Object Detection with Incomplete Supervision

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Joint work with: Gokberk Cinbis and Cordelia Schmid
Why learning from incomplete supervision?

- Fully supervised training requires costly bounding box annotations
- Weakly supervised learning only uses image-wide labels
Overview of this presentation

- Preliminaries on object localization
  - Challenges
  - Representations
  - Search and learning

- Learning with incomplete supervision
  - Multiple instance learning approach
  - Multi-fold training to improve performance
  - Object instance hypothesis refinement

- Experimental evaluation and analysis
Challenging factors in object detection

- Intra-class appearance variation
  - Deformable objects: e.g. animals
  - Transparency: e.g. bottles
  - Sub-categories: e.g. ferry vs yacht

- Scene composition
  - Heavy occlusions: e.g. tables and chairs
  - Clutter: coincidental image content present in bounding box

- Imaging conditions
  - viewpoint, scale, lighting conditions
State-of-the-art visual representations

- Need for strong appearance features to separate classes despite strong intra-class variability and subtle inter-class variations
  - Consider deformability of cats and dogs
  - Similarity between furry cats and dogs in the similar poses

- Fischer vector representation
  - [Sanchez et al., IJCV, 2013]
    - Local SIFT descriptors, PCA to 64 dim.
    - 64 component GMM for soft quantization
    - Record first and second order moments of features assigned to each Gaussian
    - 4x4 SPM grid, power and L2 normalization
    - 140K dimensional descriptor
    - PQ compression to reduce storage cost
State-of-the-art visual representations

- Need for strong appearance features to separate classes despite strong intra-class variability and subtle inter-class variations
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- Global Convolutional Neural Network feature
  
  [Jia et al., caffe.berkeleyvision.org]
  - Trained on 1000 ImageNet 2012 categories
  - Caffe framework
  - Use last shared layer for representation
  - Resize detection windows to 224x224 pixels
  - L2 normalization
  - 4K dimensional descriptor
A typical object detection system

- Training a binary classifier that will score object windows
  - Positives given by manual annotation (hundreds to thousands)
  - Potential pool of negatives outside positive boxes (zillions)
    - Repetitive access to find useful/hardest negative samples
    - Store or re-extract feature vectors of these examples
- At test image, classify windows of different shapes and sizes
  - Detection speed proportional to number of considered windows
Issues with classic scanning windows

- Number of detection windows in an image is huge
  - Quadratic in image size

- Features are expensive to evaluate

- Features are expensive to store

- Alternatives to dense exhaustive search are needed
Alternatives to exhaustive sliding window search

- **Sliding window**
  (Viola and Jones 2002; Felzenszwalb et al. 2008, ...)

- **Branch & bound**
  (Lampert et al. 2008; Lehmann et al. 2013)

- **Selective Search**
  (Alexe et al. 2010; Sande et al. 2011)
Alternatives to exhaustive sliding window search

- Branch-and-bound techniques
  - Imposes requirements on type of classifiers / features
    [Lampert, Blaschko, Hofmann, PAMI 2009]

- Feature cascades
  - Requires set of fast features in early stages
    [Viola & Jones, IJCV 2004]

- Coarse-to-fine search
  - Requires compositionality of classifier score
    [Felzenszwalb, Girshick, McAllester, CVPR 2010]

- Data driven generic object hypotheses
  - Consider boxes aligned with low-level image contours
  - Does not impose constraints on classifiers / features
    [Alexe, Deselaers, Ferrari, CVPR 2010]
Search: restricted scanning of bounding box space

- Selective search method [Uijlings et al., IJCV, 2013]
  - 1000 - 2000 windows per image
  - Covers over 95% of true objects with sufficient accuracy
  - Unsupervised multi-resolution hierarchical segmentation
  - Candidate detections generated as bounding box of segments
- Candidate windows used for hard negative mining and testing
- Feature compression using PQ codes and lossless compression
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Learning from incomplete supervision

