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IMAGE QUOTIENT SET TRANSFORMS IN SEGMENTATION PROBLEMS

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Abstract: Image content interpretation is much dependent on segmentations efficiency. Requirements for the image recognition applications lead to a necessity to create models of new type, which will provide some adaptation between low-level image processing, when images are segmented into disjoint regions and features are extracted from each region, and high-level analysis, using obtained set of all features for making decisions. Such analysis requires some a priori information, measurable region properties, heuristics, and plausibility of computational inference. Sometimes to produce reliable true conclusion simultaneous processing of several partitions is desired. In this paper a set of operations with obtained image segmentation and a nested partitions metric are introduced.

Keywords: image, spatial reasoning, partitions, covers, interpretation.

ACM Classification Keywords: I.4.6 Segmentation: region growing, partitioning

Introduction

Modern phase of developing intellectual systems for information processing in correlation-extremal tracking, industry robotics vision, graphical and graphological information processing, medical diagnostic complexes, etc. requires ability to process different visual data for its unsupervised context interpretation. Increasing of arbitrary image identification reliability in real time necessitates refinement of complex images recognition under uncertainty factors.

Efficiency of image structuring and understanding strongly depends on a segmentation as a process of separating an image into several disjoint (or weakly intersecting) regions whose characteristics such as intensity, color, texture, shape, etc. are similar [see e.g. 1-4]. Segmentation is a key step in early vision and it has been widely investigated in image processing. Generally this process is rather laborious and not completely algorithmized for arbitrary images. Different data registration conditions, by-product facts, lack of robustness for the disturbing effects – this is a far not complete list of the reasons, which refers the process of image recognition to the class of not ordinary tasks. In practical applications the choice of methods which are able to form the most accurate regions of interest is of the prior importance. Unfortunately most of existing methods produce only the primary partitions which can not guarantee adequate image interpretation as image content formal descriptions obtained by using only low-level features are not necessarily the case for true conclusions. We may get totally correct segmentation, but in most cases we obtain under-segmentation, over-segmentation, missed regions, and

noise regions. It should be emphasized that a fair segmentation can be provided if and only if we know exactly what we are looking for in an image.

To obtain a reliable image interpretation we have to transform a row image into an image data structure, then into an image knowledge structure and finally into a user-specific knowledge structure. Spatial reasoning plays a most important part in decision making. In this respect partition transforms (e.g. set theoretic) are serviceable in order to find regions that are heavily correlated with significant objects in the scene and it is essential to have tools in order to compare segmented image accurately.

The three classes of distance function (point to point, point to set, and set to set) are usually discussed as measures of proximity or dissimilarity in image processing [5-8]. It is desirable to define an image metric that can be efficiently embedded in segmentations methods. A partition metric is consequently a candidate because it represents images as a finite subsets assemblage that takes into account mutual dependences of equivalence class corresponding to separate regions of interest. Metrics on nested partitions take on special significance since they give possibilities to define hierarchical content descriptions. We propose spatial relations operations for segmented images and a metric on nested partitions useful for such applications as object tracking and pattern matching.

Operations with segmented images

Let $B(x)$ be an image and $x \in D = \mathbf{Z}_n^+ \times \mathbf{Z}_m^+$ (here D is a viewing field). It should be noted that any faithful segmentation (a crisp clustering) generates a partition of the viewing field, i.e. $X = \{[x]_1, \dots, [x]_\alpha, \dots, [x]_s\}$ where $[x]_\alpha \neq \emptyset$, $X = \bigcup_{\alpha=1}^s [x]_\alpha$, $\forall \alpha \neq \beta \Rightarrow [x]_\alpha \cap [x]_\beta = \emptyset$ (hereafter α, β, γ denote all allowable indices). Suppose that a region labeling $F: B(x) \rightarrow \mathbf{Z}_r^+$ corresponds to obtained segmentation then arbitrary two points $x', x'' \in D$ belong to the same equivalence class $x', x'' \in [x]_\alpha$ if the binary relation $\langle B(x'), B(x'') \rangle \in \tau \Leftrightarrow \Leftrightarrow F(B(x')) = F(B(x'')) = \alpha$ is fulfilled.

In practice it is not always possible to obtain crisp segmentation, in this case it is necessary to work with fuzzy elements, i.e. covers.

