

# Deep Learning Based Domain Adaptation with Data Fusion for Aerial Image Data Analysis

---

Jingyang Lu, Chenggang Yu, Erik Blasch, Roman Ilin, Hua-mei Chen,  
Dan Shen, Nichole Sullivan, Genshe Chen, Robert Kozma

Intelligent Fusion Technology, Inc.  
Air Force Research Laboratory  
The University of Memphis  
01/15/2021



# Outline

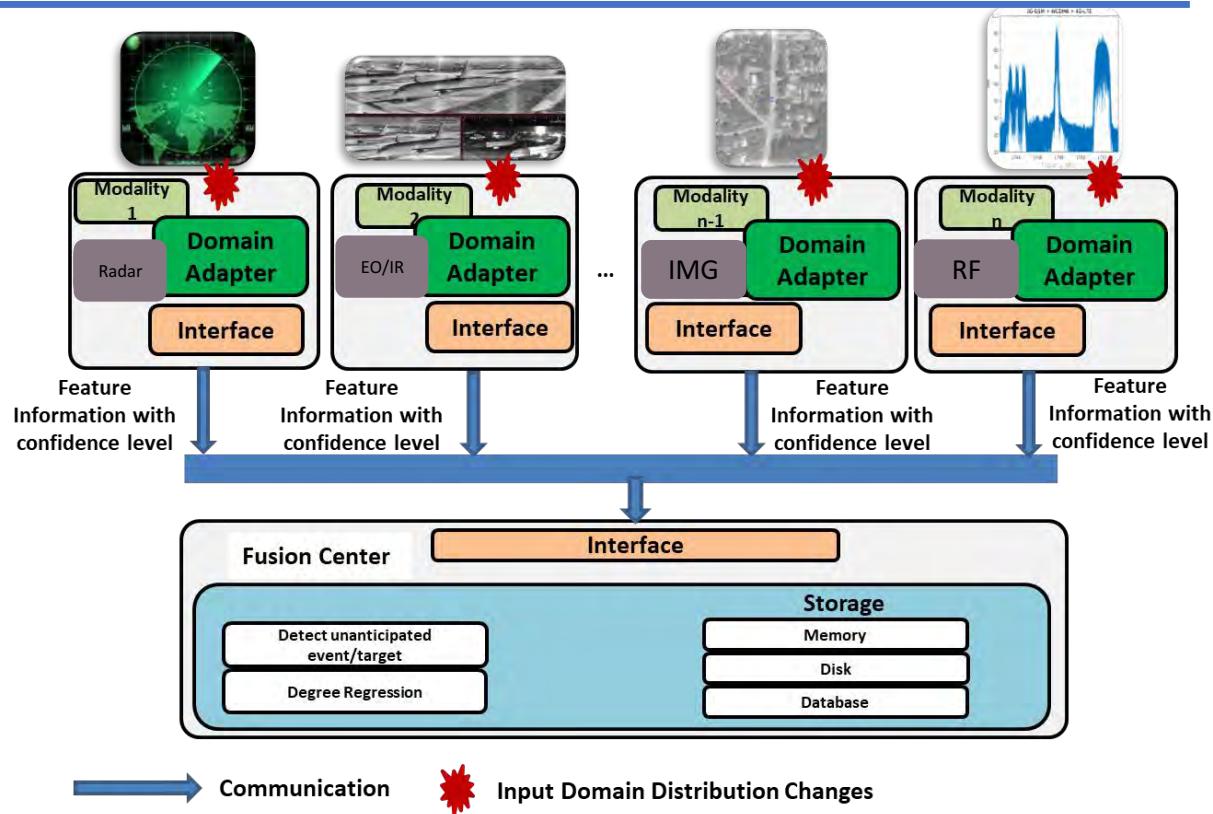
---

- **Introduction and Motivation**
- **Problem Formulation**
- **Benchmark Dataset Test**
- **Data Fusion Approaches**
- **Conclusion and Future Work**

# Machine Learning based Domain Adaptation for Multiple Source Classification and Fusion

## Motivation

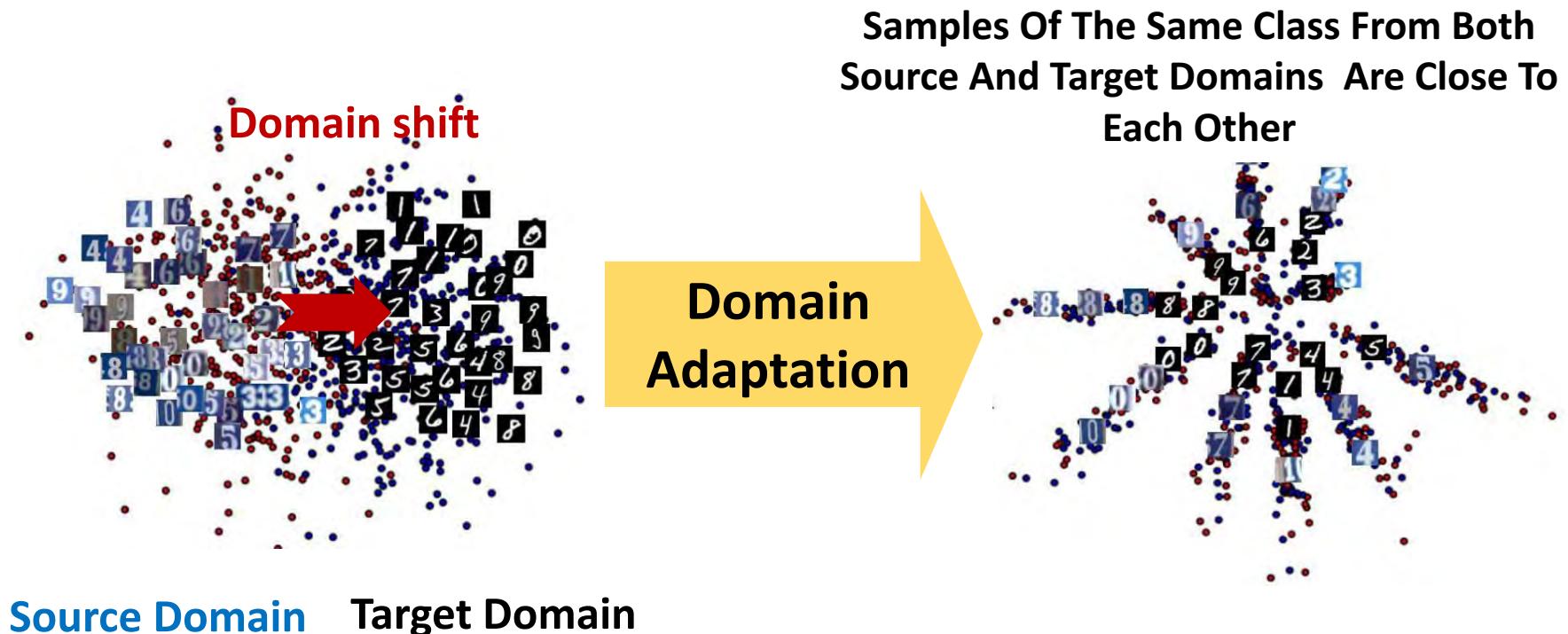
- Classifier accuracy decreases due to the domain shift
- Higher false alarm rates and consequently decreases trust in the classifier system
- Quick adaptation to changes in domain distributions without retraining the classifiers



The benefits of the proposed solution, Machine Learning based Domain Adaptation (MLB-DA) :

