Towards Open World Recognition

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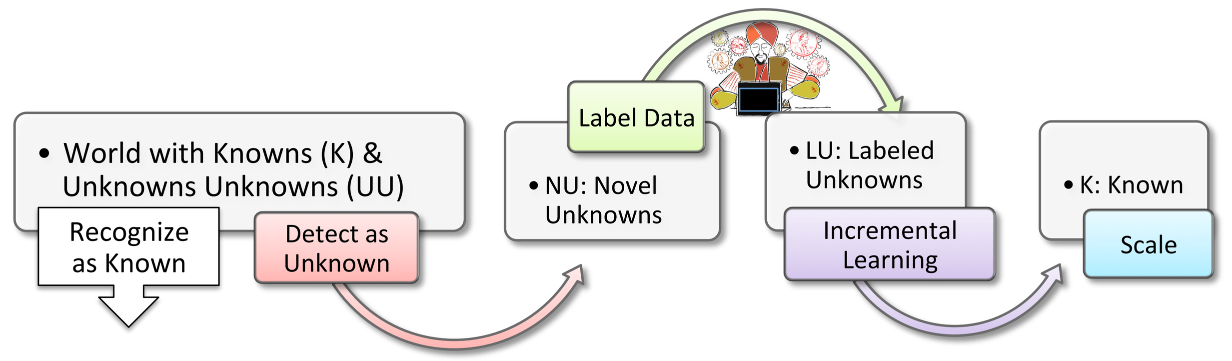
Contributions

1. Formal definition of **"Open World Recognition"**, which extends the existing definition of Open Set Recognition defined for static notion of set.
2. A recognition system that can continuously learn new incoming categories in an open world model.
3. We show that **thresholding sums of monotonically decreasing functions of distances** of linearly transformed feature space can have arbitrarily small "open space risk".
4. Open World Evaluation Protocol

Open World Recognition



A **solution** to Open World Recognition is a tuple $[F, \varphi, \nu, L, I]$

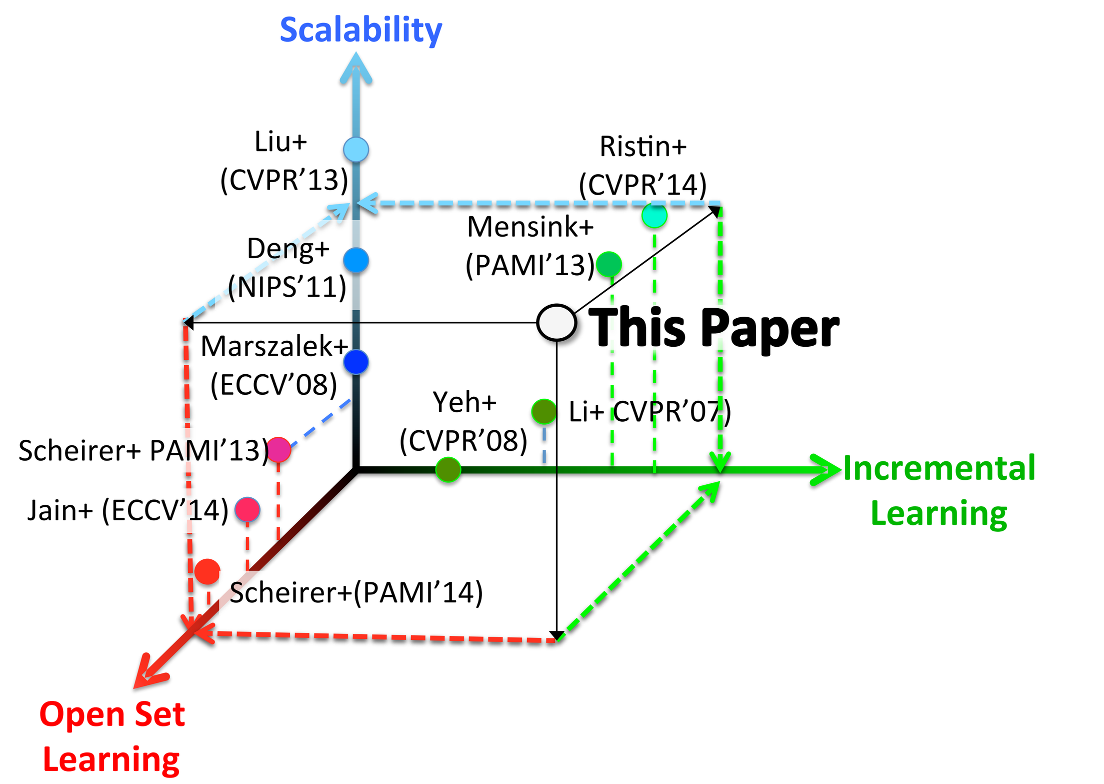
1. $F(x)$ is a multi-class open set recognition function
2. $\varphi = [f_1(x), \ldots, f_k(x)]$ vector function of per-class recognition functions
3. $\nu(\varphi) : \mathbb{R}^i \mapsto [0,1]$ is a novelty detector (to determine if the class is known/unknown)
4. $L(x)$ is labeling process applied to novel unknown data
5. $I_t(\varphi, D_t)$ is an incremental learning function to scalably learn and add new measurable recognition functions to φ