A system of sets $[x]_i$ is a cover Ξ of set D if for $\exists x \in D$ it holds true that $[x]_\alpha \cap [x]_\beta \neq \emptyset$ for any α and β .

Cover generating sets $[x]_\alpha$ intended not to necessarily be singly connected.

If two sets of the cover have a non-empty intersection, i.e. $[x]_\alpha \cap [x]_\beta \neq \emptyset$, we shall consider them to be tolerant: $[x]_\alpha \tau [x]_\beta$.

For fixed $[x]_0 \in \Xi$, union of all intersections $[x]_0 \cap [x]_\alpha = \emptyset$, $([x]_\alpha \neq [x]_0, [x]_\alpha \in \Xi)$ forms so-called boundary set d_0 , which we shall conditionally call a 'boundary' of set $[x]_0$. Joint border of two tolerant sets $[x]_\alpha \tau [x]_\beta$, which belong to Ξ , we shall call a union of all intersections:

$$([x]_\alpha \cup [x]_\beta) \cap [x]_\gamma,$$

where $[x]_\gamma \neq [x]_\alpha$; $[x]_\gamma \neq [x]_\beta$; $[x]_\gamma \in \Xi$.

A total boundary of the tolerant sets chain is defined by induction

$$[x]_\alpha \tau [x]_\beta \tau \dots \tau [x]_s.$$

It is presumed that each element of cover $[x]_0 \in \Xi$ includes a set $[a]_0 : [a]_0 = [x]_0 \setminus d_0$, which we shall call as an equivalence set held in $[x]_0$.

Further we shall introduce the following designation: $[x]_0 = [\tilde{a}]_0$, $[\tilde{a}]_0 = [a]_0 \cup d_0$. If $[\tilde{a}]_\alpha \tau [\tilde{a}]_\beta$, then sets $[a]_\alpha$ and $[a]_\beta$ we shall also call tolerant: $[a]_\alpha \tau [a]_\beta$.

Let us consider a set of points $\mathbf{M} \in D$ as an observed object. It is expected that some cover Ξ_{temp} is extracted, and we shall call it as object's template cover.

Thus, instead of a given object \mathbf{M} we consider its cover \mathbf{M}_{temp} . On sets $[x]_{\text{temp}}^i \in \mathbf{M}_{\text{temp}}$ (which obviously

are the elements of cover Ξ_{temp}) K binary relations b_1, b_2, \dots, b_k are introduced. Given relations induced on subsets Ξ_{temp}^i , define template features of the object.

Let Ξ_n now be some cover, different from the template one (another observation of the object), for elements of which same K relations b_1, b_2, \dots, b_k are defined. We shall extract from the cover Ξ_n features Ξ_n^1, \dots, Ξ_n^n as sunsets of elements Ξ_n with given relations.

Combination (union) of features $M_n = \bigcup \Xi_n^i$ forms the observed cover of the object which we shall call as objects observation. Besides «inner» relations for each feature on M_n elements, there are some relations which establish connection between features themselves.

If there is a mapping of elements from M_n on elements from M_{temp} , which is a homomorphism of each binary relation $b_j, j = 1, \dots, k$, than we say that the object observation is consistent.

If under mapping there is a homomorphism between some observed and template features at least for some binary relations, then we shall call the observation of M_n as partially consistent, and will define it concretely for every certain case.

Thus, the object feature will be a family (collection) of cover elements with given binary relations. The object itself we shall interpret as a finite system of such features. At that except the scleronomous for each feature binary relations, there can be some relations between elements of different features.

When extracting the object features we shall use the topology of cover sets. As it was mentioned above, set $[x]_o \in \Xi$ is not necessarily simply connected.

It is necessary to define k_1, k_2 , where k_1 is a total number of closed (connected) boundaries of set $[x]_o$, k_2 is number of closed boundaries of set $[x]_o$, which are situated inside some region, bounded by some outer boundaries of the given set. The border of 'frame' can be included into the own border of the set.

If $k_1 - k_2 = 2$, then «outer» border consist of two closed contours, if $k_1 - k_2 = 1$ the border consist of one closed contour solely (fig. 1).

