X-ray images

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ARTICLE INFO

Article history:
Received 29 August 2017
Received in revised form 29 March 2018
Accepted 20 April 2018
Available online 1 May 2018

Keywords:
Hierarchical classifier
String language
Primitive
Equivalence class
Contour analysis
Fuzzy set
Bone contour

ABSTRACT

In this paper, a new hierarchical method of contour analysis is proposed. The first stage of the analysis is based on the syntactic approach in which elementary segments of the contour are extracted by using geometric features. As a result, each extracted segment belongs to one of the equivalence classes which make the set of primitives. The contour is described as a string of primitives. The applied syntactic approach is a generalization of a classical shape language. Such description enables to classify some cases, but not all. Therefore, the second stage of the classification is applied. It consists in analysing other local geometric features of the contour in the context of the syntactic description obtained at the first stage of the analysis. The values of these features are used to define the arguments of the membership functions of the family of fuzzy sets which is the basis for the contour classification at the second stage of the analysis. The proposed formalism has been applied effectively to the recognition of bone contours in X-ray images. Healthy bones, the bones with erosions and the bones with osteophytes have been classified correctly. The proposal described in this paper turned out to be effective in the classification of contours of bones.

1. Introduction

Many investigations in pattern recognition have taken as a goal the creation of a general method for constructing an effective system which would be able to recognize or analyse objects or scenes. So far, however, only biological systems, first of all, humans, are the only ones who have abilities for solving this task in general. The artificial systems, including computer ones, suffer from lack of the general method of pattern recognition and scene analysis. All the proposed approaches are partial which means that, on the one hand, they are based on various theoretical foundations and, on the other hand, they are effective in some applications and ineffective in many others [27]. Therefore, the strategy which consists in increasing the possibilities of the artificial systems, which turned out to be effective in some applications, seems to be a good approach.

The analysis of contours is the topic discussed in this paper. This problem is crucial in engineering and in numerous papers it has been considered in the context of robotics and intelligent manufacturing [11–13,16,29,30,34]. There exists, however, another interesting area in which analysis of contours plays an important role. The analysis of bone contours in X-ray pictures is the starting point of detection and localization of such pathological changes as osteophytes and erosions.

In this paper, a two-stage hierarchical classifier of contours is proposed. The introduced methodology follows the idea of the hierarchical classification proposed in [49]. Thus, according to this idea, at the first stage, the introductory classification is done. At the second stage, the final classification is performed in the classes in which introductory classification turned to be insufficient.

In the proposed classifier, the string language, introduced by Jakubowski and applied by him to intelligent manufacturing [29–34], is the basis for bones contour analysis as the first stage of classification. Since the original Jakubowski's approach suffers from crucial disadvantages when it is applied to the analysis of contours of bones, a crucial generalization of his approach is proposed. On the other hand, however, Jakubowski's approach allows us to create complex contour features description which is useful for the bone contours analysis in the context of detecting pathological changes – erosions and osteophytes. The classical Jakubowski's approach based on a finite collection of predefined primitives, sufficient for description of regular shapes of machine parts, is not sufficiently flexible to describe far more irregular contours of natural objects. In this paper, the formalism, based on primitives defined as equivalence classes, is proposed. In the first step the potentially infinite set of line segments and curves, which are characterized

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https://doi.org/10.1016/j.asoc.2018.04.038
1568-4946/

by geometric features, is introduced. Then, on the introduced set, an equivalence relation is defined. In such a way sixteen classes of abstraction, which are a generalization of the primitives introduced by Jakubowski [29], are obtained – see Theorem 3.1 and Corollary 3.3 that are the main result of the theoretical part of this paper. Analysis of complex contours in a purely syntactic approach turned to be insufficient. Therefore, the proposal of hierarchical analysis, in which the proposed syntactic approach is the first stage, is put forward. The second stage of the classification consists in analysing local geometric features of the contour in the context of the syntactic description obtained at the first stage of the analysis. The values of these features are used to define the arguments of the membership functions of the family of fuzzy sets which is the basis for the contour classification at the second stage of the analysis.

The effective application of the introduced formalism to bone contours analysis in X-ray images is shown. The contours recognition has been performed in the context of finding pathological changes such as erosions and osteophytes, which identification is crucial for the medical diagnosis of inflammatory and degenerative diseases [18–20]. The proposed method allowed us to classify correctly healthy bones, the bones with erosions and the bones with osteophytes.

It should be mentioned that this paper is a continuation of studies described in [4,5,9,14,15,37], that concern automatic hand radiographs analysis. Such studies are a part of the extensive stream of studies concerning artificial intelligence methods application, in particular, syntactic ones, in medical image understanding [2,46,47,55].

