Open Set Domain Adaptation via Known Joint Distribution Matching and Unknown Classification Risk Reformulation

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***Abstract*—Open set domain adaptation (OSDA) is an important problem in machine learning and computer vision. In OSDA, one is given a labeled dataset from a source domain (source joint distribution) and an unlabeled dataset from a target domain (target joint distribution), where the target domain contains not only the known classes presented in the source domain but also the unknown class. The goal of OSDA is to train a neural network with minimal target classification risk. From the statistical learning perspective, there are two fundamental challenges in this problem: (1) the source–target joint distribution difference regarding the known classes and (2) the target classification risk estimation regarding the unknown class. Although prior works have proposed various sophisticated solutions to the problem and achieved inspiring experimental results, they do not fully resolve these two challenges. In this article, we introduce a principled approach named known joint distribution matching and unknown classification risk reformulation (KMUR). KMUR tackles the first challenge by matching the source joint distribution to the target known joint distribution such that the distribution difference can be reduced and addresses the second challenge by reformulating the target unknown classification risk such that the reformulated risk can be estimated on the unlabeled target and source data. To be specific, we exploit cross entropy as the classification loss and triangular discrimination (TD) distance as the joint distribution matching loss. Since the TD distance needs to be estimated from data, we develop an innovative technique named least squares TD estimation (LSTDE), which casts the estimation into least squares classification. To achieve the OSDA goal, we train the network to minimize the estimations of target classification risk and TD distance. Experiments on benchmark and real-world datasets confirm the effectiveness of our approach. The introductory video and PyTorch code are available on GitHub (https://github.com/sentaochen/Known-Joint-Distribution-Matching-and-Unknown-Classification-Risk-Reformulation). One can also visit https://github.com/sentaochen for more source code on domain adaptation (DA), multi-source DA, partial DA, and domain generalization approaches.**

***Index Terms*—Distribution matching, open set classification, risk minimization, statistical estimation.**

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I. Introduction

IN SUPERVISED classification, it is generally assumed that the training joint distribution $p^{tr}(\boldsymbol{x}, y)$ and testing joint distribution $p^{te}(\boldsymbol{x}, y)$ are identical and share the same class label space, where $\boldsymbol{x}$ is the input features and y is the class label [1], [2], [3]. Given a labeled training dataset $\{(\boldsymbol{x}_i^{tr}, y_i^{tr})\}_{i=1}^{m_{tr}}$ from the training joint distribution $p^{tr}(\boldsymbol{x}, y)$, the goal of supervised classification is to train a neural network $\boldsymbol{f}(\boldsymbol{x})$ with minimal testing classification risk $\int \ell(\boldsymbol{f}(\boldsymbol{x}), y)p^{te}(\boldsymbol{x}, y)d\boldsymbol{x}dy$, where ℓ is the classification loss [1], [2], [3]. Since the training and testing joint distributions are identical and share the same label space, the testing classification risk can therefore be directly estimated as the average training classification loss $\frac{1}{m_{tr}}\sum_{i=1}^{m_{tr}} \ell(\boldsymbol{f}(\boldsymbol{x}_i^{tr}), y_i^{tr})$, and the network can be practically trained by minimizing this loss. This is known as the empirical risk minimization (ERM) principle [1] in statistical learning.

Open set domain adaptation (OSDA) [4] extends supervised classification by relaxing the assumptions of identical joint distribution and identical class label space. In OSDA, the source domain (source joint distribution) $p^s(\boldsymbol{x}, y)$ and the target domain (target joint distribution) $p^t(\boldsymbol{x}, y)$ are different, and the target label space is also different from the source one and contains it as a subset. This means that besides the known classes presented in the source domain, the target domain also contains additional unknown classes. Since there is no prior knowledge on the unknown classes, following mainstream OSDA works [4], [5], [6], [7], this article combines all the unknown classes into a single class. Given a labeled source dataset and an unlabeled target dataset containing the unknown class, the goal of OSDA is to train a neural network $\boldsymbol{f}(\boldsymbol{x})$ with minimal target classification risk $\int \ell(\boldsymbol{f}(\boldsymbol{x}), y)p^t(\boldsymbol{x}, y)d\boldsymbol{x}dy$. Namely, the trained network should well classify the unlabeled target data into one of the known classes or the unknown class.

From the statistical learning perspective, there are two fundamental challenges in OSDA. One is the difference between source joint distribution $p^s(\boldsymbol{x}, y)$ and target known joint distribution $p^t(\boldsymbol{x}, y|\text{kn})$, i.e., $p^s(\boldsymbol{x}, y) \neq p^t(\boldsymbol{x}, y|\text{kn})$. This challenge hinders the neural network from classifying the unlabeled target data into the correct known classes since the network is trained and tested on different distributions [8], [9], [10]. The other one is the estimation of target unknown classification

risk, whose result is a natural optimization objective to train the network for classifying the unknown. In general, estimating the classification risk requires the input features and class labels to compute the average classification loss [1], [2], [3]. However, in OSDA, the unknown class labels are not given, which poses a challenge in estimating the target unknown classification risk.