- Joint identification problem: recognition model and training instances
- Alternating optimization: fix one, optimize the other
State-of-the-art weakly-supervised detector training

- Vast majority of work relies on multiple-instance learning

- Approaches vary in terms of
  - Initialization strategy
  - Object descriptors and detector
  - Utilization of pair-wise window similarities

- Some alternative recent approaches are based on topic models
The multiple instance learning (MIL) approach

- Examples come in labeled “bags”
  Dietterich et al., *Artif. Intell.*, 1997
  - Selective search gives ~1500 windows per image = bag
  - Positive images contain at least one positive window
  - Negative images only have negative windows in the bag

- Multiple Instance SVM
  Andrews et al., NIPS 2002
  - Initialize initial selection of samples from positive bags
  - Train SVM with selection
  - Select top scoring sample in each positive bag
  - Repeat until convergence
Problems in standard multiple instance learning

- MIL gets stuck at poor local optima
  - Non-convex optimization problem
- Windows used in training get higher score than other windows
  - Biased towards re-localizing on the training windows
Problems in standard multiple instance learning

- Linear SVM classifier score is weighted sum of dot products
  \[ w^T x = \sum_i \alpha_i (x_i^T x) \]

- Fisher Vector descriptors are near-orthogonal = near zero dot product
  - But recall that descriptors are unit normalized!

- Linear SVM scores much higher for windows used in training
  - This causes the degenerate re-localization behavior
Problems in standard multiple instance learning

- MIL gets stuck at poor local optima
  - Non-convex optimization problem
- Windows used in training get higher score than other windows
  - Biased towards re-localizing on the training windows
Solution: Multi-fold training for multiple instance learning

- Separate sets of positive images for training and re-localization
  - Negative images do not need to be split, since no relocalization there

- Repeat two steps
  - Divide positive training images randomly into K folds
  - For fold $k = 1, ..., K$
    - Train detector from all training images, except those in fold $k$
    - Select top-scoring window in each positive image in fold $k$

- Avoids the re-localization bias since windows used for training and evaluation are always different
Solution: Multi-fold training for multiple instance learning

Algorithm 1 — Multi-fold weakly supervised training

1) Initialization: positive and negative examples are set to entire images up to a 4% border.
2) For iteration $t = 1$ to $T$
   a) Divide positive images randomly into $K$ folds.
   b) For $k = 1$ to $K$
      i) Train using positive examples in all folds but $k$, and all negative examples.
      ii) Re-localize positives by selecting the top scoring window in each image of fold $k$ using this detector.
   c) Train detector using re-localized positives and all negative examples.
   d) Add new negative windows by hard-negative mining.
3) Return final detector and object windows in train data.
A quick look at standard and multi-fold training

- Separate sets of positive images for training and re-localization.
The trouble with cats and dogs ...

- By construction, weakly supervised learning can only learn the most repetitive and discriminative patterns between the pos. and neg. images.
- These patterns sometimes correspond to parts instead of full object.
... and our solution to cats and dogs

- Refinement of the output of the multi-fold training procedure
- Final detector trained using these refined hypotheses
- Exploit low-level (non-category) contour detection to promote windows aligning with contours
Object hypothesis refinement

- Edge-driven method to generate object hypotheses
  “Edge Boxes”, Zitnick & Dollar, ECCV'14
- Promotes windows that
  ▶ align with long contours,
  ▶ few contours straddle the window boundary
- Here used to re-assess windows using average of detection and objectness score, only considering top-10 detection windows
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Evaluations based on PASCAL VOC'07 benchmark
Evaluation of multi-fold training

- Standard detection AP on test set
- Localization performance on positive training images
  - Fraction of images with correct localization (CorLoc)
    Deselaers et al., PAMI 2012
- Both averaged over all 20 classes
- Improvements for both features and both performance measures