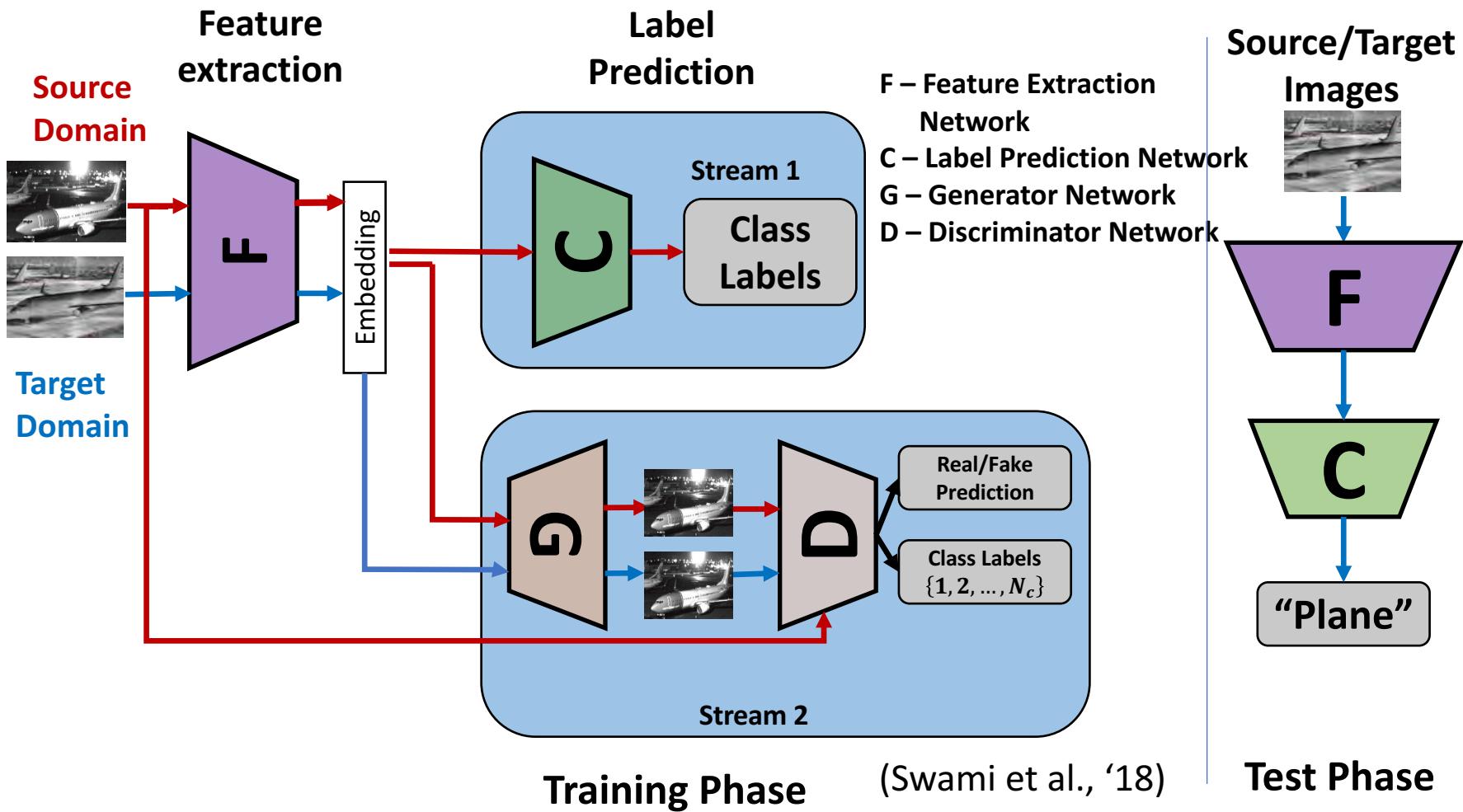
- Focused on learning features that combine: (i) discriminativeness and (ii) domain invariance.
- Does not need to retrain the model to adapt to input distribution change.
- Provides a sound foundation for the more realistic *Open Set Domain Adaptation* scenario.

# Problem Formulation



- Domain Adaptation Attempts To Mitigate The Discrepancy Between Source And Target Domain.
- After Adaptation, The Source And Target Domains Are Expected To Share The Same Or Similar Distribution.

# Domain Adaptation for Each Modality



The proposed MLB-DA is designed by employing a variant of the conditional GAN called Auxiliary Classifier GAN where the discriminator is modeled as a multi-class classifier instead of providing conditioning information at the input

# Domain Adaptation for Each Modality

1. Given a real data  $x$  as input to  $F$ , the input to the generator network  $G$  is  $x_g = [F(x), z, l]$ ,

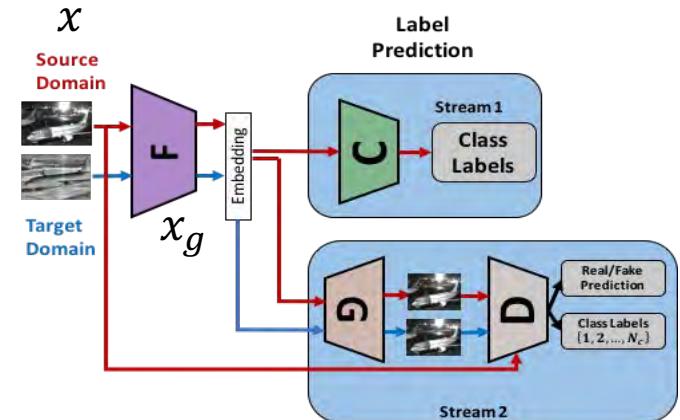
where  $z$  is random noise vector  $z \in \mathbb{R}^d$  sampled from  $N(0,1)$ ;

$l$  is a one hot encoding of the class label,  $l \in \{0,1\}^{(N_c+1)}$  with  $N_c$  real classes and  $\{N_c + 1\}$  being the fake class.

2. A classifier network  $C$  that takes as input the embedding generated by  $F$  and predicts a multiclass distribution  $C(x)$

3. The discriminator mapping  $D$  takes the real input data  $x$  or the generated input  $G(x_g)$  as input and outputs two distributions:

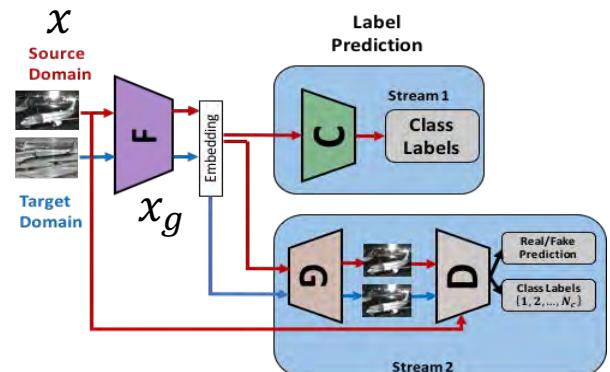
- (1)  $D_{data}(x)$ : the probability of the input being real, which is modeled as a binary classifier
- (2)  $D_{cls}(x)$ : the class probability distribution of the input  $x$ , which is modeled as a  $N_c$ -way classifier.



**It should be noted that, for target data, as the class labels are unknown,  $D_{data}(x)$  is only used to update the gradients**

# Cost Function Domain Adaptation for Each Modality

1. In the case of source inputs, the gradients are generated using the following loss functions,



$$L_{data,src} + L_{cls,src} = \mathbb{E}_{x \sim \mathcal{S}} \max_D \log D_{data}(x) + \log \left( 1 - D_{data}(G(x_g)) \right) + \log(D_{cls}(x)_y)$$

## 1<sup>st</sup> D Update

The third entity in the cost function is utilized as the label data information is available in the source domain dataset.