Mainstream OSDA works match marginal distributions [4], [5], [7] or class-conditional distributions [11], [12], [13] regarding the known classes between domains and recognize the target unknown class via setting threshold value [4] or designing weighting mechanisms [5], [7], [14]. For example, Saito et al. [4] introduced an adversarial learning method that matches the source marginal distribution $p^s(\boldsymbol{x})$ to the target known marginal distribution $p^t(\boldsymbol{x}|\text{kn})$ in the feature space and recognizes the target unknown class by a predefined threshold value. Liu et al. [11] matched the source class-conditional distribution $p^s(\boldsymbol{x}|y)$ to the target known class-conditional distribution $p^t(\boldsymbol{x}|y, \text{kn})$ in the subspace, and trained the classifier by minimizing the average source classification loss and the average classification loss computed on the pseudo-labeled target unknown data. Jang et al. [7] optimized an adversarial learning objective to align the source and target known marginal distributions and segregate the target unknown marginal distribution $p^t(\boldsymbol{x}|\text{uk})$ and trained the neural network by minimizing the average source classification loss and the weighted average target classification loss. Besides, there also exist works that propose to address OSDA via self-supervised learning [15], causal alignment [16], or other strategies [17], [18]. While these works have achieved inspiring experimental results, in essence, they do not fully resolve the two fundamental OSDA challenges. As a result, it is not clear whether their solutions can achieve the OSDA goal and train a neural network with minimal target classification risk.

Our research in this article aims to address the two fundamental challenges and achieve the OSDA goal. We use a basic neural network that contains a featurizer and a classifier. Starting from the OSDA goal, we express the target classification risk as the mixture of two risks: the target known classification risk and the target unknown classification risk, which are associated with the target known joint distribution $p^t(\boldsymbol{x}, y|\text{kn})$ and the target unknown joint distribution $p^t(\boldsymbol{x}, y|\text{uk})$, respectively. To address the first challenge, we exploit the featurizer to match the source joint distribution $p^s(\boldsymbol{x}, y)$ to the target known joint distribution $p^t(\boldsymbol{x}, y|\text{kn})$ in the feature space to reduce their difference. Since the joint distributions are matched, the target known classification risk can therefore be estimated as the average source classification loss computed on the labeled source data. To address the second challenge, we reformulate the target unknown classification risk in terms of the target marginal distribution $p^t(\boldsymbol{x})$ and target known marginal distribution $p^t(\boldsymbol{x}|\text{kn})$. Since the previous joint distribution matching also leads to the matching of target known marginal distribution $p^t(\boldsymbol{x}|\text{kn})$ and source marginal distribution $p^s(\boldsymbol{x})$, the reformulated risk can therefore be estimated as the difference of two average classification losses computed on the unlabeled target and source data, without requiring the target unknown class labels. By combining the estimation results of target known and unknown risks, we derive the estimated target classification risk. In the reminder, we name this OSDA approach known joint distribution matching and unknown classification risk reformulation (KMUR). See Fig. 1(a) and (b) for the illustration of KMUR. To be specific, we exploit cross entropy as the classification loss and triangular discrimination (TD) distance [19] as the joint distribution matching loss. Since the source joint distribution and target known joint distribution are unknown in practice, the TD distance between them is also unknown and needs to be estimated from data. We show that the estimation of TD distance can be elegantly cast into the kernel-based least squares classification problem that has an analytic solution. With this solution, we manage to express the estimated TD distance as an explicit function of the featurizer. Hence, we can directly optimize the featurizer to minimize the estimated TD distance and match joint distributions in the feature space. In the reminder, we name this estimation technique least squares triangular discrimination estimation (LSTDE). See Fig. 1(c) for the illustration of LSTDE. Of course, it is also feasible to use other statistical distances as the joint distribution matching loss, e.g., the related Kullback–Leibler (KL) divergence and Jensen–Shannon (JS) divergence. However, as practiced in [5], [7], [20] and [21], optimizing the featurizer to minimize these distances usually results in adversarial training, which is time-consuming and unstable [22]. Considering such a drawback, we use TD distance to free us from the challenging adversarial training. To achieve the OSDA goal, we train the neural network to minimize both the estimated target classification risk and the estimated TD distance. In summary, we list the main contributions of this research as follows.

1) We introduce the KMUR approach to solve the OSDA challenges. Our approach matches the source and target joint distributions regarding the known classes in the feature space, and reformulates the target classification risk regarding the unknown class such that the reformulated risk can be estimated on unlabeled target and source data.
2) We develop the LSTDE technique to estimate the TD distance (joint distribution matching loss) from data. Our technique casts the estimation into least squares classification, and expresses the estimated TD distance as an explicit function of the featurizer, which allows us to directly optimize the featurizer to minimize the distance and match joint distributions in the feature space.
3) We conduct experiments on several benchmark image datasets and a real-world skin disease dataset. Our experimental results and analysis demonstrate the advantage of our approach compared to other methods.

II. Methodology

A. Problem Formulation

In OSDA, there exists a source joint distribution $p^s(\boldsymbol{x}, y)$ defined on the source label space with c classes, and a target

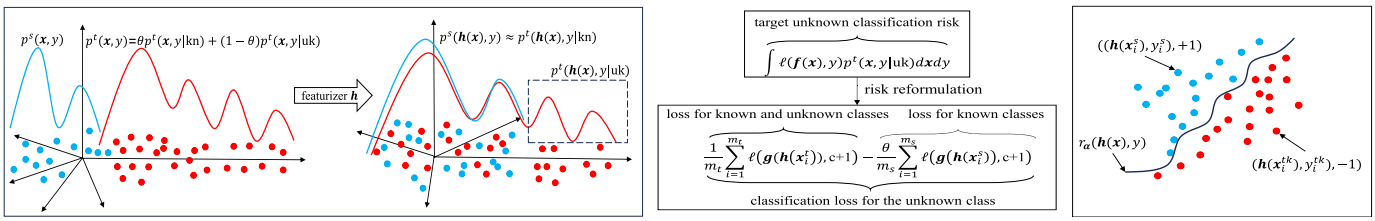


Fig. 1. Illustration of our KMUR approach and LSTDE technique. (a) KMUR matches source joint distribution $p^s(\boldsymbol{x},y)$ to target known joint distribution $p^t(\boldsymbol{x},y|\text{kn})$ via featurizer $\boldsymbol{h}$. (b) KMUR reformulates target unknown classification risk and estimates the reformulated risk as the difference between the average loss on unlabeled target data (of known and unknown classes) and the average loss on unlabeled source data (of known classes). (c) LSTDE estimates the TD distance between $p^s(\boldsymbol{h}(\boldsymbol{x}),y)$ and $p^t(h(x),y|\text{kn})$ via kernel-based least squares classification, where the kernel-based model $r_\alpha(\boldsymbol{h}(\boldsymbol{x}),y)$ classifies the source sample $(\boldsymbol{h}(\boldsymbol{x}_i^s),y_i^s)$ into positive class $+1$ and the target known sample $(\boldsymbol{h}(\boldsymbol{x}_i^{tk}),y_i^{tk})$ into negative class -1.