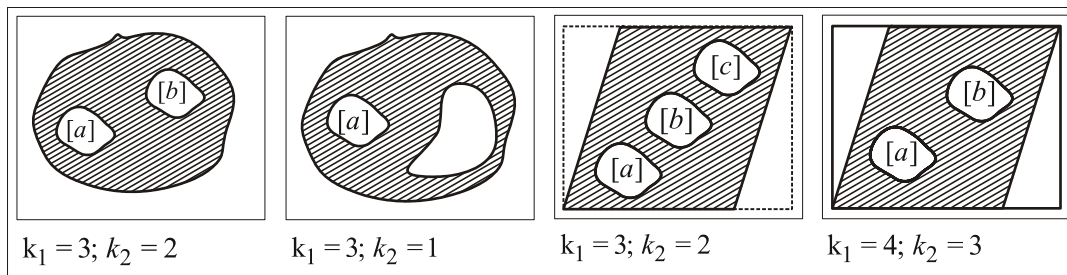


Figure 1. Example of total numbers of inner and outer borders of sets

«Inner» sets can be tolerant (have mutual border), and also it is possible for them to have mutual outer border with the outer set.

Let us assume that the border of set A is situated inside of the outer border if $[a] \tau [b]$, but $[a]$ is not tolerant to any set $[c]$ situated outside of outer border of set $[b]$. But if $[a] \tau [b]$ and $[a] \tau [c]$, then we assume that set $[a]$ is situated outside of set $[b]$, as it is shown in fig. 2.

As a matter of fact, one should differ three types of connectivity: connectivity of tree components ν_s ; connectivity into simply connected domain $\nu_1: [a]_1 \nu_1 [a]_3; [a]_2 \nu_1 [a]_3$; and including into doubly-connected domain $\nu_2: [a]_1 \nu_2 [a]_2$. A simply-connected domain case is not a case of multiple connection $[a]_1 \subset [a]_3$, as in fig. 2 $[a]_3$ is a set with two holes.

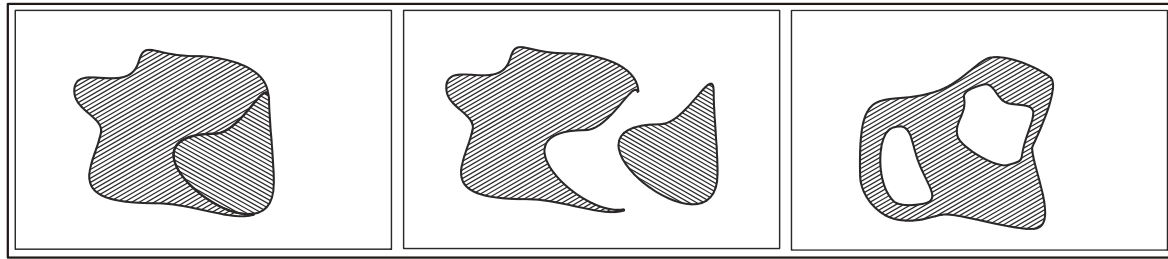


Figure 2. Example of sets connections:

a – sets have a joint boundary, b – sets do not intersect, c – a set with two holes

On cover of Ξ elements we shall introduce a relation S , and in addition to relation \subset for components we shall also introduce a components tolerance τ_s . Let $S_{[a]}$ and $S_{[b]}$ be two arbitrary components. We shall state that $S_{[a]} \tau_s S_{[b]}$, if at least two sets $[a] \in S_{[a]}$ and $[b] \in S_{[b]}$ are tolerant.

Let $S_{[a]}$ be a connecting set of cover elements. We shall consider a set of this component boundary sets, i.e. a family of Ξ elements intersections (without sets included in $S_{[a]}$) with sets belonging to $S_{[a]}$. The boundary set which contains all the rest of the boundaries inside we shall call as outer boundary. Any arbitrary set $[c]$ situated inside the region limited by outer boundary we shall consider to be connected to component $S_{[a]}$ by relation $[c] \nu_s S_{[a]}$. If all sets of component $S_{[b]}$ are connected by this relation with $S_{[a]}$, then $S_{[b]} \nu_s S_{[a]}$, i.e. $S_{[b]}$ "enters" $S_{[a]}$. It is obvious, that $S_{[b]}$ is connected, i.e. it either is completely situated in $S_{[a]}$, or none of S_B the sets "enters" $S_{[a]}$ (fig. 3).