2. Based on the loss function for D, Generator (G) is updated based on the combination of adversarial loss and classification loss.

$$L_G = \min_G \mathbb{E}_{x \sim \mathcal{S}} -\log \left( D_{cls}(G(x_g))_y \right) + \log(1 - D_{data}(G(x_g)))$$

Source domain data is used to update the G

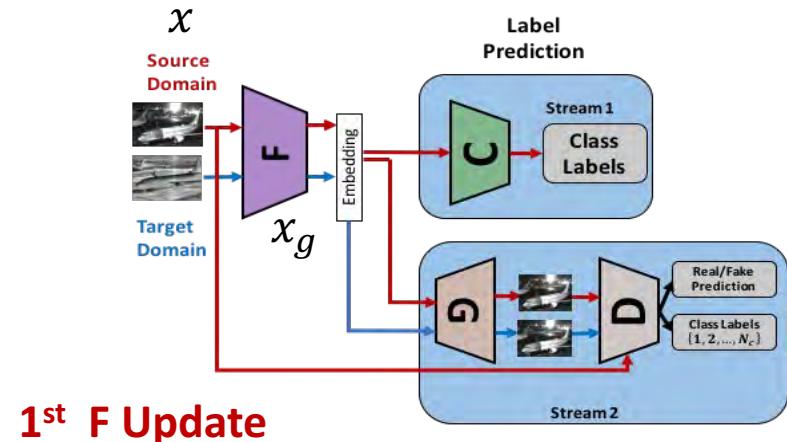
In our proposed frame work, target domain data is also used to update the G

# Cost Function Domain Adaptation for Each Modality

### 3. $F, C$ Update

$$L_c = \min_C \min_F E_{x \sim s} - \log \left( C(F(x))_y \right),$$

$$L_{cls,src} = \min_F E_{x \sim s} - \alpha \log \left( D_{cls} \left( G(x_g) \right)_y \right)$$



$F$  is also updated using the adversarial gradients which is similar to the loss function for  $G$

4.  $D$  is updated to determine the generated target domain as fake as follows,

$$L_{adv,tgt} = \max_D E_{x \sim \mathcal{T}} \log(1 - D_{data}(G(x_g))) \quad \text{2nd D Update}$$

In order to transfer the knowledge of target distribution to the embedding,  $F$  is updated using the gradients from  $D_{data}$  that corresponds to the generated target data being classified as real,

$$L_{F_{adv}} = \min_F E_{x \sim \mathcal{T}} \beta \log(1 - D_{data}(G(x_g))) \quad \text{2nd F Update}$$

# Training Process for Domain Adaptation

---

## Algorithm Iterative Training Procedure Of MLB-DA

---

- 1: Training Iterations = N
- 2: For t in 1: N do
- 3:     Sample k raw data with labels from source domain  $S$ :  $\{s_i, y_i\}_i^k$   
   Let  $f_i = F(s_i)$  be the embeddings computed for the source images  
   Sample k images from target domain  $T$ :  $\{t_i\}_i^k$   
   Let  $h_i = F(t_i)$  be the embeddings computed for the target images  
   Sample  $k$  random noise samples  $\{z_i\}_{i=1}^k \sim \mathcal{N}(0,1)$ .  
   Let  $f_{g_i}$  and  $h_{g_i}$  be the concatenated inputs to the generator.

- 4: Update discriminator (D) using the following objectives:

$$L_D = L_{data,src} + L_{cls,src} + L_{adv,tgt}$$

Target domain  
data

- 5: Update the generator (G), only for source data, through the discriminator (D) gradients computed using

$$L_G = \min_G \frac{1}{k} - \log \left( D_{cls} \left( G(f_{g_i}) \right) \Big|_{y_i} \right) + \log \left( 1 - D_{data} \left( G(f_{g_i}) \right) \right) + \log \left( 1 - D_{data} \left( G(h_{g_i}) \right) \right)$$

- 6: Update the embedding  $F$  using a linear combination of the adversarial loss and classification loss. Update the classifier  $C$  for the source data using a cross entropy loss function.

$$\begin{aligned} L_F &= L_c + \alpha L_{cls,src} + \beta L_{F_{adv}} \\ \bullet L_c &= \min_C \min_F \frac{1}{k} \sum_i^k -\log(C(f_i)_{y_i}) \\ \bullet L_{cls,src} &= \min_F \frac{1}{k} \sum_i^k -\log \left( D_{cls} \left( G(f_{g_i}) \right) \Big|_{y_i} \right) \\ \bullet L_{F_{adv}} &= \min_F \frac{1}{k} \sum_i^k \log \left( 1 - D_{data} \left( G(h_{g_i}) \right) \right) \end{aligned}$$

# Benchmark Dataset Test

---

1. GTA performance evaluation based on digits dataset.
2. Study the new dataset UCM and AID including the Baseball field, beach, medium residential, sparse residential, and parking lot. \*
3. Improve the GTA approach: the feature extraction model F is replaced by the ResNet-50 in order to extract efficient feature from the input data.
4. Implement GTA Domain Adaptation From AID to UCM, the numerical results show GTA approaches can efficiently classify the data from target domain.
5. Conduct the GTA approach sensitivity analysis.

# Benchmark Dataset- Digits Dataset

Results shown in the original paper

Method	MN → US (p)	MN → US (f)	US → MN	SV → MN
Source only	$75.2 \pm 1.6$	$79.1 \pm 0.9$	$57.1 \pm 1.7$	$60.3 \pm 1.5$
RevGrad [4]	$77.1 \pm 1.8$	-	$73.0 \pm 2.0$	$73.9$
DRCN [5]	$91.8 \pm 0.09$	-	$73.7 \pm 0.04$	$82.0 \pm 0.16$
CoGAN [15]	$91.2 \pm 0.8$	-	$89.1 \pm 0.8$	-
ADDA [32]	$89.4 \pm 0.2$	-	$90.1 \pm 0.8$	$76.0 \pm 1.8$
PixelDA [1]	-	<b>95.9</b>	-	-
Ours	<b><math>92.8 \pm 0.9</math></b>	<u><math>95.3 \pm 0.7</math></u>	<b><math>90.8 \pm 1.3</math></b>	<b><math>92.4 \pm 0.9</math></b>

Implemented by IFT

62% (Source Only)

88.90% (GTA)

Implemented by IFT

89.9% accuracy (Source Only)

93.8 % (GTA)

Implemented by IFT

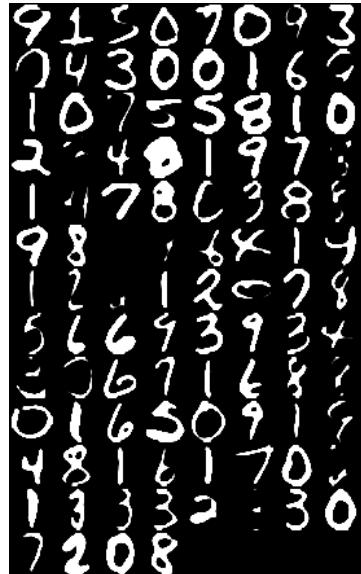
74.5 % (Source Only)

97.0% (GTA)

Each model was trained 500 epochs

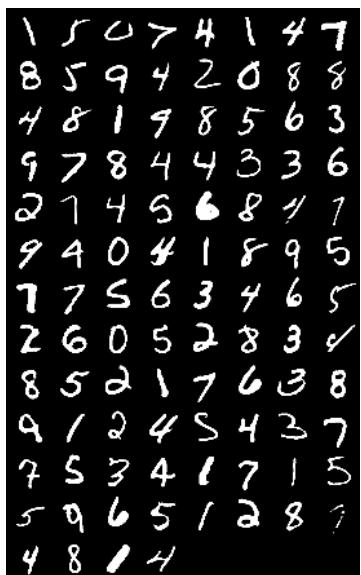
**Validation:** In the experiment set up, for example, SVHN->MN, the target domain data is for the MNIST, SVHN is the source domain data, and after each epoch of training, a fixed subset of data from source domain is used to validation, which is different from the test.

