Weapon Ontology Annotation Using Boundary Describing Sequences

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***Abstract*—This paper presents an approach to identify a weapon from a single image using a weapon ontology. Ontological nodes selected by experts store convex hull (CH) sequences for their descendants, whereas the ontological leafs are labeled with object boundary sequences. The latter are generated from object boundary vertices, while the CH sequences are generated from objects' CHs. The object's boundary and CH are extracted by an active contour model. Ontology search is performed top-down using cyclic sequence alignment, which provides a scaling and rotational invariant matching. Experimental results are given to validate the theory, and the paper concludes with a list of contributions and discussion.**

***Keywords*-shape, active contour, cyclic sequence, annotation, object identification**

I. Introduction

Security is an increasingly important issue in our society. The ability to analyze an image and identify the presence of a weapon automatically would both decrease the cost and increase the feasibility and availability of remote surveillance, going beyond airports and train stations, to include other public spaces. Furthermore, the capacity to identify the kind of weapon, allows for a first-response threat-level assessment: if a hypothetical surveillance system identifies a pistol, the police may be called to the scene; if the weapon is a machine gun, the swat team may be alerted.

In this work, we describe a weapon ontology designed for quick and accurate weapon identification, from a single image. We propose ontology nodes annotation by using geometric information extracted by active contour model S-ACES [12], [15]. Further, we focus on using this ontology to help identify the closest weapon or group of weapons to a query object. The query object is extracted from an input image using S-ACES as discussed in [13], [15]. Thus, we define the weapon identification problem as the following:

> *Given an input image object, find in an ontology, a weapon or a group of weapons with significant similarity to the input.*

In the ontology every leaf and selected intermediate nodes are labeled with cyclic sequences. The ontology is searched for labels similar to the input label. To label the ontology nodes, and the query object cyclic sequences are used. We extract the (2D) object boundary and CH for every weapon in the ontology using S-ACES [12], [13], [15]. We generate a sequence from its CH and a sequence from its boundary. Weapon identification is done via shape sequence similarity search in the ontology. In the literature, shape matching for object identification has been a topic of interest (e.g. [2]), and the idea of using sequences for representing and comparing shapes has been used (e.g. [4], [6], [17]). We propose a new sequence representation for shapes. We compare the sequences for the input object with the sequences in the ontological nodes. For every shape sequence (label) comparison we apply modified cyclic sequence alignment introduced in [9]. We consider in this paper that the total number of CHs is bounded from above [16] (343 distinct convex hulls) and the number of vertices in a CH is relatively small. To decrease the complexity of ontology search, comparisons start with the upper nodes where only CH sequences are used for annotation. The CH comparison is used as a filter in the upper levels before a more thorough comparison between boundary sequences is performed at the leafs. The output of this search is a group of weapons with varying degree of similarity with the input. Final output contains nodes with similarity higher than a given threshold.

The outline of this paper is as follows: The initial weapon ontology is given in Section II. We summarize the features extraction in Section III, cyclic sequence generation, from object's CH vertices and boundary, in Section IV, and cyclic sequence alignment in Section V. We show our experimental results in Section VI, and discuss them along with conclusions in Section VII.

II. Weapon Ontology Annotation

In Fig. 1 we show part of our initial ontology [13]. An ontology is a formal representation of the knowledge available to a system concerning a given domain. In particular, the ontology developed for weapon identification privileges the ISA relationship (hyponymy/hyperonymy). The ontology can be conceptualized as a directed graph, consisting of

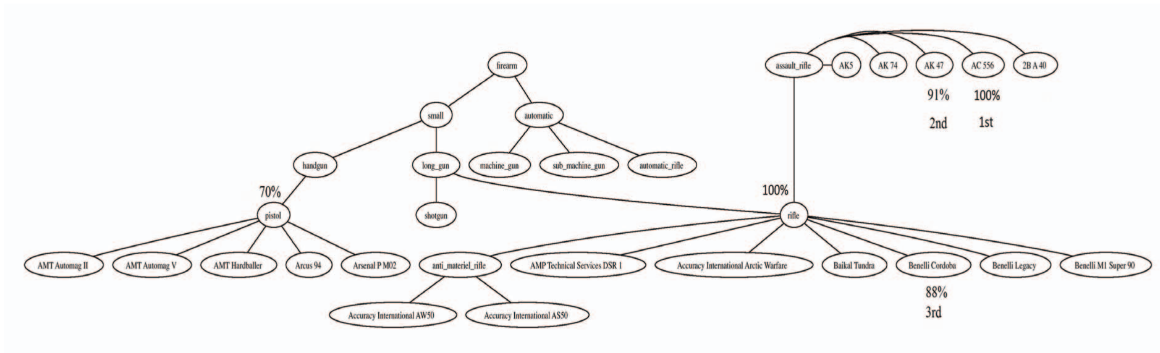

Figure 1. Graphical summary of our weapon ontology. The CHs of the pistol and the rifle respectively have 70% and 100% similarity with the CH of AC556 (see Fig. 6). The leafs of rifle are ranked by their boundary similarity to AC556

nodes (repositories of information about a concept) and edges (the ISA links). Unlike most ontologies, we enrich the leafs with images of objects and boundary sequences. The CH sequences are used to annotate select upper level nodes. The ontology is populated offline by experts with the help of semi-automatic procedures [13]. The cyclic sequence describing a CH is relatively short, and the comparison of two CHs takes only a few milliseconds. Also, the total number of CHs is bounded (343) [16]. Thus upper levels are used as filter for the search on the lower level(s).

