Augmenting reality in the tasks of classifying objects in aerospace images

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Abstract. The problem of increasing the reliability of object recognition in aerospace images consists in the insufficient quality of image segmentation based on pixel colour characteristics and boundary shape descriptors. The paper proposes an approach based on description logic with an extension on graphs. The essence of the approach is the searching for relevant cases in the ontological base by calculating the degree of similarity and identifying differences of attributed graphs of cases. With the help of retrieved cases, the object structure and the boundary shape are refined. After that, objects can be augmented with subject domain information stored in the ontological base. Representation of the structure of cases in the form of attributed relational graphs allows avoiding the rapid growth of the case base, since the similarity of connected subgraphs is generally sufficient. The experiments are conducted on urban area aerospace images.

1. Introduction
Continuous growth in the volume of aerospace monitoring data leads to the need of increasing the automation degree of image processing and analysis, identification and structured description of objects, since manual image labelling is very slow and costly. This reduces the speed of decisions in such areas as territory development planning, environmental measures, etc.

The problem of increasing the reliability of algorithms of object recognition in aerospace images consists in the insufficient quality of known methods of image segmentation based on pixel color characteristics and boundary shape descriptors.

Our goal is to image analysis, to increase the efficiency of decision support systems on the basis of logical approach at the expense of:
- Augmenting poorly distinguishable image areas with information from cases accumulated in the course of practice in the ontological knowledge base on the relevant topics.
- Having determined the semantics of the image, it is possible to go to the next step – augmenting visible objects/scenes with the associated information from other thematic sections, depending on the task.

What can be considered as cases in this context? These are characteristic areas of the terrain and buildings – sets of various objects and spatial relationships between them, perhaps under various weather and lighting conditions.
2. Related Work

For recognition of objects in aerospace images, the methods that calculate and analyze low-level features of image areas are mostly used. For example, morphological index [1], angular difference feature [2], and angle detector [3]. The efficiency of such methods is limited due to the lack of relationships with the subject domain semantics.

Methods that decrease the semantic gap between low-level features like color and simplest shapes and the high-level human semantics include the use of object ontology for defining concepts, machine learning, genetic algorithms as well as combination of visual and textual content in image retrieval [4].

In the field of automation of aerospace image analysis, the GEOBIA (Geographic Object-Based Image Analysis) approach is actively being developed [5]. In this approach, regions resulted from the image segmentation procedure are processed and classified using expert rules. GEOBIA systems rely on methods of object-based image analysis (OBIA) [5, 6], in which decision making is performed by analysis of higher level units of information – image segments (superpixels). Color image segmentation is performed, features of segments are calculated, and objects are classified into target categories using a rule base, for example [7, 8, 9]. However, the drawback of the OBIA approach is that due to the strong distortion of region boundaries, the shape features are unstable [10]. Accordingly, the reliability of the classification is reduced.

The paper [11] proposes an ontology-based approach to representing knowledge of GEOBIA systems. Using the description logics formalism, links between target object categories and image patterns are set. Actually, the formed logical descriptions contain rules of assigning automatically segmented image objects to desired categories. The advantage of the approach is the accumulation of experts’ knowledge in the explicit and structured form, elimination of subjectivity of decision rules, and the possibility to automatically check the consistency of the knowledge base. Unfortunately, there is no form of context-based analysis of objects. Recognition is based on individual spectral and geometric features of objects (normalized difference vegetation index, rectangular fit feature, etc.). The authors noted that automatic segmentation did not always perfectly delineate the boundaries of objects, especially in the case of shadows and trees. In this regard, the existing free database of cartographic data was used to refine the results of segmentation.

The work [12] proposes an object-oriented method for semantic classification of satellite images with the use of ontology. The method gave some statistical improvements in terms of accuracy for the specific images used in the work compared to a decision tree method that does not apply an ontology.

The goal of the study [13] is the classification of urban area satellite images into certain classes like road, buildings, vegetation, etc., with the use of fuzzy logic and object-based analysis. It is noted that the main problems in the classification of high-resolution images are uncertainties in the position of the object boundaries as well as the similarity of the parameters of segments belonging to different classes. To solve this problem, fuzzy logic is used, making it possible to analyze images using several parameters without the need to include certain thresholds in the class assignment process.

The work [14] proposes an ontological multilevel universal system for classifying satellite images. The multiple and multilevel classification is considered as the iterative process of step-by-step refinement of results by comparing the extracted values with the acceptable ranges of spatial and temporal characteristics of the domain from concepts of a higher level of ontology.

In the work [15] a system is presented, in which satellite images are classified and augmented with semantic information in order to allow queries about what can be found on the map at a particular location as well as about paths that can be taken. This is achieved by the system of ontological reasoning based on qualitative spatial reasoning. The system is able to find answers to high level queries that may vary on the current situation.

Thus, we can conclude that in the existing implementations of the GEOBIA approach, relatively simple classification rules are applied that describe the logic of a user’s visual interpretation, but practically do not take into account the context of an object. The decision-making mechanism is based on the production model of knowledge and fuzzy logic. A significant drawback is the lack of effective
tools for analyzing the shape of the objects presented in the image. In conditions of imperfection of
automatic image segmentation, it is not always possible to achieve high performance indicators.