Source dataset (USPS)

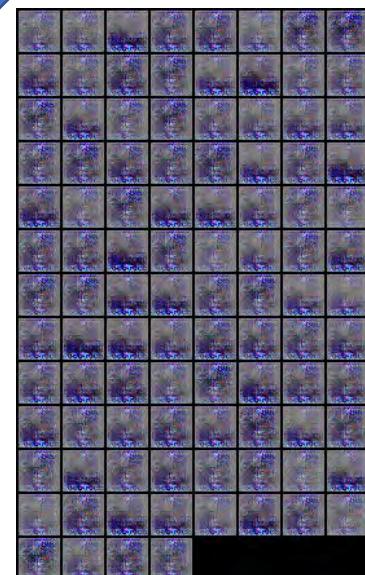
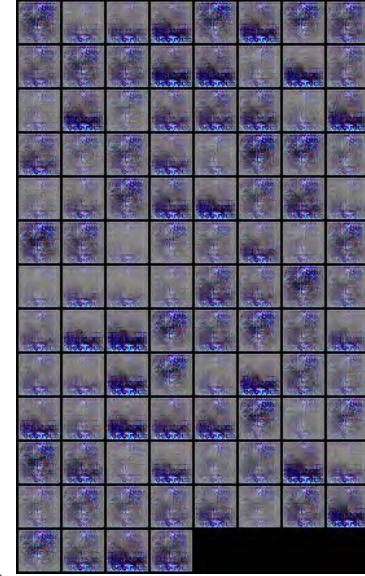


100 samples from the two datasets are transferred by **netF + netG** after 1 round of training

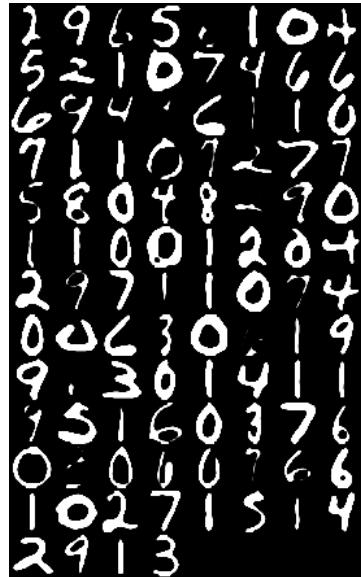
netF + netG



Target dataset (MNIST)



Source dataset (USPS)



100 samples from the two datasets are transferred by **netF + netG** after **190** rounds of training

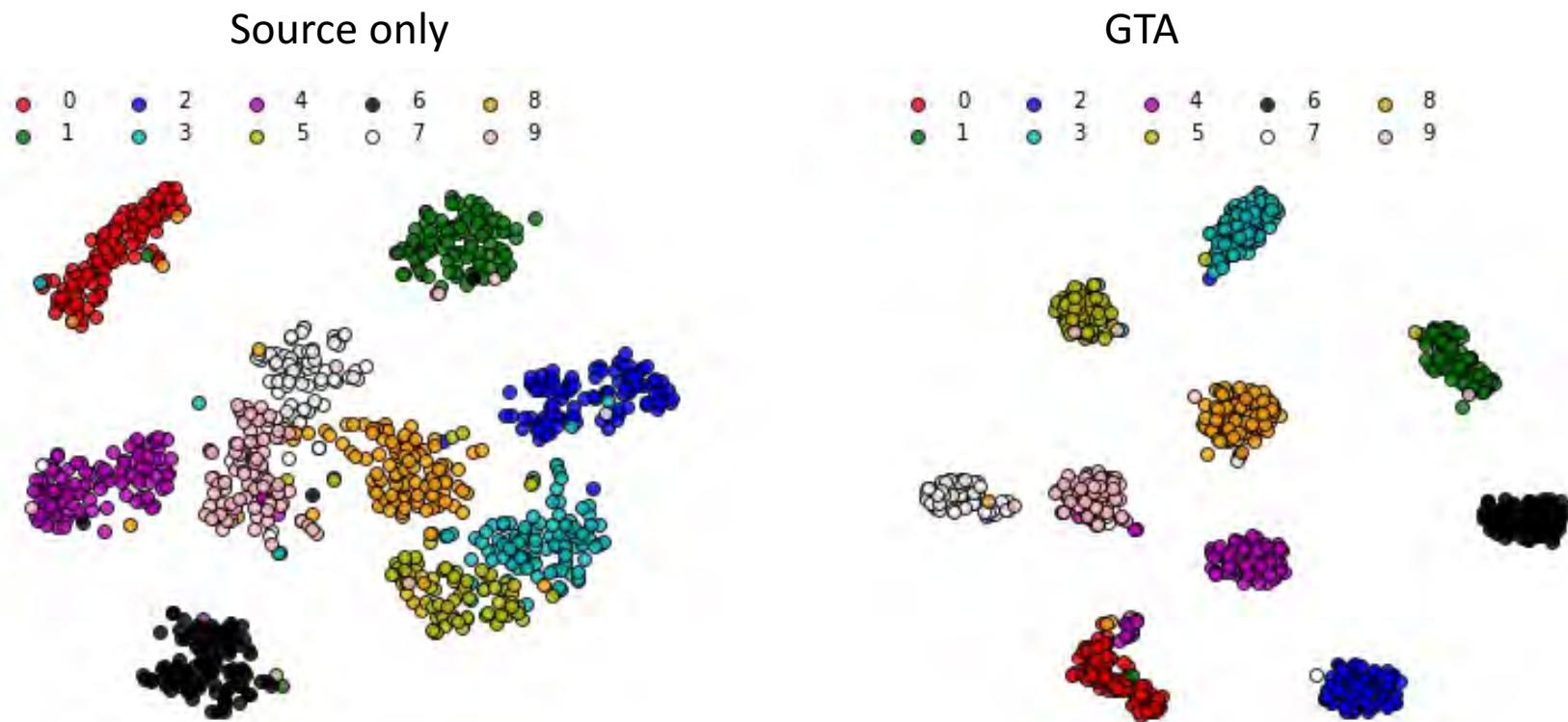
netF + netG



Target dataset (MNIST)



# TSNE visualization of target data



TSNE visualization of target data (MNIST) separation by features out of netF that is trained by source data (USPS) only and by GTA (Each point represent one sample randomly selected from the MNIST testing set. Same 1000 random samples are used in the two plots)

# Benchmark Dataset- Aerial Datasets

---

## 1. UCM

- Manually extracted images from United States Geological Survey National Map Urban Area Imagery
- 21 classes
- Image size is 256x256 pixels
- Ground Sample Distance (GSD) 1 foot/pixel
- 100 images per class ([UCM] Yi Yang et. al., "Bag-Of-Visual-Words and Spatial Extensions for Land-Use Classification," ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (ACM GIS), 2010)



## 2. AID

- More than 10,000 aerial images
- 30 classes
- Multi source Google Earth images from various countries
- Image size is 600x600 pixels
- Multi GSD (8 meter to 0.5 meter)