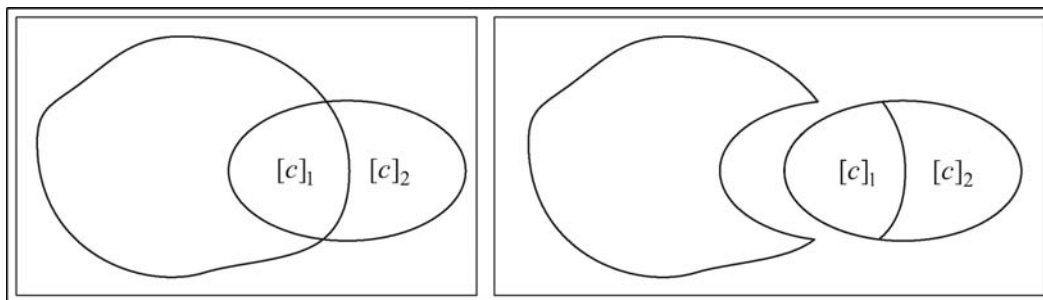


Figure 3. Intersecting and connected sets

Another important part in describing image/object structure is a spatial layout.

Let us introduce a characteristic function on equivalence classes

$$\lambda_{[x]_\alpha}(x) = \begin{cases} 0, & x \in [x]_\alpha, \\ 1, & x \in D \setminus [x]_\alpha. \end{cases} \tag{1}$$

It follows immediately that boundary conditions for spatial reasoning are

$$\lambda_D(x) = 0, \lambda_\emptyset(x) = 1.$$

In addition it is reasonable to indicate the expression providing certain duality in order to analyze image contents

$$\lambda_{D \setminus [x]_\alpha}(x) = 1 - \lambda_{[x]_\alpha}(x).$$

The direct check-up allows to introduce explicitly definable formulae of spatial interdependence between characteristic functions of two elements of arbitrary partitions X and Y

$$\lambda_{[x]_\alpha \cup [y]_\beta}(x) = \lambda_{[x]_\alpha}(x) \lambda_{[y]_\beta}(x), \tag{2}$$

$$\lambda_{[x]_\alpha \cap [y]_\beta}(x) = \lambda_{[x]_\alpha}(x) + \lambda_{[y]_\beta}(x) - \lambda_{[x]_\alpha}(x) \lambda_{[y]_\beta}(x), \tag{3}$$

$$\lambda_{[x]_\alpha \dot{\cup} [y]_\beta}(x) = 1 - \lambda_{[x]_\alpha}(x) + \lambda_{[y]_\beta}(x). \quad (4)$$

Appreciably intense interest consists in simultaneous transformations of equivalence class families since namely splitting and merging of partitions can get totally correct and complete segmentation of complex scenes. It easily seen that for any unions and intersections we get

$$\Xi = \bigcup_{\gamma \in \Gamma} [x]_\gamma \Rightarrow \lambda_\Xi(x) = \min_{\gamma \in \Gamma} \lambda_{[x]_\gamma}(x), \quad (5)$$

$$\Xi = \bigcap_{\gamma \in \Gamma} [x]_\gamma \Rightarrow \lambda_\Xi(x) = \max_{\gamma \in \Gamma} \lambda_{[x]_\gamma}(x). \quad (6)$$

The 169 types of spatial relations between two rectangles in 2-D space had been proposed in [9]. However, if we introduce a representation of each equivalence class as union of sets (rather points of boundaries and interior) it suffices to use combinations only of four relations in general case. Indeed, suppose that

$$\lambda_{[x]_\alpha}(x) = \partial\lambda_{[x]_\alpha} \cup \lambda_{[x]_\alpha}^\circ$$

where $\partial\lambda_{[x]_\alpha}$ denotes the boundary of the partition element describing by the characteristic function (1) and $\lambda_{[x]_\alpha}^\circ$ corresponds to interior points of this partition element. Let us introduce relations defining spatial relationships between any two objects $[x]_\alpha$ and $[x]_\beta$, $\alpha \neq \beta$

$$\begin{cases} \langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{11} \Leftrightarrow \partial\lambda_{[x]_\alpha} \cap \partial\lambda_{[x]_\beta} \neq \emptyset, \\ \langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{12} \Leftrightarrow \partial\lambda_{[x]_\alpha} \cap \lambda_{[x]_\beta}^\circ \neq \emptyset, \\ \langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{21} \Leftrightarrow \lambda_{[x]_\alpha}^\circ \cap \partial\lambda_{[x]_\beta} \neq \emptyset, \\ \langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{22} \Leftrightarrow \lambda_{[x]_\alpha}^\circ \cap \lambda_{[x]_\beta}^\circ \neq \emptyset. \end{cases} \quad (7)$$