Ideally, all of these steps should be automated, but herein we presume supervised learning with labels obtained by human labelling.

Dynamic Multi-Class Classification

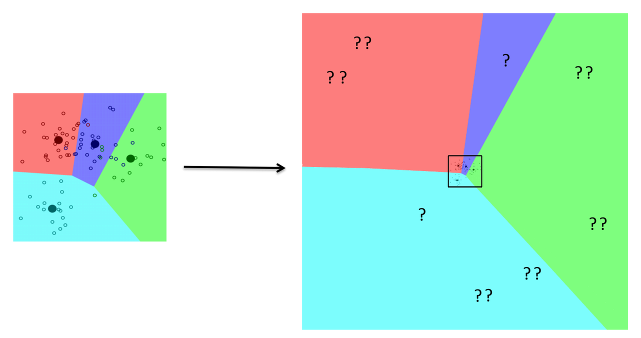
A recognition system in the "open world" has to continuously update with additional object categories and be robust to unseen categories and have minimum downtime

Related Work



Our work lies at the intersection of scalable learning, open set learning and incremental learning

Open Space



Let **Open Space** is the space sufficiently far from any known positive training sample $x_i \in \mathcal{K}, i = 1 \ldots N$, be defined as:

$$\mathcal{O} = S_o - \bigcup_{i \in N} B_r(x_i) \qquad (1)$$

Then probabilistic **Open Space Risk** $R_{\mathcal{O}}(f)$ for a class y can be defined as

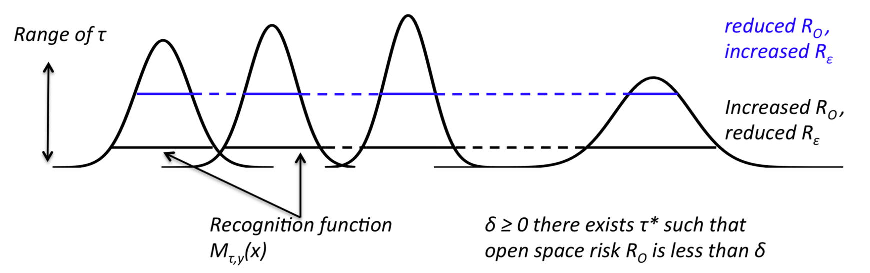
$$R_{\mathcal{O}}(f_y) = \frac{\int_{\mathcal{O}} f_y(x)dx}{\int_{S_o} f_y(x)dx} \qquad (2)$$

Given an empirical risk function $R_{\mathcal{E}}$, the objective of **Open Set Recognition** is to find a measurable recognition function that manages (minimizes) the Open Set Risk:

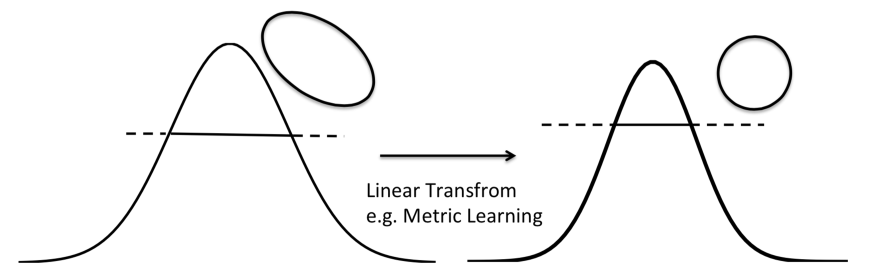
$$\underset{f \in \mathcal{H}}{\operatorname{argmin}} \{R_{\mathcal{O}}(f) + \lambda_r R_{\mathcal{E}}(f)\} \qquad (3)$$