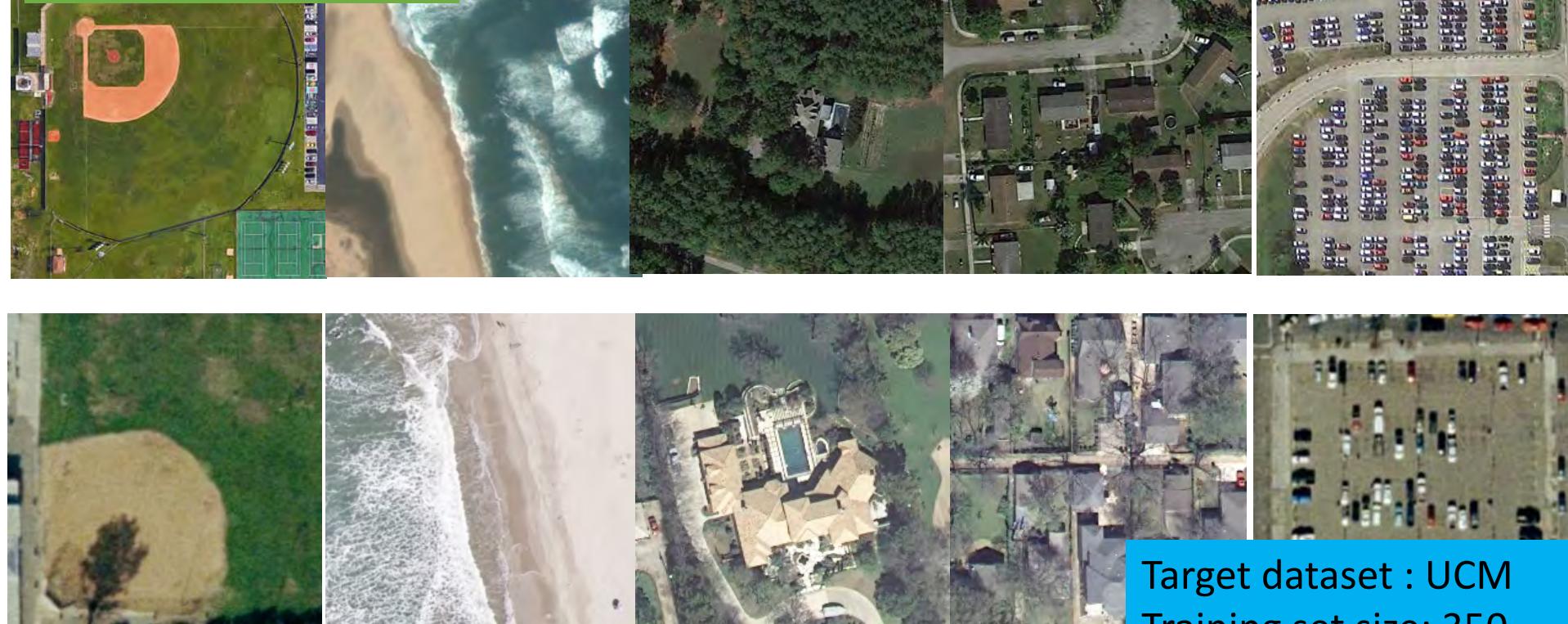


# GTA Domain Adaptation From AID to UCM

Source dataset: AID

Training set size: 1129

Testing set size: 489



Task: Classifying images into five categories:

Baseball field, beach, medium residential, sparse residential, and parking lot

Target dataset : UCM

Training set size: 350

Testing set size: 150

# GTA Networks Architectures

NetF

**ResNet 50**  
**(Last layer out)**

NetC

**Linear**  
**2048 → 5**

NetG

ConvT  
(512ch, 2x2, 1, 0)  
BN, ReLU

ConvT  
(256ch, 4x4, 2, 1)  
BN, ReLU

ConvT  
(128ch, 4x4, 1, 0)  
BN, ReLU

ConvT  
(128ch, 4x4, 2, 1)  
BN, ReLU

ConvT  
(64ch, 4x4, 2, 1)  
BN, ReLU

ConvT  
(3ch, 4x4, 2, 1)  
Tanh

NetD

Conv  
(128ch, 5x5, 1, 2)  
BN, ReLU, Max(4x4)

Conv  
(128ch, 5x5, 1, 2)  
BN, ReLU, Max(2x2)

Conv  
(128ch, 5x5, 1, 2)  
BN, ReLU, Max(7x7)

Linear  
128 → 500

Linear  
500 → 500

Linear  
500 → 5

X3

X3

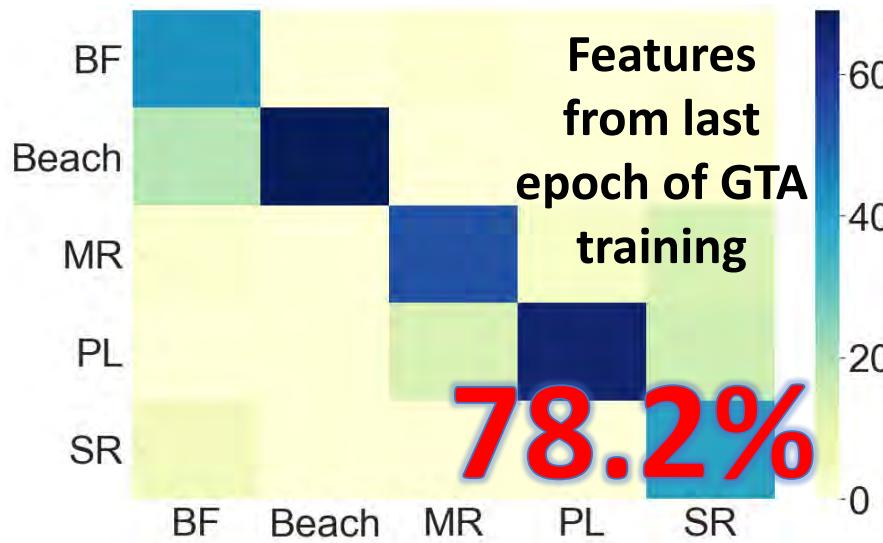
# Benchmark Dataset- Aerial Datasets

---

		Case 1	Case 2	Case 3	Case 4	Case 5
Parameters	Learning rate	0.0004	0.0004	0.0004	0.0001	0.0004
	Learning rate decay	0.0002	0.0002	0.0002	0.001	0.001
	Alpha	0.05	0.01	0.08	0.05	0.05
	Beta	0.05	0.01	0.08	0.05	0.05
Target accuracy	Source only	69.7	69.7	69.7	69.7	69.7
	Best GTA model	66.4	56.2	66.6	54.7	65.1
	Last GTA model	<b>78.2</b>	48.5	<b>75.6</b>	60.3	65.7