Consequently, the (2×2) matrix (ς_{ij}) entirely determines all eight possible mutual locations of regions, viz:

- i) $[x]_\alpha$ disjoins $[x]_\beta$, i.e. all parts of $[x]_\alpha$ are separated from all parts of $[x]_\beta$ iff $\langle [x]_\alpha, [x]_\beta \rangle \notin \varsigma_{ij} \forall i, j$;
- ii) $[x]_\alpha$ contains $[x]_\beta$, i.e. all parts of $[x]_\beta$ are completely overlapping with any part of $[x]_\alpha$ iff $\varsigma_{21}, \varsigma_{22}$, are valid and the relations are not true;
- iii) similarly, $[x]_\alpha$ belongs $[x]_\beta$ iff $\langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{12}, \varsigma_{22}$ and $\langle [x]_\alpha, [x]_\beta \rangle \notin \varsigma_{11}, \varsigma_{21}$;
- vi) $[x]_\alpha$ equals to $[x]_\beta$ iff $\langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{11}, \varsigma_{22}$ and $\langle [x]_\alpha, [x]_\beta \rangle \notin \varsigma_{12}, \varsigma_{21}$;
- v) $[x]_\alpha$ is partly overlapping $[x]_\beta$ iff all relations ς_{ij} hold;
- vi) $[x]_\alpha$ is externally bound to bound with $[x]_\beta$, i.e. there exist common points of boundaries and no part of $[x]_\alpha$ is overlapping with any part of $[x]_\beta$ iff $\langle [x]_\alpha, [x]_\beta \rangle \in \varsigma_{11}, \varsigma_{22}$ and $\langle [x]_\alpha, [x]_\beta \rangle \notin \varsigma_{12}, \varsigma_{21}$;
- vii) $[x]_\alpha$ is internally bound to bound with $[x]_\beta$, i.e. there exist common points of boundaries and $[x]_\alpha$ belongs $[x]_\beta$ iff only the relation ς_{21} is not true;
- viii) $[x]_\beta$ is internally bound to bound with $[x]_\alpha$, i.e. there exist common points of boundaries and $[x]_\alpha$ contains $[x]_\beta$ iff only the relation ς_{12} is not true.

Now we can formalize intersection and conditional union operations with partitions. For simplicity of notations we write μ instead of a matrix (ς_{ij}) elements sum then introducing an indicator function

$$\varphi(\alpha, \beta) = \begin{cases} -1, s = 1; \\ 0, s = 0; \\ 1, s > 1. \end{cases}$$

we get for $X = \{[x]_\alpha\}$, $Y = \{[y]_\beta\}$

$$Z = X \otimes Y, Z = \{[z]_\gamma: \lambda_{[z]_\gamma}(x) = \lambda_{[x]_\alpha}(x) + \lambda_{[y]_\beta}(x) - \lambda_{[x]_\alpha}(x)\lambda_{[y]_\beta}(x)\} \quad (8)$$

and

$$Z = X \oplus Y, Z = \{[z]_\gamma\}, [z]_\gamma = \begin{cases} \{[x]_\alpha, [y]_\beta\}, & \text{if } \varphi(\alpha, \beta) = 0; \\ [x]_\alpha \cup [y]_\beta, & \text{if } \varphi(\alpha, \beta) = 1. \end{cases} \quad (9)$$

It is obvious evident that under $\varphi(\alpha, \beta) = -1$ a complementary analysis is required since merging of adjoining region is admissible action if features of $[z]_\gamma$ with the characteristic function $\lambda_{[z]_\gamma}(x) = \lambda_{[x]_\alpha}(x)\lambda_{[y]_\beta}(x)$ satisfy, for instance, requirements to the sought-for shape.

Thereby, expressions (2)–(4) determine operations with separate equivalence classes, relationships (5), (6) predetermine transformations of equivalence class families and (8), (9) on the base of relations (7) provide partition manipulations. The main goal of such segmented image reforming is a guaranteeing trade-off decision about regions of interest.