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Multi-fold</th>
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<tbody>
<tr>
<td>CorLoc</td>
<td></td>
<td></td>
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<tr>
<td>FV</td>
<td>29.7</td>
<td>38.8 (+9.1)</td>
</tr>
<tr>
<td>CNN</td>
<td>41.2</td>
<td>45.0 (+3.8)</td>
</tr>
<tr>
<td>Detection AP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FV</td>
<td>15.5</td>
<td>22.4 (+6.9)</td>
</tr>
<tr>
<td>CNN</td>
<td>24.3</td>
<td>25.9 (+1.6)</td>
</tr>
</tbody>
</table>
Evaluation of multi-fold training

- CorLoc over the re-training / re-localization iterations
- Iteration n: n-th iteration after initialization from full image
- For both features: averaged over all 20 classes

- Multi-fold training improves learning from both features
  - 10 folds suffice
  - 5 to 10 iterations suffice
Window refinement and combining features

- Refinement helps improve performance
- Combining features boosts performance

<table>
<thead>
<tr>
<th>Refinement</th>
<th>No</th>
<th>Yes</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>CorLoc</td>
<td></td>
</tr>
<tr>
<td>FV</td>
<td>38.8</td>
<td>46.1 (+7.3)</td>
</tr>
<tr>
<td>CNN</td>
<td>45.0</td>
<td>54.2 (+9.2)</td>
</tr>
<tr>
<td>FV+CNN</td>
<td>47.3</td>
<td>52.0 (+4.7)</td>
</tr>
<tr>
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<td></td>
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</tr>
</tbody>
</table>
Analysis: The relation between CorLoc and detection AP

- Relation between localization during training and final test performance
  - Each of the 20 classes gives a point on the graph
  - Very highly correlated, similar coefficient for both features
Analysis: The relation between CorLoc and detection AP

- Relative performance of weakly supervised learning with respect to performance with full supervision
  - Ratio of AP with weak vs full supervision
  - Stable performance when CorLoc is > 40%, around 80% relative
  - Smaller CorLoc results in rapid deterioration
Analysis: What type of errors are made?

- More correct localization with multi-fold training
- Less overshoot of true object for multi-fold training, more undershoot
- Refinement fixes “undershoot” cases
- Complete failure (<10%) relatively rare: explains robustness
### Analysis: what makes weakly supervised learning hard?

- Performance for the shades of grey between fully and weakly supervised learning scenario

<table>
<thead>
<tr>
<th>Supervision</th>
<th>Neg on Pos</th>
<th>Positive Set</th>
<th>mAP(FV)</th>
<th>mAP(CNN)</th>
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<td>Image labels only</td>
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<td>Non-diff/trunc</td>
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<td>Cand box for one obj</td>
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<td>40.5</td>
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<tr>
<td>Exact box for all obj</td>
<td>Yes</td>
<td>All</td>
<td>35.4</td>
<td>42.8</td>
</tr>
</tbody>
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- The two most critical factors for performance
  - Getting one example right per positive image
  - Hard-negative mining on positive images
Comparison the recent state of the art

- Separation between methods based on whether they leverage external training data to learn CNN features

<table>
<thead>
<tr>
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<th>aero</th>
<th>bicy</th>
<th>bird</th>
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<td>Russakovsky et al.’12 [35]</td>
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<tr>
<td>Ours (FV-only)</td>
<td>36.9</td>
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methods using additional training data

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- Improvements over the state of the art without external training data
- With external training data: comparable to best methods [Wang et al.,'14]
Summary and outlook

- State-of-the-art weakly supervised object detection performance
  - Strong appearance cues for recognition: FV and CNN descriptor
  - Re-localization bias suppression: Multi-fold MIL training
  - Recognition and localization decoupling: hypothesis refinement

- From here on forward:
  - Dealing with noise on the image labels (eg google-image download)
  - Concurrent training of categories: leverage explaining away
  - Richer interactions between recognition and segmentation

- Relevant publications
  - “Multi-fold MIL training for weakly supervised object localization”, CVPR'14
  - Journal paper under review: CNN features and refinement
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