**~12.0% Improvement**

# Experiment 1

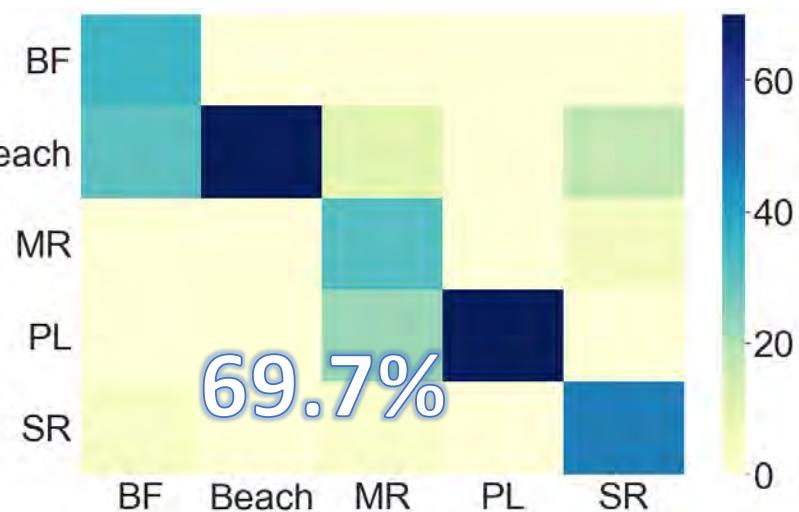
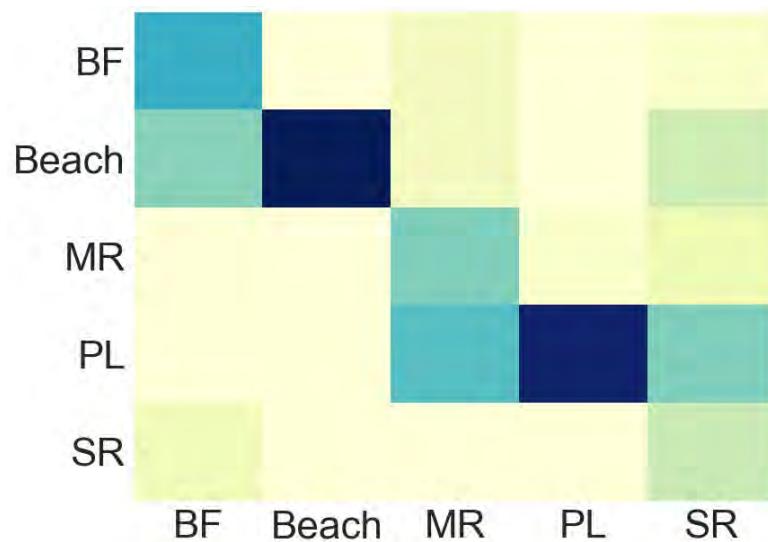


Learning rate 0.0004

Learning rate decay 0.0002

Alpha 0.05

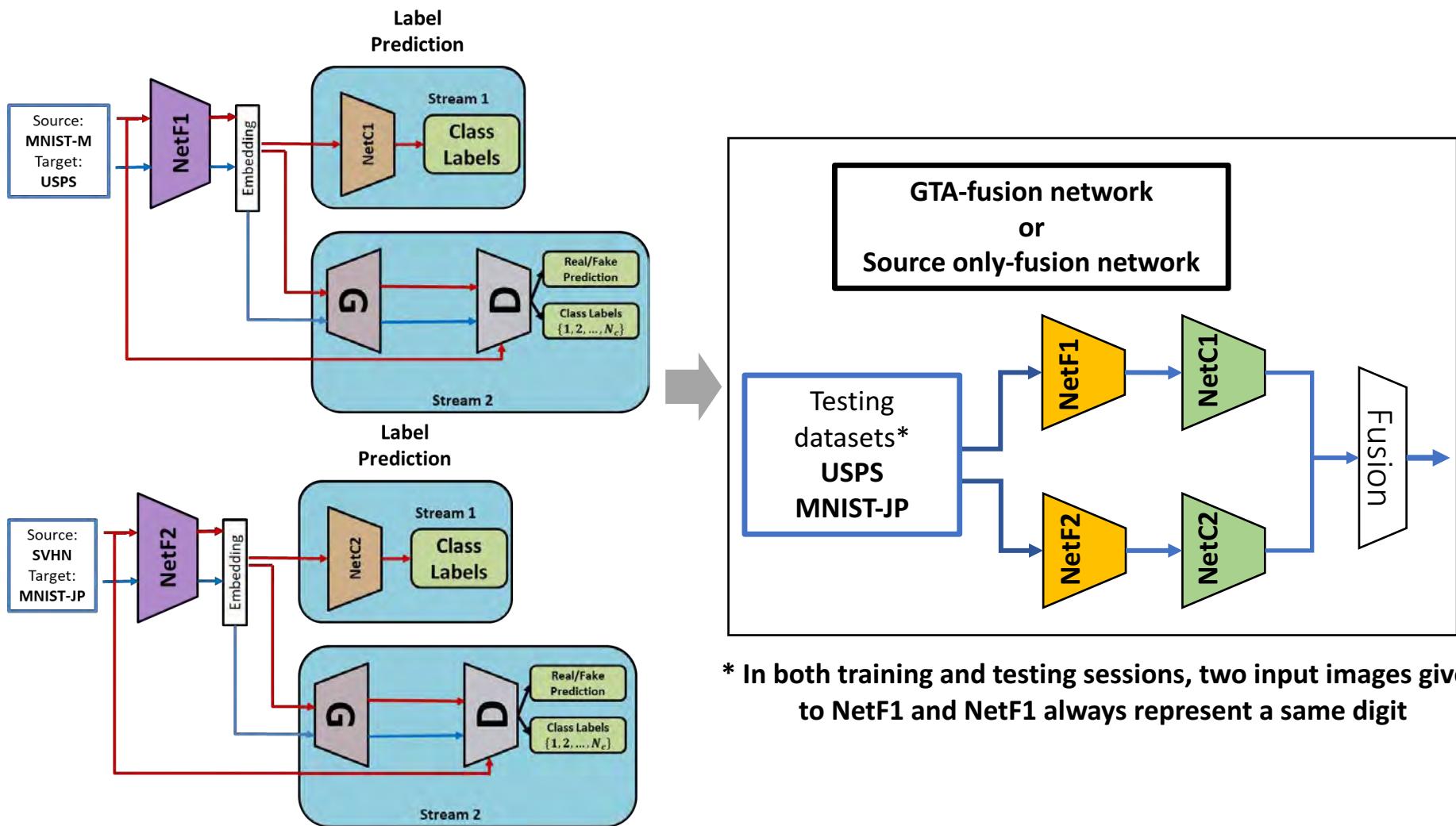
Beta 0.05



Features from source only training

# **Development of Data Fusion Approaches from Different Sensors and Different Modalities**

# Decision Level Fusion for Heterogeneous Multiple Sensor Modalities



# Decision Level Fusion for Heterogeneous Multiple Sensor Modalities

- Entropy  $\mathcal{H}_k$  for each sensor k

$$\mathcal{H}_k = - \sum_{i=1}^N p_{k,i} \log(p_{k,i}), i = 1, \dots, N$$

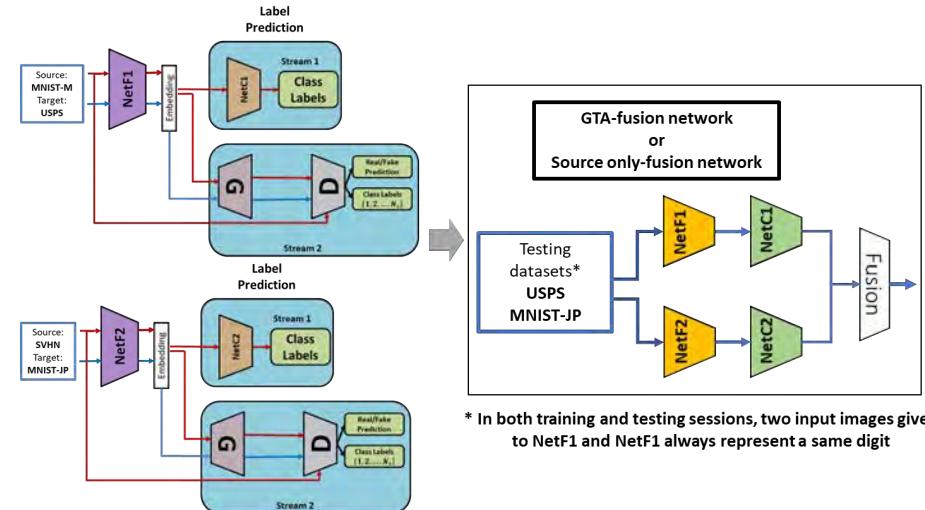
- Decision by each sensor k

$$d_k = \text{argmax}(p_{k,i}), i = 1, \dots, N$$

- Final decision by Fusion Center

$$D = d_{opt}, H_{opt} \leq H_k \quad k = 1, \dots, K$$

Where K is the total number of sensor modalities.