Opening an Existing Algorithm

Theorem 1: Open Space Risk for Model Combination



Theorem 2: Open Space Risk for Transformed Spaces



Nearest Non-Outlier Algorithm

Nearest Class Mean Classifier: Assign an image i to the class closest to the class mean by $\mu_k = \frac{1}{|\mathcal{I}_k|}\sum_{i \in \mathcal{I}_k} x_i$. Then class conditional probabilities are given by

$$p'(c|x) = \frac{1}{Z} exp(x^T W^T W \mu_c + s_c) \qquad (4)$$

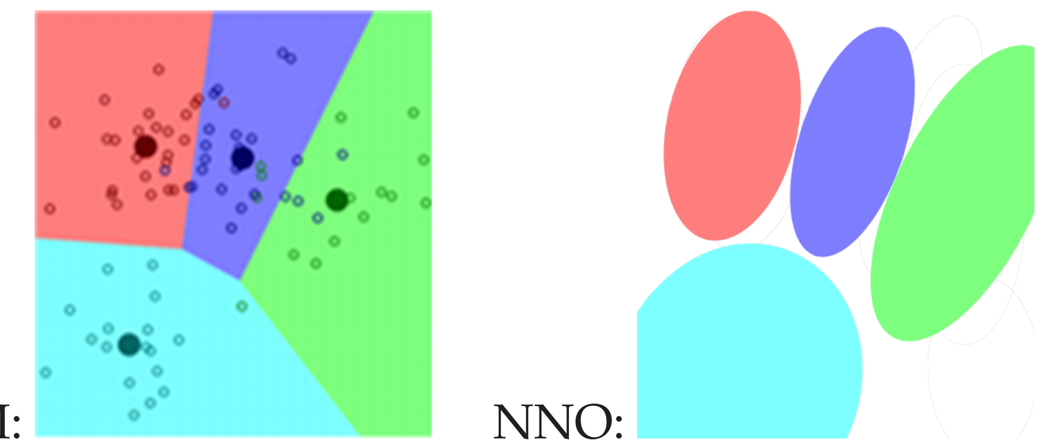
where Z denotes the normalizer and s_c is a per class bias.

Nearest Non-Outlier Algorithm: Let $W \in \mathbb{R}^{d \times m}$ be the linear transformation dimensional reduction weight matrix (metric learning phase). Then given τ, let

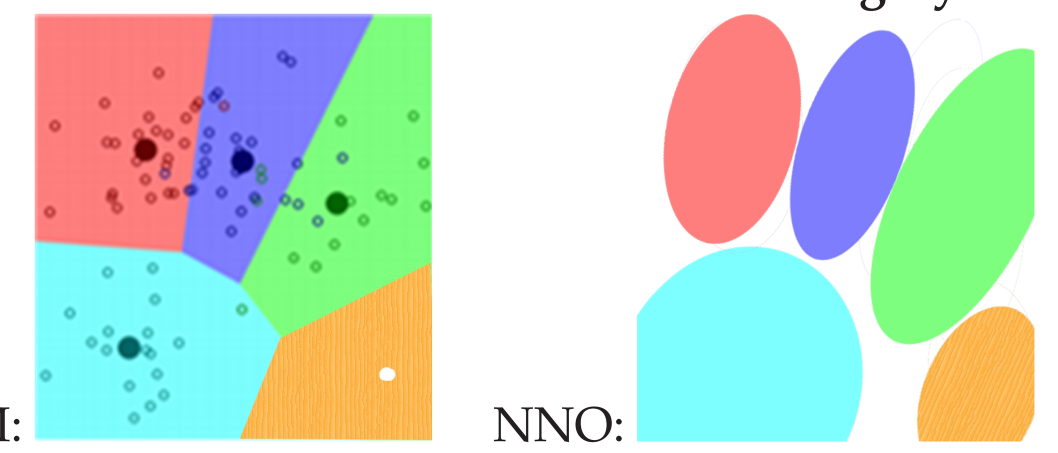
$$\hat{f}_i(x) = \frac{\Gamma(\frac{m}{2}+1)}{\pi^{\frac{m}{2}}\tau^m}\left(1 - \frac{1}{\tau}\|W^\top x - W^\top \mu_i\|\right) \qquad (5)$$

be our measurable recognition function with $\hat{f}_i(x) > 0$ giving the probability of being in class.