joint distribution $p^t(\boldsymbol{x},y)$ defined on the target label space with $c+1$ classes. For the target label space, its first c classes are the known classes shared with the source label space, and its last $c+1$ class is the unknown class not presented in the source label space. This research combines all the unknown classes into a single class since there is no prior knowledge on the unknown classes [4], [5], [6], [7]. Given a labeled source dataset $\mathcal{D}^s=\{(\boldsymbol{x}_i^s,y_i^s)\}_{i=1}^{m_s}$ from source joint distribution $p^s(\boldsymbol{x},y)$ and an unlabeled target dataset $\mathcal{D}^u=\{\boldsymbol{x}_i^t\}_{i=1}^{m_t}$ from target joint distribution $p^t(\boldsymbol{x},y)$, the goal of OSDA is to train a neural network $\boldsymbol{f}(\boldsymbol{x})$ with minimal target classification risk $\int \ell(\boldsymbol{f}(\boldsymbol{x}),y)p^t(\boldsymbol{x},y)d\boldsymbol{x}dy$, where $\boldsymbol{f}(\boldsymbol{x})$ has $c+1$ outputs and ℓ is the classification loss. In other words, the trained network should well classify the unlabeled target data into one of the known classes or the unknown class. The classification rule is given by $\widehat{y}=\text{argmax}_{k\in\{1,\ldots,c+1\}}f_k(\boldsymbol{x})$, where $f_k(\boldsymbol{x})$ is the kth output of $\boldsymbol{f}(\boldsymbol{x})$. In this OSDA problem, there are two challenges: 1) the source–target joint distribution difference regarding the known classes and 2) the target classification risk estimation regarding the unknown class.

B. KMUR Approach

1) Target Classification Risk: Unlike prior works [14], [16], [17] that focus on designing complex neural networks, this research uses a basic neural network $\boldsymbol{f}(\boldsymbol{x})=\boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$ that contains the featurizer $\boldsymbol{h}$ and classifier $\boldsymbol{g}$. The featurizer generates the feature space and the classifier yields the $c+1$ outputs. Starting from the OSDA goal, we express the target classification risk as

$$\begin{aligned}&\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y\right)d\boldsymbol{x}dy\\&=p^t\left(\text{kn}\right)\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y|\text{kn}\right)d\boldsymbol{x}dy\\&\quad+p^t\left(\text{uk}\right)\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y|\text{uk}\right)d\boldsymbol{x}dy \qquad (1)\\&=\theta\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y|\text{kn}\right)d\boldsymbol{x}dy\\&\quad+(1-\theta)\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y|\text{uk}\right)d\boldsymbol{x}dy. \qquad (2)\end{aligned}$$

Equation (1) uses the law of total probability [23] and decomposes the target joint distribution as $p^t(\boldsymbol{x},y)=p^t(\text{kn})p^t(\boldsymbol{x},y|\text{kn})+p^t(\text{uk})p^t(\boldsymbol{x},y|\text{uk})$, where $p^t(\text{kn})$ is the prior probability for the known classes, $p^t(\text{uk})$ is the prior probability for the unknown class, and $p^t(\text{kn})+p^t(\text{uk})=1$. Equation (2) introduces the mixture parameter $\theta=p^t(\text{kn})$ and writes the target joint distribution as a mixture distribution

$$p^t\left(\boldsymbol{x},y\right)=\theta p^t\left(\boldsymbol{x},y|\text{kn}\right)+(1-\theta)\,p^t\left(\boldsymbol{x},y|\text{uk}\right). \qquad (3)$$

As a result, the target classification risk is expressed as the mixture of two risks: the target known classification risk $\int \ell(\boldsymbol{f}(\boldsymbol{x}),y)p^t(\boldsymbol{x},y|\text{kn})d\boldsymbol{x}dy$ and the target unknown classification risk $\int \ell(\boldsymbol{f}(\boldsymbol{x}),y)p^t(\boldsymbol{x},y|\text{uk})d\boldsymbol{x}dy$.

2) Known Joint Distribution Matching: To address the first OSDA challenge, we exploit featurizer $\boldsymbol{h}$ to match the source joint distribution $p^s(\boldsymbol{x},y)$ to the target known joint distribution $p^t(\boldsymbol{x},y|\text{kn})$ in the feature space (see Fig. 1(a) for the illustration). Accordingly, the target known classification risk can be estimated as

$$\begin{aligned}&\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y|\text{kn}\right)d\boldsymbol{x}dy\\&=\int \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right),y\right)p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right),y|\text{kn}\right)d\boldsymbol{h}\left(\boldsymbol{x}\right)dy \qquad (4)\\&\approx\int \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right),y\right)p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right),y\right)d\boldsymbol{h}\left(\boldsymbol{x}\right)dy \qquad (5)\\&\approx\frac{1}{m_s}\sum_{i=1}^{m_s}\ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right),y_i^s\right). \qquad (6)\end{aligned}$$

Equation (5) approximates (4) via the known joint distribution matching

$$p^s(\boldsymbol{h}\left(\boldsymbol{x}\right),y)\approx p^t(\boldsymbol{h}\left(\boldsymbol{x}\right),y|\text{kn}). \qquad (7)$$

Equation (6) estimates the expectation in (5) via data average and computes the average source classification loss on the labeled source data. Obviously, (6) is a natural optimization objective to train the neural network $\boldsymbol{f}(\boldsymbol{x})=\boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$ for classifying the known classes.