\* In both training and testing sessions, two input images given to NetF1 and NetF2 always represent a same digit

For a system with two sensor modalities:

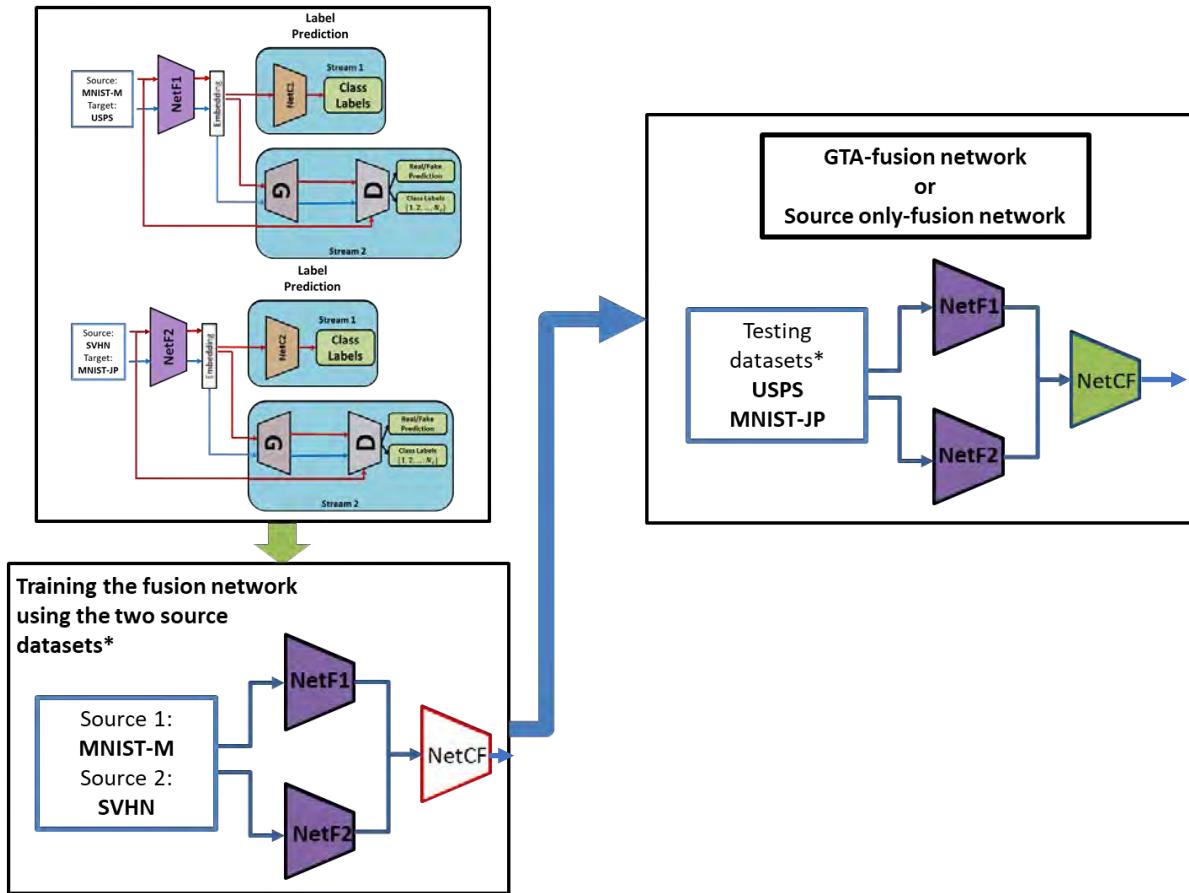
$$d = \text{argmax}(p_i), i = 0, \dots, 9$$

$$H = - \sum_{i=1}^N p_i \log(p_i), i = 0, \dots, 9$$

$$D = \begin{cases} d_1, & \text{if } H_1 < H_2 \\ d_2, & \text{if } H_1 > H_2 \end{cases}$$

In order to make a final prediction D from the predictions of the two decision networks, we assessed each prediction's reliability by computing an entropy, where p0 through p9 are 10 output values from one netC.

# Feature Level Fusion for Heterogeneous Multiple Sensor Modalities



\* In both training and testing sessions, two input images given to NetF1 and NetF2 always represent a same object.

# Architectures for Fusion Networks

**NetF**

ConvT (64ch, 5x5, 1,0) BN, ReLU, Max(2x2)
ConvT (64ch, 5x5, 1,0) BN, ReLU
Conv (128ch, 4x4, 1,0) BN, ReLU

**NetC**

Linear $128 \rightarrow 128$ ReLU
Linear $128 \rightarrow 10$ SoftMax*

**NetG**

ConvT (512ch, 4x4, 2, 2) BN, ReLU
ConvT (256ch, 4x4, 2, 2) BN, ReLU
ConvT (128ch, 4x4, 2, 2) BN, ReLU
ConvT (64ch, 4x4, 2, 2) BN, ReLU
ConvT (1ch, 4x4, 2, 2) BN, ReLU

**NetD**

Conv (64ch, 3x3) BN, LeakyReLU(0.2), Max(2x2)
Conv (128ch, 3x3) BN, LeakyReLU(0.2), Max(2x2)
Conv (256ch, 3x3) BN, LeakyReLU(0.2), Max(2x2)
Conv (128ch, 3x3) BN, LeakyReLU(0.2), Max(4x4)
Linear $128 \rightarrow 10$ $128 \rightarrow 2$

**NetCF\*\***

Linear $256 \rightarrow 256$
Linear $256 \rightarrow 128$ ReLU
Linear $128 \rightarrow 10$