The paper proposes an approach based on a description logic with an extension on graphs. The
essence of the approach is the searching for relevant cases in the ontological base by calculating the
degree of similarity and identifying differences of attributed graphs of cases. With the help of retrieved
cases, the object structure and the boundary shape are refined. After that, objects can be augmented with
subject domain information stored in the ontological base. Representation of the structure of cases in
the form of attributed relational graphs allows avoiding the rapid growth of the case base, since the
similarity of connected subgraphs is generally sufficient. Section 3 describes the features of the
description logic on graphs. Section 4 proposes similarity measures for attributed graphs of cases and a
method for identifying differences of cases. Section 5 describes the experiment carried out on aerospace
images of urban areas. Finally, in Section 6, conclusions are drawn and prospects for the further
development of the proposed approach are shown.

3. Features of the Description Logic on Graphs

Description logics (DLs) allow describing concepts of a subject area in a formalized form. Using logical
operations, rules and axioms, the correctness of the definitions is automatically checked and information
is searched in the ontology database. The logic ALC (Attributive Concept Language with Complements)
is one of basic DLs [16]. On the basis of it, many other DLs are built for working with knowledge bases and
ontologies.

To describe concepts in the case ontology including aerospace images of urban areas, we use the
ALC logic, expanding it to attributed relational graphs by analogy with the work [17], in which the
description logic ALC(GI) is proposed. This work is interesting as an example of modeling reasoning
in such subject areas where the data is presented in the form of attributed relational graphs (ARGs) or
fuzzy attributed relational graphs (FARGs). The authors showed the ability to use existing solutions in
the graph theory and its applications for the interpretation of DL descriptions of concepts.

The following unary (concepts) and binary (roles) relations are additionally introduced into the set
of atomic concepts and roles:

- **Node(x)** – x is a node of the graph;
- **Edge(x)** – x is an edge of the graph;
- **SubGraph(x)** – x is a subgraph of the considered graph;
- **hasSource(x: Edge, y: Node)** – the node y is the beginning of the edge x;
- **hasTarget(x: Edge, y: Node)** – the node y is the end of the edge x.

We add two new constructs into the set of standard syntax constructs of the logic ALC:

- **Existential quantification with object identification:**
  \[ \exists R.(a : C), \]
  where R is a role, a is the name (identifier) of an individual, and C is a concept (atomic or derived). This
  construct specifies the requirement \( \exists R.C \) and introduces the designation a for the object (individual)
  with which the described object is connected by the relation R. The construct \( \exists R.(a : C) \) is applied in
  situations when in another place of the definition (formula) it is required to refer to the individual a. In
  other cases, the standard simpler expression \( \exists R.C \) is used.

- **Atomic concrete attribute calculated relative to given individuals:**
  \[ h_{a_1,a_2,\ldots,a_n} \]
  where h is the name of the attribute and \( a_1,a_2,\ldots,a_n \) are the names of individuals, \( n \geq 1 \). For brevity, we
  will call such attributes relative attributes. Examples of relative attributes are presented in table 1.
Table 1. Examples of relative attributes.

| Attribute       | Value Example | Interpretation                                      |
|-----------------|---------------|----------------------------------------------------|
| hasAngle\(a\)  | \(x\) hasAngle\(a\) 90 | The angle between \(x\) and \(a\) is 90          |
| hasRatioSize\((a,b)\) | \(x\) hasRatioSize\((a,b)\) 60% | The area of \(x\) relative to the total area of \(a\) and \(b\) is 60% |

Consider an example of a description of a spatial scene (figure 1) in the proposed language:

Building ≡ SubGraph ⊓ Rectangle
Scene ≡ SubGraph ⊓ ∃ hasSubGraph.
∃ hasSubGraph.(a: Building ⊓ ∃ hasLeftFrontCorner.(c: ⊓))⊓
∃ hasSubGraph.(b: Building ⊓ ∃ hasRightSide.(d: ∃ hasDistance\(c, a\) = 50) ⊓ ∃ hasAngle\(a\) = 90)

Figure 1. Example of a scene (case) consisting of two objects.

The concept SubGraph determines a set of all subgraphs of the graph of the analyzed image. The role hasSubGraph states the presence of a certain subgraph in the given graph. The role hasLeftFrontCorner identifies a subgraph in the given graph, which represents the left front corner of the object. The role hasRightSide identifies a subgraph in the given graph, which represents the right side of the object. The concept Scene determines a set of subgraphs consisting of two rectangles arranged in such a way that there is the relation Angle=90 between one building and another building, and the relation Distance=50 exists between the right side of the second building and the left front corner of the first building.

4. Attributed Graph and the Measure of Similarity of Cases Represented as Graphs

Algorithms for generating attributed graphs of images are described in detail in [18].