3) Unknown Classification Risk Reformulation: To address the second OSDA challenge, we reformulate and estimate the target unknown classification risk as

$$\begin{aligned}&\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),y\right)p^t\left(\boldsymbol{x},y|\text{uk}\right)d\boldsymbol{x}dy\\&=\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),c+1\right)p^t\left(\boldsymbol{x}|\text{uk}\right)d\boldsymbol{x} \qquad (8)\\&=\frac{1}{1-\theta}\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right),c+1\right)p^t\left(\boldsymbol{x}\right)d\boldsymbol{x}\end{aligned}$$

$$
\begin{aligned}
&- \frac{\theta}{1-\theta} \int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right), c+1\right) p^t\left(\boldsymbol{x}|\mathrm{kn}\right) d\boldsymbol{x} && (9)\\
&\approx \frac{1}{1-\theta} \int \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right), c+1\right) p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right) d\boldsymbol{h}\left(\boldsymbol{x}\right)\\
&\quad - \frac{\theta}{1-\theta} \int \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right), c+1\right) p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right) d\boldsymbol{h}\left(\boldsymbol{x}\right) && (10)\\
&\approx \frac{1}{1-\theta} \frac{1}{m_t} \sum_{i=1}^{m_t} \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^t\right)\right), c+1\right)\\
&\quad - \frac{\theta}{1-\theta} \frac{1}{m_s} \sum_{i=1}^{m_s} \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right), c+1\right). && (11)
\end{aligned}
$$

Equation (8) simplifies the target unknown classification risk by the factorization $p^t(\boldsymbol{x}, y|\mathrm{uk}) = p^t(\boldsymbol{x}|\mathrm{uk}) p^t(y|\boldsymbol{x}, \mathrm{uk})$, where $p^t(y|\boldsymbol{x}, \mathrm{uk})$ equals 1 if y is the unknown class c+1 or 0 if y is one of the c known classes. Equation (9) is a crucial step in the unknown classification risk reformulation. It reformulates the simplified target unknown classification risk over $p^t(\boldsymbol{x}|\mathrm{uk})$ in terms of the target marginal distribution $p^t(\boldsymbol{x})$ and the target known marginal distribution $p^t(\boldsymbol{x}|\mathrm{kn})$ since $p^t(\boldsymbol{x}|\mathrm{uk})$, $p^t(\boldsymbol{x})$, and $p^t(\boldsymbol{x}|\mathrm{kn})$ are related by the equation $p^t(\boldsymbol{x}|\mathrm{uk}) = \frac{1}{1-\theta} p^t(\boldsymbol{x}) - \frac{\theta}{1-\theta} p^t(\boldsymbol{x}|\mathrm{kn})$. This equation is derived from (3), which implies that $p^t(\boldsymbol{x}) = \theta p^t(\boldsymbol{x}|\mathrm{kn}) + (1-\theta) p^t(\boldsymbol{x}|\mathrm{uk})$. Equation (10) approximates (9) via the known marginal distribution matching $p^t(\boldsymbol{h}(\boldsymbol{x})|\mathrm{kn}) \approx p^s(\boldsymbol{h}(\boldsymbol{x}))$, which is a result from (7). To be specific, by marginalizing both sides of (7) over y: $\int p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn}) dy \approx \int p^s(\boldsymbol{h}(\boldsymbol{x}), y) dy$, we have $p^t(\boldsymbol{h}(\boldsymbol{x})|\mathrm{kn}) \approx p^s(\boldsymbol{h}(\boldsymbol{x}))$. Equation (11) estimates the two expectations in (10) via data averages and derives the estimated target unknown classification risk as the difference of two average classification losses computed on the unlabeled target data and unlabeled source data (see Fig. 1(b) for the illustration). Obviously, without requiring the target unknown class labels, we successfully derive the estimated target unknown classification risk in (11). It is a natural optimization objective to train the network $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$ for classifying the unknown.

4) Estimated Target Classification Risk: We combine the results from (6) and (11) to estimate the target classification risk as

$$
\begin{aligned}
&\int \ell\left(\boldsymbol{f}\left(\boldsymbol{x}\right), y\right) p^t\left(\boldsymbol{x}, y\right) d\boldsymbol{x} dy \approx \frac{\theta}{m_s} \sum_{i=1}^{m_s} \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right), y_i^s\right)\\
&\quad + \left(\frac{1}{m_t} \sum_{i=1}^{m_t} \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^t\right)\right), c+1\right)\right.\\
&\qquad \left. - \frac{\theta}{m_s} \sum_{i=1}^{m_s} \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right), c+1\right)\right), \qquad (12)
\end{aligned}
$$

where $\boldsymbol{h}$ is the featurizer that matches joint distributions in the feature space such that $p^s(\boldsymbol{h}(\boldsymbol{x}), y) \approx p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$.