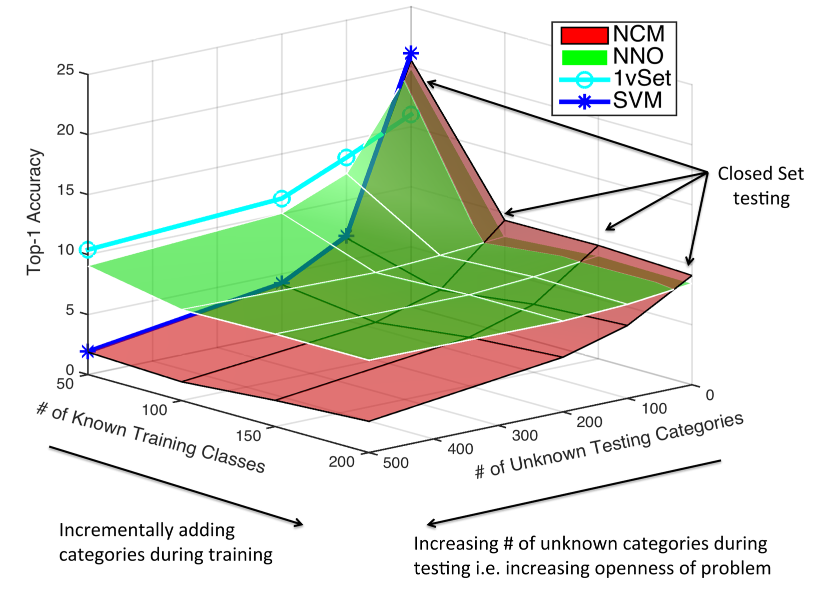
Incremental Category Learning

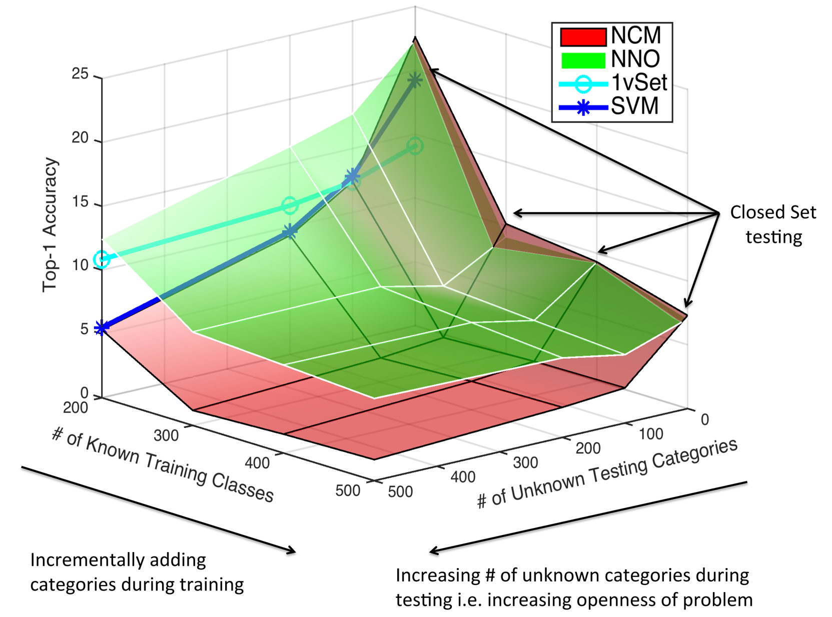


Above base model. Below with new category.



Experiments





Experiment Details

1. **Dataset:** ILSVRC'10 (and '12): 1.2M training images, 1K classes
2. **Features:** Dense SIFT features quantized in 1000 BoW
3. **Algorithms:** Nearest Class Mean Classifier, Nearest Non-Outlier Algorithm, 1vsSet, Linear SVM
4. **Training Phase:**
   - Parameter Learning with initial set of categories, followed by estimation of τ to balance open space risk
   - Incrementally add categories
5. **Testing Phase:** Test with known and unknown categories

Acknowledgements: The work support in part by NSF Research Grant IIS-1320956 and UCCS Graduate School Fellowship.

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Code/Data: http://vast.uccs.edu/OpenWorld