The attributed graph of a case is the fuzzy spatially-attributed graph, whose nodes and edges contain quantitative and qualitative (fuzzy) values of geometric parameters:

\[ G = (V, A, E, R), \]

where \(V \subseteq V\) is a set of structural elements of the object, whose parameters \(a \subseteq A\) is a set of linguistic variables taking values from the corresponding fuzzy sets; \(e \subseteq E\) is a set of edges (non-oriented arcs) representing spatial relationships between structural elements with the help of parameters \(r \subseteq R\) — linguistic variables taking values from fuzzy sets.

The set of nodes’ attributes \(A = AT \cup AN \cup AL\), where \(AT\) is a set of attributes taking text values, \(AN\) is a set of numeric attributes, and \(AL\) is a set of fuzzy (linguistic) attributes.

Let us introduce the concept of a beam graph intended for analyzing the environment of a given node at a given depth determining the length of the chains outgoing from this node. The beam graph \(GB(\nu_0, G(I))\) centered at the point \(\nu_0\) for the graph \(G(I)\) is the graph [19]:

\[ GB(\nu_0, G(I)) = (VB, AB, EB, RB, RLA), \]

\(\nu_0 \subseteq V, VB \subseteq V, AB \subseteq A, EB \subseteq E, RB \subseteq R, \)
where $RLA$ is a set of relative fuzzy angles of arcs, which are calculated as follows: the first is the counterclockwise angle from the vector of the incoming arc, the rest are relative to the vector of the nearest previous arc; if there is no incoming arc, then the first angle is calculated relative to the abscissa axis.

Due to the fact that the beam graph necessarily contains parameters of the spatial orientation of the edges, regardless of how the object is oriented in the image, the beam graph shows a correspondence with a fragment of the reference object, and the angle value taken from the original graph makes it possible to determine the difference in spatial orientation up to the used fuzziness.

The algorithm of comparison of the analyzed graph $GA$ with the reference graph $GE$ on the base of beam graphs consists in comparing the attributes of all nodes and edges of the reference graph with the corresponding attributes of all nodes and edges of the analyzed graph. The feature of the algorithm is that in order to improve the reliability, the similarity of nodes is estimated by comparing their beam graphs, in which arcs are ordered by spatial orientation attributes. Thus, this algorithm compares nodes with their neighbors, which significantly reduces the number of "rollbacks" in case of random matches.

Evaluation of the similarity of the case with the analyzed graph:

$$ETQuality(i) = \frac{\sum_{i=1}^{n} found_{i}}{n}$$

where $found_{i}$ is the number of matched beam graphs in the graph of the case.

As a result of the algorithm, the nodes of the analyzed graph are marked with indices of the nodes of the reference graph, which is very convenient for visualizing the results of the process of identifying similarities and differences. Short chains arising from "false" matches are absorbed (covered) by longer ones. For example, if some fragment of the reference graph coincides simultaneously with several fragments of the analyzed graph, then the numbers of nodes of the reference graph that form longer chains of continuous matches in the analyzed graph are put into the correspondence array and replace the numbers of short chains.

Representation of the structure of cases in the form of attributed relational graphs allows avoiding the rapid growth of the case base, since the similarity of connected subgraphs is generally sufficient.

With the help of the cases found in the ontological base, the shape of the boundaries of the structural elements of objects is refined. After that, objects can be supplemented with subject domain information from the ontology.

5. **Experiment**

An experiment on the semantic augmentation of visual information was carried out on an urban area aerospace image taken from the dataset described in [20]. The spatial resolution of the image is 30 cm. With such a high resolution, there is an abundance of various details and local spectral variations, which greatly complicates the work of standard low-level detectors that do not take into account the context.

Image processing included sequential execution of the following steps:

1) Color segmentation and detection of boundaries of color segments.
2) Calculation of features of color segments.
3) Construction of the color segment adjacency graph.
4) Classification of color segments into target object categories [21, 22].
   4.1) Based on the analysis of the own characteristics of regions.
   4.2) Taking into account the adjacency of regions and cases from the ontology.

Figure 2 shows the detection results obtained at step 4.1. These results were obtained on the basis of requirements that provide sufficient recall of object detection, but not very good precision. Without involving additional knowledge about situations, it is impossible to determine requirements maximizing both recall and precision simultaneously.
Figure 2. Objects classified as buildings by analyzing only their own characteristics.

Figure 3 shows detected buildings in step 4.2, after analyzing the neighborhood relations between regions as well as supplementing information by searching for cases.

Figure 3. Buildings detected as a result of contextual analysis based on cases.

As a result of the contextual analysis of the scene, we achieved an increase in the F1 measure, which is an integrated indicator of the object detection quality, to 0.748. This confirms the importance of applying additional knowledge in the process of image analysis and the prospects of semantic interpretation methods based on the ontological model of knowledge and associative relations.

6. Conclusion

So, recognition and classification of objects in satellite images with the use of a base of cases represented in the form of attributed relational graphs allows:

- refining poorly distinguishable areas of a real image on the base of information from cases accumulated during practice in an ontological knowledge base on relevant topics;
- augmenting visible objects/scenes with associative information from other thematic sections of the ontology to support decision making.

The directions for further development of the proposed approach are synthesizing DL descriptions of images and creating a language for describing context-dependent strategies of image analysis.

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