C. LSTDE Technique

1) Triangular Discrimination (TD) Distance: We exploit the TD distance [19] as the joint distribution matching loss. Mathematically, the TD distance between source joint distribution $p^s(\boldsymbol{h}(\boldsymbol{x}), y)$ and target known joint distribution $p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$ is defined as

$$
\begin{aligned}
&\mathrm{TD}\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right), p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)\right)\\
&= \int \frac{\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) - p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)\right)^2}{p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) + p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)} d\boldsymbol{h}\left(\boldsymbol{x}\right) dy. \qquad (13)
\end{aligned}
$$

It is symmetric, lower bounded by 0, and upper bounded by 2. Importantly, when $p^s(\boldsymbol{h}(\boldsymbol{x}), y) = p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$, the TD distance reduces to zero. Therefore, the TD distance is a suitable joint distribution matching loss and minimizing it with respect to the featurizer $\boldsymbol{h}$ matches joint distributions $p^s(\boldsymbol{h}(\boldsymbol{x}), y)$ and $p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$. Besides, the TD distance is related to the KL divergence and JS divergence since they all belong to the f-divergence family, which is a popular class of statistical distance in machine learning [21], [22], [24], [25]. In our research, it is also feasible to use the KL or JS divergence. However, minimizing them with respect to the featurizer usually results in adversarial training [5], [7], [20], [21], which is time-consuming and unstable [22]. By contrast, we find that the TD distance can free us from adversarial training since it can be estimated as an explicit function of the featurizer. See our result in (21). This charming characteristic motivates us to select the TD distance, instead of the KL or JS divergence. We know that the maximum mean discrepancy (MMD) [26] can also avoid adversarial training. However, to our best knowledge, MMD has not yet been well defined to measure the distance between two joint (features and class label) distributions in theory.

2) TD Distance Estimation via Least Squares Classification: Since source joint distribution $p^s(\boldsymbol{h}(\boldsymbol{x}), y)$ and target known joint distribution $p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$ are both unknown, the TD distance between them is also unknown and needs to be estimated from data. In the following, we show that the TD distance estimation can be elegantly cast into least squares classification

$$
\begin{aligned}
&\mathrm{TD}\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right), p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)\right)\\
&= \int \frac{\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) + p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)\right)^2}{p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) + p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)} d\boldsymbol{h}\left(\boldsymbol{x}\right) dy\\
&\quad - \int \frac{4 p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)}{p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) + p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)} d\boldsymbol{h}\left(\boldsymbol{x}\right) dy \qquad (14)\\
&= 2 - \int \frac{4 p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)}{p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) + p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)} d\boldsymbol{h}\left(\boldsymbol{x}\right) dy \qquad (15)\\
&= 2 - \min_r \left(\int \left(r\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) - 1\right)^2 p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) d\boldsymbol{h}\left(\boldsymbol{x}\right) dy\right.\\
&\qquad \left. + \int \left(r\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) + 1\right)^2 p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right) d\boldsymbol{h}\left(\boldsymbol{x}\right) dy\right) \qquad (16)\\
&\approx 2 - \min_\alpha \left(\frac{1}{m_s} \sum_{i=1}^{m_s} \left(r_\alpha\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right), y_i^s\right) - 1\right)^2\right.\\
&\qquad \left. + \frac{1}{m_{tk}} \sum_{i=1}^{m_{tk}} \left(r_\alpha\left(\boldsymbol{h}\left(\boldsymbol{x}_i^{tk}\right), y_i^{tk}\right) + 1\right)^2\right). \qquad (17)
\end{aligned}
$$

Equation (14) rewrites the original definition of TD distance in (13) by using the equation $(a-b)^2 = (a+b)^2 - 4ab$, where $a =$

Algorithm 1 TD Distance Estimation via LSTDE Technique

Input: Labeled datasets $\mathcal{D}^s, \mathcal{D}^{tk}$.
Output: Estimated value $\widehat{\mathrm{TD}}(p^s(\boldsymbol{h}(\boldsymbol{x}), y), p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn}))$.
1: Build matrices $\boldsymbol{A}$, $\boldsymbol{B}$ and vector $\widehat{\boldsymbol{\alpha}}$ by Eqs. (22)–(24).
2: Obtain $\widehat{\mathrm{TD}}(p^s(\boldsymbol{h}(\boldsymbol{x}), y), p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn}))$ via Eq. (21).

$p^s(\boldsymbol{h}(\boldsymbol{x}), y)$ and $b = p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$. Equation (15) is due to the fact that $p^s(\boldsymbol{h}(\boldsymbol{x}), y)$ and $p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$ are probability distributions, and as a result, $\int (p^s(\boldsymbol{h}(\boldsymbol{x}), y) + p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn}))d\boldsymbol{h}(\boldsymbol{x})dy = 2$. Note that (15) also suggests that the TD distance is upper bounded by 2 since the second term is nonnegative. Equation (16) leverages the correspondence between least squares loss and TD distance [27] and expresses the TD distance as a minimization problem with respect to the function $r(\boldsymbol{h}(\boldsymbol{x}), y)$. The minimal value is attained when $r(\boldsymbol{h}(\boldsymbol{x}), y) = (p^s(\boldsymbol{h}(\boldsymbol{x}), y) - p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn}))/(p^s(\boldsymbol{h}(\boldsymbol{x}), y) + p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn}))$. Equation (17) estimates the two expectations in (16) by the averages of the labeled source dataset $\mathcal{D}^s = \{(\boldsymbol{x}_i^s, y_i^s)\}_{i=1}^{m_s}$ from $p^s(\boldsymbol{x}, y)$ and the labeled target known dataset $\mathcal{D}^{tk} = \{(\boldsymbol{x}_i^{tk}, y_i^{tk})\}_{i=1}^{m_{tk}}$ from $p^t(\boldsymbol{x}, y|\mathrm{kn})$. Here, we assume that the labeled target known dataset is available. The process of obtaining this dataset is detailed in the next subsection. Besides, inspired by the RBF network [28], (17) utilizes a kernel-based model

$$r_{\boldsymbol{\alpha}}\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right) = \sum_{i=1}^{m_s} \alpha_i k\left(\boldsymbol{h}\left(\boldsymbol{x}\right), \boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right) \delta\left(y, y_i^s\right) \tag{18}$$