The above facts allow us to store the CHs at a number of nodes selected by ontology and weapon experts. These nodes are “basic categories” [11], i.e., they are psychologically salient and can be operationalized as the ratio of daughters to a parent. A basic category is a non-leaf node with daughter to parent ratio higher than a given threshold, defined by the experts.

For the purpose of query object identification a search is performed downward from the root. A comparison with the query CH is performed if CHs are located in current node, otherwise the walk on the ontology is continued. If the score of a match between the CHs is above a threshold a sequence match with the boundary sequences in the daughters' level is performed. If the match is below, the search does not go deeper in the ontology on this subgraph.

III. Features Extraction

Active contours (AC) have been introduced in [7], [10] and become the most useful approach for image segmentation [3], [8]. The present work applies the fast and accurate AC named S-ACES [12], [13] which consists of parametric evolution equation with initial and boundary conditions [12], [13], [15]:

$$r(s,t) = e^{as-4a^2t}\{C_1 \cos\alpha(s), C_2 \sin\alpha(s)\}, \tag{1}$$

where $\alpha(s) = ca$, $a = \frac{|ds|}{2}$, s is a space parameter, t is a time parameter, the period of the function is $p = 2\pi/ca$. The initial conditions for Eq. 1 are:

$$\begin{aligned} 4a^2t = 0.001,\ c = 1000, \\ C_1 = C_2 = R = \sqrt{nc^2 + nr^2}. \end{aligned} \tag{2}$$

In Eq. 2 nc denotes the number of columns in the image, nr is the number of rows. For $4a^2t = 0.001$ the AC envelops the entire image. Then, increasing t such that $9 > t > 0.001/4a^2$, shrinks the AC toward the image center.

The boundary condition to halt the AC on an object's boundary for $t \to \infty$, is:

$$\begin{aligned} r(s,t) = r(s, t + \partial t) \\ \text{if } \frac{\partial f}{\partial t}(r(s,t)) > \epsilon,\ t > 0.001/4a^2. \end{aligned} \tag{3}$$

An active CH model based on Eqs. 1,2,3 and a distance function [15] are applied to define the CH of every weapon (see Fig. 2).

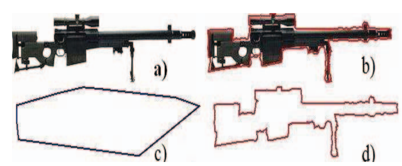

Figure 2. a) Accuracy International AW50; b) along with its extracted boundary; c) CH; d) boundary

IV. Sequence Construction

From the CH of each weapon we create a cyclic sequence. We traverse CH vertices in clockwise direction, and at each vertex we calculate the angle defined by the two sides that intersect at this vertex (see Fig. 3). We generate a sequence from angles in clockwise order, and delete the angles each larger than a given threshold (e.g. $\geq .9\pi$ radian). Thus, the resulting CH does not contain vertices that are close to forming a line. Recall that the basic categories in our ontology store the CHs of their descendants. Fig. 3 shows two different pistols with similar CH angle sequences.

We also generate sequences from weapon's boundaries extracted by S-ACES. From each object boundary we create a sequence of segments using the CH vertices. Each segment

Figure 3. Two different pistols with similar CHs

is a sequence of angles. The angle vertex p is a boundary point connecting the closest CH points b and e. Each angle has the following attributes: sign ($-$ for concavity, $+$ for convexity, and $|$ for line segment), value in radian with a fixed precision as a factor of π, and the x and y coordinates of p. For example, segment s_2 in Fig. 4 is a sequence of angles at boundary points that appear in the concavity enclosed by CH vertices $b = a_1$ and $e = a_2$. We change concave and convex segments to line segments when the areas they form are small enough.

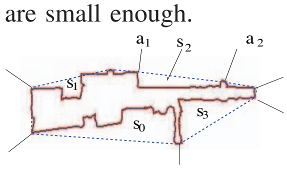

Figure 4. Segments in boundary sequence for Accuracy International AW50. Concave segments in clockwise are s_0, s_1, s_2, and s_3; a_1 and a_2 are CH vertices

We show part of our weapon ontology in Fig. 1. Each node is labeled and it carries attributes explained in [14]. CH sequences label intermediate nodes selected by experts and determined as basic categories (Section II). The boundary sequences label leafs. For example, boundary sequences for the weapons which are immediate children of the node pistol are stored in the corresponding leaf nodes. The CH sequences of these children nodes are all stored in the basic category pistol.