\* SoftMax is applied only when conducting decision-level fusion

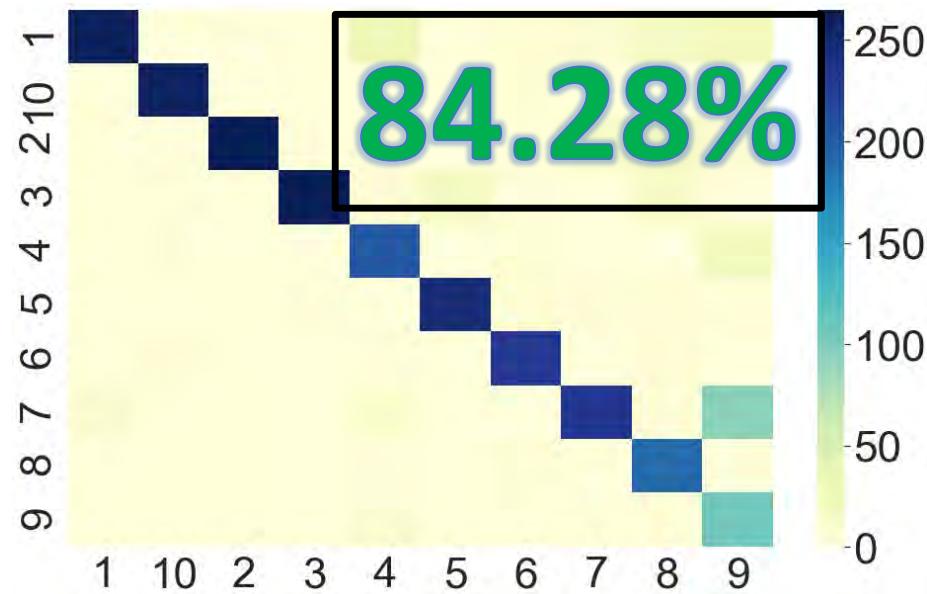
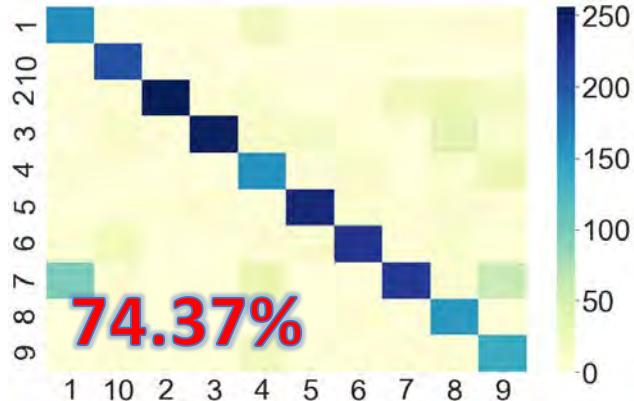
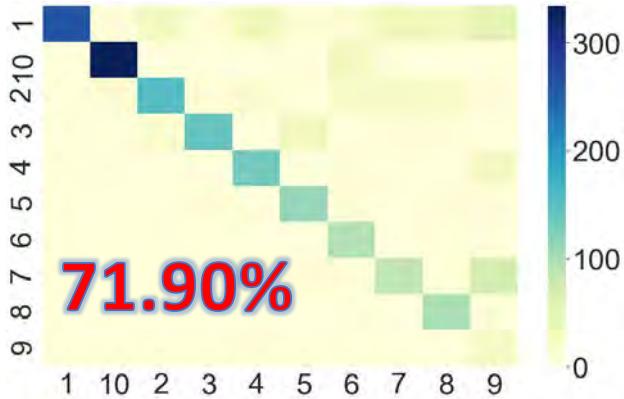
\*\* The network that fuses two NetFs

# Data Fusion Approaches Performance for Multiple Sensor Modalities

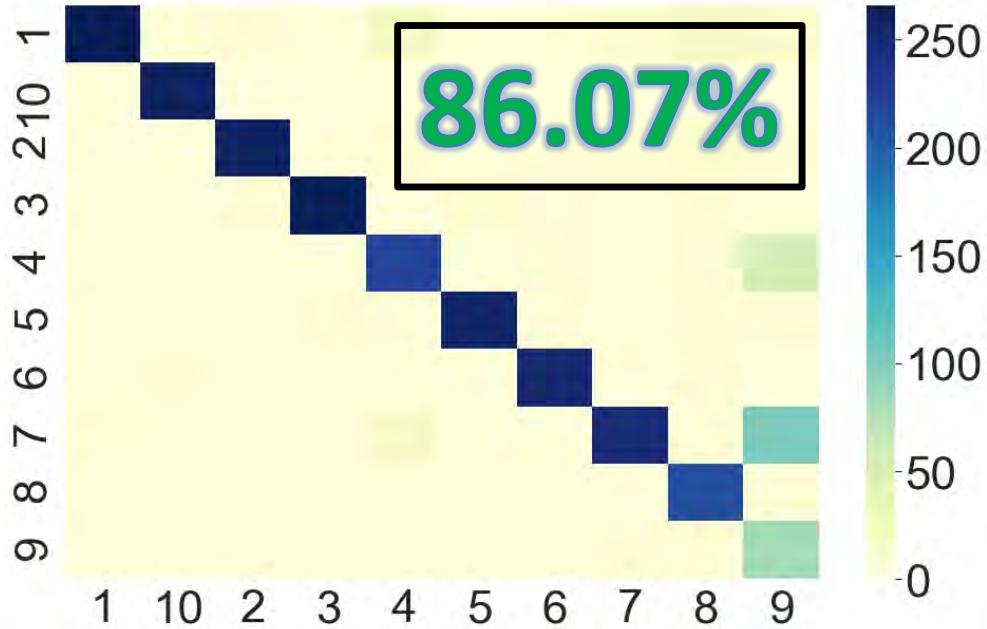
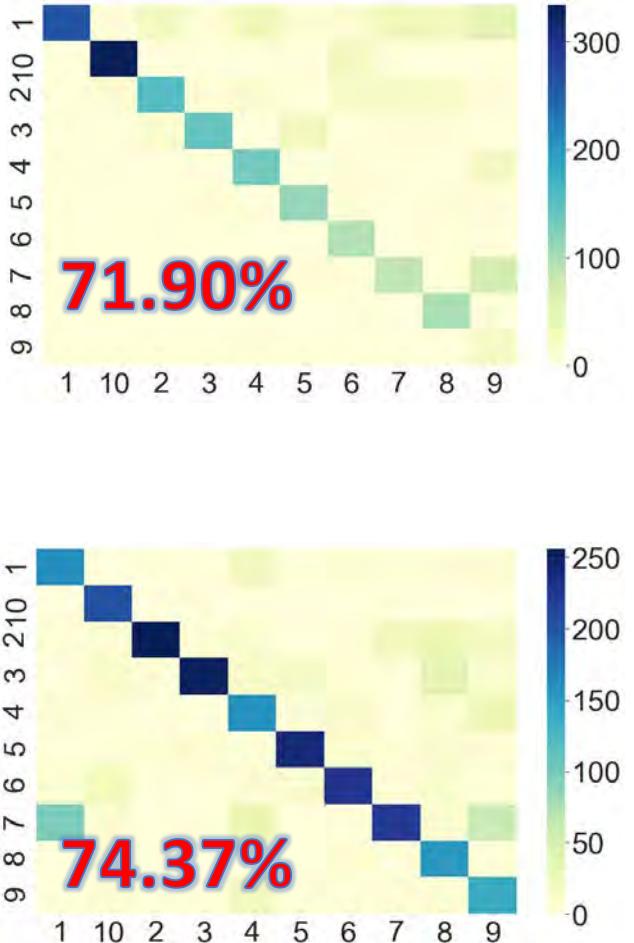
---

Testing dataset	Single network		GTA-trained	Feature-level fusion	Decision-level fusion
	MNIST-M →USPS	SVNH → MNIST-JP			
USPS	<b>71.90</b>	58.44			
MNIST-JP	56.89	<b>74.37</b>			
USPS+MNIST-JP				<b>86.07</b>	<b>84.28</b>

# Decision Level Fusion for Heterogeneous Multiple Sensor Modalities



# Feature Level Fusion for Heterogeneous Multiple Sensor Modalities



# Conclusion

---

1. Design and implemented the proposed MLB-DA approach and test it with Digits/UCM-AID dataset for cross class sets domain adaptation.
2. Developed the framework for data fusion from different sensors, and can be extended to different modalities.
3. Decision-level fusion (84% accuracy) and feature-level fusion (86% accuracy) are both implemented.
4. Initial benchmark and feasibility study of proposed approach have shown MLB-DA outperforms (min 10%) previous results of GTA for a single sensor.

thank  
you!