for $r(\boldsymbol{h}(\boldsymbol{x}), y)$, where $\boldsymbol{\alpha} = (\alpha_1, \ldots, \alpha_{m_s})^\top$ are the model parameters to be learned, $k(\boldsymbol{h}(\boldsymbol{x}), \boldsymbol{h}(\boldsymbol{x}_i^s)) = \exp(-\|\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{h}(\boldsymbol{x}_i^s)\|_2^2/\sigma)$ is the RBF kernel with kernel width σ (> 0), and $\delta(y, y_i^s)$ is the delta kernel that evaluates 1 if $y = y_i^s$ and 0 otherwise. In particular, the kernel width σ is set to the median pairwise squared distances on the unlabeled source data in the experiments. Similar to the RBF network [28], on the one hand, the model in (18) is nonlinear in its input $(\boldsymbol{h}(\boldsymbol{x}), y)$, which makes the model flexible and expressive. On the other hand, the model is linear in its parameters $\boldsymbol{\alpha}$, which, together with the least squares loss from (16), makes it possible to learn $\boldsymbol{\alpha}$ in an analytic manner. Clearly, the minimization problem in (17) is a special kernel-based least squares classification problem, where the numbers of positive and negative samples are the same. In this problem, the kernel-based classification model $r_{\boldsymbol{\alpha}}(\boldsymbol{h}(\boldsymbol{x}), y)$ classifies the source sample $(\boldsymbol{h}(\boldsymbol{x}_i^s), y_i^s)$ into positive class $+1$ and the target known sample $(\boldsymbol{h}(\boldsymbol{x}_i^{tk}), y_i^{tk})$ into negative class -1 (see Fig. 1(c) for the illustration). From (17), we learn that the harder the source samples and target known samples can be classified, the larger the average least squares classification loss will become, and the smaller the TD distance between source joint distribution $p^s(\boldsymbol{h}(\boldsymbol{x}), y)$ and target known joint distribution $p^t(\boldsymbol{h}(\boldsymbol{x}), y|\mathrm{kn})$ will be.

3) Estimated TD Distance: We solve the least squares classification problem in (17) and derive the estimated TD distance as

$$\begin{aligned}
&\widehat{\mathrm{TD}}\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right), p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)\right) \\
&= \max_{\boldsymbol{\alpha}} \left(\frac{2}{m_s} \sum_{i=1}^{m_s} r_{\boldsymbol{\alpha}}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right), y_i^s\right) - \frac{2}{m_{tk}} \sum_{i=1}^{m_{tk}} r_{\boldsymbol{\alpha}}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^{tk}\right), y_i^{tk}\right) \right. \\
&\qquad \left. - \frac{1}{m_s} \sum_{i=1}^{m_s} r_{\boldsymbol{\alpha}}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right), y_i^s\right)^2 - \frac{1}{m_{tk}} \sum_{i=1}^{m_{tk}} r_{\boldsymbol{\alpha}}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^{tk}\right), y_i^{tk}\right)^2 \right) \qquad (19) \\
&= \max_{\boldsymbol{\alpha}} \left(2\left[\frac{1}{m_s}\mathbf{1}_{m_s}^\top \boldsymbol{A} - \frac{1}{m_t}\mathbf{1}_{m_{tk}}^\top \boldsymbol{B}\right]\boldsymbol{\alpha} \right. \\
&\qquad \left. - \boldsymbol{\alpha}^\top \left[\frac{1}{m_s}\boldsymbol{A}^\top\boldsymbol{A} + \frac{1}{m_t}\boldsymbol{B}^\top\boldsymbol{B}\right]\boldsymbol{\alpha} \right) \qquad (20) \\
&= 2\left[\frac{1}{m_s}\mathbf{1}_{m_s}^\top \boldsymbol{A} - \frac{1}{m_t}\mathbf{1}_{m_{tk}}^\top \boldsymbol{B}\right]\widehat{\boldsymbol{\alpha}} \\
&\quad - \widehat{\boldsymbol{\alpha}}^\top \left[\frac{1}{m_s}\boldsymbol{A}^\top\boldsymbol{A} + \frac{1}{m_{tk}}\boldsymbol{B}^\top\boldsymbol{B}\right]\widehat{\boldsymbol{\alpha}}. \qquad (21)
\end{aligned}$$

Equation (19) expands the quadratic terms in (17) and rewrites the minimization problem as a maximization problem. Equation (20) introduces new notations to explicitly present the quadratic maximization problem, where $\mathbf{1}_{m_s}$ and $\mathbf{1}_{m_{tk}}$ are two column vectors of ones with m_s and m_{tk} dimensions, and $\boldsymbol{A} \in \mathbb{R}^{m_s \times m_s}$ and $\boldsymbol{B} \in \mathbb{R}^{m_{tk} \times m_s}$ are kernel matrices defined as

$$(\boldsymbol{A})_{ij} = k\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right), \boldsymbol{h}\left(\boldsymbol{x}_j^s\right)\right) \delta\left(y_i^s, y_j^s\right) \tag{22}$$

$$(\boldsymbol{B})_{ij} = k\left(\boldsymbol{h}\left(\boldsymbol{x}_i^{tk}\right), \boldsymbol{h}\left(\boldsymbol{x}_j^s\right)\right) \delta\left(y_i^{tk}, y_j^s\right). \tag{23}$$

Finally, (21) solves the max problem with analytic solution

$$\begin{aligned}
\widehat{\boldsymbol{\alpha}} = &\left(\frac{1}{m_s}\boldsymbol{A}^\top\boldsymbol{A} + \frac{1}{m_t}\boldsymbol{B}^\top\boldsymbol{B} + \epsilon\mathbf{I}\right)^{-1} \\
&\times \left[\frac{1}{m_s}\boldsymbol{A}^\top\mathbf{1}_{m_s} - \frac{1}{m_t}\boldsymbol{B}^\top\mathbf{1}_{m_{tk}}\right].
\end{aligned} \tag{24}$$