V. Cyclic Alignment for Shape Matching

To ensure rotational invariant shape matching we modify and apply *cyclic sequence alignment* introduced in [9]. By definition, in cyclic sequence alignment, one input sequence is compared with all possible cyclic shifts of the other sequence. For example, if the score of each match is $+1$ and all other scores are -0.5, then an optimal cyclic alignment of `circle` and `iccycl` is obtained by aligning `circle` to `cyclic` (cyclic shift of `iccycl` by four positions). This alignment is shown in Fig. 5. The alignment has 3 matches shown by vertical lines, two mismatches, and two indels (inserts/deletes: columns that contain '-'). The total score of this alignment is $+1$. We use cyclic alignment for comparing

```
c i r c l e -
|     | |
c y - c l i c
```

Figure 5. A sample alignment

two CH sequences, and two boundary sequences. We assign a match score for comparison of any two angles based on their magnitudes. For boundary sequence alignment we also consider signs: score for aligning a concave segment to a convex segment is $-\infty$ (not allowed); a line segment can be aligned to a concave and convex segment with penalties; and alignment score for two segments with the same sign is the alignment score of their sequences of angles. In aligning CH sequences, we align one sequence with every cyclic shift of the other sequence. In aligning boundary sequences, we treat each segment (a sequence of angles) as a single character and calculate scores for deleting (or inserting) entire segments. We align all segments pairwise to find their similarity scores, and use them as pairwise segment-match scores in cyclically aligning boundary sequences (sequences of segments).

VI. Experimental Results

Fig. 1 illustrates results when the input query image is an $AC556$ assault rifle (the query in Fig. 6). Our algorithm traversed the ontology top down matching the CH sequence extracted from $AC556$ with those located in the basic categories. CH comparisons using cyclic sequence alignment concludes that in the upper ontology level a match of 70% is found with the pistols and 100% with rifle (Fig. 1). Since the threshold for our CH match is 85% the search continued in the descendants of rifle only. Among all rifle's descendants the above-threshold matches are with $AC556$ (100%), $AK47$ (91%), and Benelli Cordoba (88%). Their scores of similarity are shown in Fig. 1, whereas their shapes are shown in Fig. 6. With respect to boundary similarity to the query they are ordered as follows: $AC556$, $AK47$, and Benelli Cordoba. Fig. 7 includes results for two additional

Figure 6. Nearest matches for query $AC556$ from left to right: $AC556$, $AK47$, Benelli Cordoba. Percentages are for CH similarity to the query

ontology searches: 1) When the query is the pistol Arsenal

Figure 7. Additional results for queries: 1) Pistol Arsenal P AM02; 2) Riffle Benelli Cordoba. Percentages are for CH similarity to the query

P AM02, the following pistols pass the CH similarity threshold, and have the highest border similarity to the query: Arsenal P AM02, Arcus 94, AMT Automag V, and AMT Automag II; 2) When the query is the riffle Benelli Cordoba, the result list derived from ontology is: Benelli Cordoba, $AC556$, $AK47$, and Accuracy International Arctic Warfare.

For the weapons in our ontology we observe the following run times. When we use a PC with 1.6GHz clock, extracting the boundary and CH of input shape takes approximately 50 msec; generating a sequence from the boundary takes 16 msec; and comparing two boundary sequences cyclically takes about 16 msec. Generating a CH sequence and comparing two CH sequences take only a few msec. The total run time of a search in the present ontology is approximately 300 msec.

Let n denote the number of ontological nodes, and c be the total number of CH sequences extracted from the objects in the leafs and distributed over basic categories. We perform c cyclic CH-sequence alignment. Since CH sequence length is small (≤ 15) assume that its length is $O(1)$ for all weapons. Let each boundary sequence be of length $O(m)$ (currently $m \leq 150$), and ℓ be the number of weapons whose CHs are similar enough to that of the query. We cyclically align the boundary sequences for each of these and the query. The total time taken by this step is $O(\ell m^2)$, and the total time complexity of the method including traversal-time is $O(n + c + \ell m^2)$.

VII. Discussions and Conclusions

The contributions of this work are the following: we created the first weapon ontology; we use the object's CH sequences and boundary sequences to label ontology nodes; and use these sequences for computationally efficient rotational and scaling invariant searching. The cyclic properties ensure rotational invariance. For scaling invariance we use one and the same $|ds|$ in finding weapons' CHs and boundaries, which yields similar sequence lengths, and in aligning segments we use affine gap penalty model [18] which assigns relatively low costs for large blocks of insertions and deletions. The above listed qualities make our method suitable for automatic detection of humans carrying weapon in public areas. Further our system may assess the level of threat with respect to the type of the weapon.

Although other fast shape search methods in databases exist (e.g. [5]), our method provides the advantage of combining ontology with shape sequence annotation allowing not only quick identification but also meta data retrieval as the search progresses (see [1]). The method we present is currently sequential, but it provides the advantage to be parallelized in the following way: each processor would search an assigned subtree of the ontology, and report their findings to a designated processor.

The work continues with further extension of our weapon ontology, performing experimental searches, parallelizing the algorithm, and extending it to one with capability of dealing with occluded objects.

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