We shall consider that for equivalence sets $[a]_i$ from Ξ (these sets do not mutually intersect) a brightness function $Y_i = S([a]_\alpha)$ is defined, such that brightness of all points of one set $[a]_\alpha$ is the same and the brightness degree of each set $[a]_\alpha$ can be ordered on increase. Given function defines quasi-order $S: [a]_1 S [a]_2$, and therefore $Y_1 \leq Y_2$ for sets $[a]_\alpha$.

Results and outlook

Significant efforts are continuously being made in development of segmentation techniques. Cognitive-like approaches require obtaining of regions strongly correlated with meaningful objects in the scene. Mentioned operations create the necessary prerequisites for partitions transformations. However, efficiency of image structuring and understanding depends on the objectivity of partitions matching. Previously for finite sets we proved [10, 11] that the functional

$$\rho(X, Y) = \sum_\alpha \sum_\beta \text{card}([x]_\alpha \Delta [y]_\beta) \text{card}([x]_\alpha \cap [y]_\beta) \quad (10)$$

(here the notation $X_i \Delta Y_j$ defines a symmetric difference) is a metric. Later for arbitrary measurable set with given measure $\mu(\circ)$, which can be interpreted as length, area, volume, mass distribution, probability distribution, and in special case cardinality, we had proved [6] that the functional

$$\rho(X, Y) = \sum_\alpha \sum_\beta \mu([x]_\alpha \Delta [y]_\beta) \mu([x]_\alpha \cap [y]_\beta) \quad (11)$$

is a metric also. Taking into consideration properties of nested partitions one can give concrete expression to metrics (10) and (11) for $X \subseteq Y$

$$\rho(X, Y) = \sum_\beta \mu([y]_\beta)^2 - \sum_\alpha \mu([x]_\alpha)^2 \quad (12)$$

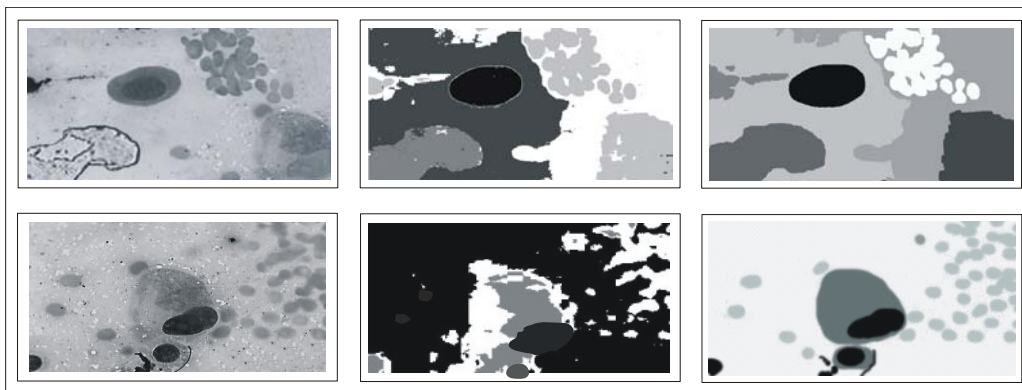


Figure 4. Example of nested partitions

Substantially metric (12) intends for combination of visual features and metadata analysis to solve a semantic gap between low-level visual features and high-level human concept. Figure 2 illustrates nested partitions that are

generated by algorithms based on adaptive thresholding, multithresholding and band-thresholding [6]. Simple geometrical shape parameters (the area and the perimeter of region, the diameters of circles with fixed area and perimeter, orthogonal projections of the figure on axes of abscissae and ordinates, the minimal and the maximal orthogonal projections of the figure on a line, the distance between opposite sides of the figure, the distance from an origin point in the figure to its boundary point for a given direction, the same average distance for all possible directions for a given point, the lengths of the long and short semi-axes of the ellipse with given area and perimeter, drainage-basin circularity, coefficient convexity ratio, etc.) were used for split and merging procedures along with relations (7) under operations (8) and (9).

The analysis of experimental results has shown that partition transforms and unbiased partitions matching substantially meant for the use at conceptual segmentation which not only builds partitions but can also explain why a set of regions confirms a desired pixel family.

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