Here, a diagonal matrix $\epsilon\mathbf{I}$ is included in the solution to ensure numerical stability, where ϵ is a small positive value set to 0.001 in our experiments and $\mathbf{I}$ is the identity matrix. For clarity, we summarize our TD distance estimation technique in Algorithm 1. In Section IV-C, we demonstrate that Algorithm 1 yields reliable estimation results. With the analytic solution $\widehat{\boldsymbol{\alpha}}$, the estimated TD distance in (21) is expressed as an explicit function of the featurizer $\boldsymbol{h}$ since $\boldsymbol{A}$, $\boldsymbol{B}$, and $\widehat{\boldsymbol{\alpha}}$ are all dependent on $\boldsymbol{h}$. Hence, we can directly optimize the featurizer to minimize the estimated TD distance and match joint distributions in the feature space.

D. Network Training

1) Network Training Objective: To achieve the OSDA goal, we use cross-entropy loss ℓ_{ce} as the classification loss and train the network $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$ to minimize the estimated target classification risk in (12) and the estimated TD distance in (21). The optimization problem is formulated as

$$\begin{aligned}
\min_{\boldsymbol{g},\boldsymbol{h}} \; &\underbrace{\frac{\theta}{m_s}\sum_{i=1}^{m_s} \ell_{\mathrm{ce}}\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right), y_i^s\right)}_{\text{classification loss for known classes}} \\
&+ \underbrace{\left|\frac{1}{m_t}\sum_{i=1}^{m_t} \ell_{\mathrm{ce}}\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^t\right)\right), c+1\right) - \frac{\theta}{m_s}\sum_{i=1}^{m_s} \ell_{\mathrm{ce}}\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right), c+1\right)\right|}_{\text{classification loss for unknown class}} \\
&+ \underbrace{\lambda_{\mathrm{TD}}\widehat{\mathrm{TD}}\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y\right), p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right), y|\mathrm{kn}\right)\right)}_{\text{joint distribution matching loss for known classes}},
\end{aligned} \tag{25}$$

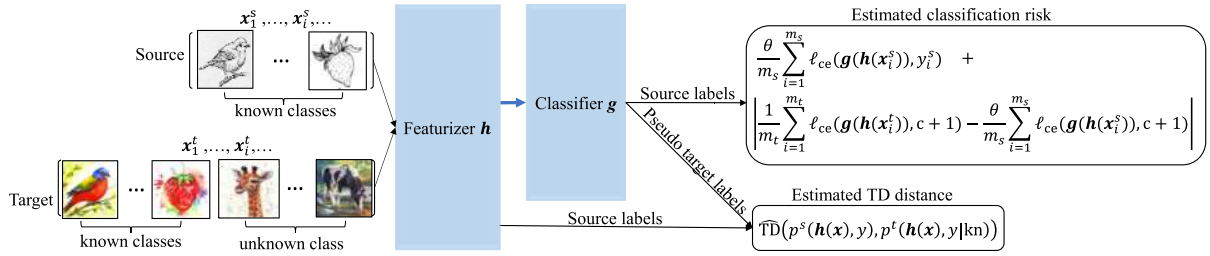


Fig. 2. Illustration of the input data $\boldsymbol{x}$, the neural network architecture $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$, and the losses in our KMUR approach.

Algorithm 2 Neural Network Training via KMUR Approach

Input: Labeled source and unlabeled target datasets $\mathcal{D}^s$, $\mathcal{D}^u$.
Output: Trained neural network $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$.

% Pre-training for generating pseudo labels
while training does not end **do**
  for b in $1 : B$ **do**
    Sample minibatches $\mathcal{D}_b^s$, $\mathcal{D}_b^u$ from datasets $\mathcal{D}^s$, $\mathcal{D}^u$.
    Compute objective function (25) without the estimated TD distance on $\mathcal{D}_b^s$, $\mathcal{D}_b^u$.
    Update network parameters by the objective function.
  end for
end while
Generate pseudo labeled target dataset $\mathcal{D}^t$ by utilizing the network to label $\mathcal{D}^u$.
% Formal training
while training does not end **do**
  for b in $1 : B$ **do**
    Sample minibatches $\mathcal{D}_b^s$, $\mathcal{D}_b^t$ from datasets $\mathcal{D}^s$, $\mathcal{D}^t$.
    Compute objective function (25) on $\mathcal{D}_b^s$, $\mathcal{D}_b^t$, where the estimated TD distance is computed on $\mathcal{D}_b^s$ and $\mathcal{D}_b^{tk}$ via Algorithm 1 and $\mathcal{D}_b^{tk}$ is a subset selected from $\mathcal{D}_b^t$ with the known class labels.
    Update network parameters by the objective function.
  end for
  Update $\mathcal{D}^t$ by utilizing the network to label $\mathcal{D}^u$.
end while

where $\theta \in (0, 1)$ and $\lambda_{\text{TD}} (> 0)$ are the parameters. Theoretically, the classification loss for the unknown class should be nonnegative. However, due to the data average approximation and the flexibility of neural networks, the loss can become negative during training and adversely affect performance. A similar issue was also encountered and addressed in the previous study of Lu et al. [29]. Following [29], we wrap the loss by the absolute value function to ensure its nonnegativity. As shown in (25), our objective function consists of three losses: the classification loss for known classes, the classification loss for unknown class, and the joint distribution matching loss for known classes. In Section IV-C, we show that all the three losses are indispensable. For clarity, we illustrate our approach with objective function (25) in Fig. 2.