The paper is organized in the following way. Motivations are presented in Section 2. The proposed hierarchical classifier of the contour analysis is described in Section 3. The application to the analysis of bone contours is shown in Section 4.

2. Motivations

X-ray imaging is the basis of diagnosis of musculoskeletal diseases. The imaging enables the physicians both to diagnose the disease and to monitor the disease progression and response to treatment. The early diagnosis is crucial because the time from the disease onset to treatment initiation is important for the overall prognosis.

In general, there are two groups of rheumatic diseases – with inflammation and degenerative changes without inflammation. From the clinical point of view, the key issue is to distinguish between inflammatory and degenerative diseases because inflammatory entities have a worse prognosis and require more aggressive pharmacologic treatment. Degenerative changes manifest in the presence of bony overgrowth in the form of osteophytes localized on margins of cortical bone adjacent to the attachment of joint capsule and ligaments. In inflammation diseases, pathologic process invades and destruct bone, in the form of erosions. X-ray pictures of hands allow us to detect both bone damage and bone synthesis. During early disease process the changes are often scarce and difficult to capture, and even for a very experienced radiologist or rheumatologist the definite judgment of certain X-ray signs, for example, osteophytes or erosions, is often challenging. That is why the attempt to use the artificial intelligence methods, to facilitate better diagnosing is of great value.

X-ray images automatic analysis by using computers, in particular, hand images analysis, is an intensively exploited scientific topic [2,22]. In general, there are three main topics in investigations of hand images by using computer systems: analysis of the width in joints, analysis of the bone density and analysis of the bone contours. The first topic is well worked-out [1,20,23,36,50] and there are significant contributions to the second one [51–54]. It seems, however, that apart from a few introductory papers [2,5,9,38,58], the third topic is not worked-out at all. This is caused by the lack of a proper theoretical tool which could be the basis for the analysing algorithm. In [38] the local gradient method was used to detect erosions. It is, however, impossible to assess the efficiency of the method because the authors calculated the AUC ROC curve for the whole bone instead of its epiphysis, which was pointed out in [58]. Furthermore, the method was verified for a small number of images. In [2] cellular neural networks were used to detect osteophytes. The method was also assessed by using very few images – only nine X-ray pictures of a hand were analyzed. One of them did not have osteophytes. The authors signalized that the specificity of the method was excellent only for five radiograms which means that for four pictures the proportion of false positive detections was high. In [3,5,6,9] syntactic methods were used. They are based on string languages methodology. This paper is a continuation of these studies, first of all, the ones described in [6].

Changes in finger bone contours, observed in hand radiographs, are a crucial point in medical diagnosis and they support important information for evaluation of therapy efficiency. As it has been aforementioned, it is extremely important to diagnose pathological changes, such as erosions and osteophytes, in the early stages of a disease. This means that differences of the order of 0.5mm between the contours of pathologically changed bones and unaffected ones need to be identified. According to the aforementioned introductory studies [5,9] it seems that the string language, introduced by Jakubowski, could be used as the theoretical basis for the computer system for bone contour analysis. Predefined primitives, however, in the case of the Jakubowski's string language eight line segments and eight circle quadrants, denoted as s_{ij}, $i, j \in \{1, 2, 3, 4\}$ – see Fig. 1 and [29], are improper for representation of fragments of bone contours because of their irregularities. Attempts that were made to approximate bone contours by given a priori primitives were finished by encoding the contour by a set of extremely short segments, in most cases the line ones [5]. It should be mentioned that Jakubowski tried to introduce more flexible representations of analysed contour fragments by homothetic transformation of the basic primitives and fuzzy linguistics variables [30], but these possibilities were only mentioned and were not be exploited in the formalism development and applications [31–34]. The attempt which consists in using Jakubowski-like primitives in Shaw language in order to detect erosions and osteophytes in bone contours gave the efficiency of about 70% [58] and is far from satisfactory. The approach introduced in the next section allows us to avoid using predefined primitives which causes crucial problems to adjust the primitives to irregular bone contours. Instead, the bone contour is analysed and fragments, which have the same features described by the tangent line and the sign of local curvature, are treated as primitives. It turns out that in such a way the contour can be described effectively and the transducer can be used. Thus, a proper tool for bone contours analysis is introduced.

3. Generalized contour description

As it has been aforementioned, the syntactic-geometric-fuzzy hierarchical two-stage classifier of contours (SGF classifier, for abbreviation), proposed in this paper, is analogous to the idea put forward in [49] and applied, in the context of approximation and prediction, in [17]. It should be stressed, however, that there are crucial differences between the method described in [49] and the proposed approach. First of all, every single classifier in [49], let us call it as *elementary classifier*, is a *weak* one which means that it classifies only slightly better than a random classifier [49]. This is caused, among others, by the fact that the elementary classifiers are based on simple computational intelligence systems such as