2) Network Training Algorithm: Recall from Section II-C that the estimated TD distance depends on the labeled target known dataset $\mathcal{D}^{tk} = \{(\boldsymbol{x}_i^{tk}, y_i^{tk})\}_{i=1}^{m_{tk}}$, which is not available under the OSDA problem setting. To address this issue, we follow the popular pseudo labeling idea [6], [11], [12], [13] to generate the labeled target known dataset from the unlabeled target dataset $\mathcal{D}^u = \{\boldsymbol{x}_i^t\}_{i=1}^{m_t}$. As a form of self-training, pseudo labeling has been theoretically proven to be effective for improving the target classification accuracy even when the domain shift is large [30]. Furthermore, its effectiveness has also been empirically verified by a series of works [6], [11], [12], [13], [31], [32], [33], [34]. In our research, the pseudo labeling idea is practiced via the following two-step procedure. In the first step, we use the Adam optimizer [35] to minimize the objective function (25) without the estimated TD distance term to train the neural network. In the second step, we utilize the trained network to predict pseudo labels for $\mathcal{D}^u$ and generate the pseudo-labeled target dataset $\mathcal{D}^t = \{(\boldsymbol{x}_i^t, y_i^t)\}_{i=1}^{m_t}$. The labeled target known dataset $\mathcal{D}^{tk}$ is a subset selected from $\mathcal{D}^t$ with the known class labels. We call this procedure the pretraining phase for generating the pseudo labels. In Section IV-C, we study the performance of our approach with respect to the initial pseudo labels generated under increasing domain shift and show that our approach still works when the quality of pseudo labels decreases. With the pseudo-labeled target known dataset and the resulting estimated TD distance, the objective function (25) is complete and can be optimized. In the formal training phase, we again use Adam optimizer to minimize the objective function (25) and train the neural network. Since the pseudo labels may not be accurate, during the formal training phase, we utilize the network to update the pseudo labels and improve their accuracy. For clarity, we summarize our network training procedure in Algorithm 2, where B is the number of iterations per training epoch. In Section IV-C, we demonstrate that this algorithm is convergent.

III. Related Work and Discussion

A. Domain Adaptation

Domain adaptation (DA) assumes that the source and target domains share the same class label space and aims to transfer a classification model from the source to the target by matching distributions between domains [8]. This DA problem can be regarded as a simplified OSDA problem without the open set recognition challenge. Mainstream DA works propose to match the marginal distributions $p^s(\boldsymbol{x})$ and $p^t(\boldsymbol{x})$ [20], [21], [22], [36], the class-conditional distributions $p^s(\boldsymbol{x}|y)$ and $p^t(\boldsymbol{x}|y)$ [31], [32], [37], or, more directly, the joint distributions $p^s(\boldsymbol{x}, y)$ and $p^t(\boldsymbol{x}, y)$ [33], [38], [39] between the two domains.

The distributions are matched in the feature space by adversarial training [20], [21] or minimizing statistical distances between distributions [31], [32], [33], [36], [40], [41]. On addressing the common distribution difference challenge in DA and OSDA, our OSDA work is related to the DA works [33], [38], [39] in matching the joint distributions since the joint distribution difference is a fundamental challenge that affects the transfer performance [8], [9], [10]. However, our OSDA work is different from [33], [38], [39] in that our work proposes to match the source joint distribution $p^s(\boldsymbol{x}, y)$ to the target known joint distribution $p^t(\boldsymbol{x}, y|\text{kn})$, rather than the whole target joint distribution $p^t(\boldsymbol{x}, y)$. In fact, for the OSDA problem where the target domain contains the unknown class not presented in the source domain, it can be problematic to match the source joint distribution $p^s(\boldsymbol{x}, y)$ to the whole target joint distribution $p^t(\boldsymbol{x}, y)$ in the feature space such that $p^s(\boldsymbol{h}(\boldsymbol{x}), y) \approx p^t(\boldsymbol{h}(\boldsymbol{x}), y)$. Because by marginalizing both sides of the matching equation over $\boldsymbol{h}(\boldsymbol{x})$, i.e., $\int p^s(\boldsymbol{h}(\boldsymbol{x}), y) d\boldsymbol{h}(\boldsymbol{x}) \approx \int p^t(\boldsymbol{h}(\boldsymbol{x}), y) d\boldsymbol{h}(\boldsymbol{x})$, one will get $p^s(y) \approx p^t(y)$, which results in the paradox $0 = p^s(c+1) \approx p^t(c+1) > 0$ for the unknown class $c+1$. Therefore, our OSDA work matches the source joint distribution to the target known joint distribution to improve the cross-domain transfer performance on known classes.

B. Open Set Recognition

Open set recognition (OSR) considers the problem where new classes unseen in the training phase can appear in the testing phase and aims to train a classification model that accurately recognizes not only the known classes but also the unknown classes [42]. This OSR problem can be regarded as a simplified OSDA problem without the distribution difference challenge. Most OSR works propose to explore the relationship between known and unknown classes by employing specific techniques or concepts, including open space risk [43], nearest neighbor approach [44], extreme value theory [45], [46], and reconstruction approach [47]. On addressing the common OSR challenge in OSR and OSDA, our OSDA work is different from the OSR works. To be specific, our work is founded on the general ERM principle [1] in statistical learning and minimizes the empirical unknown classification risk for classifying the unknown class, while most OSR works implicitly utilize the specific domain knowledge like the feature semantic information for recognizing the unknown.

C. Open Set Domain Adaptation

OSDA integrates the challenges from both DA and OSR. Therefore, most OSDA works propose to match distributions between domains to improve the classification performance on the known classes and design mechanisms to recognize the unknown class [4], [5], [7], [11], [12], [13], [48], [49]. Among these works, we are especially interested in the works of Liu et al. [11] and Jang et al. [7] since they are most related to our research. In the following, we elaborate on the discussion of these two works. Liu et al. [11] exploited a projection matrix $\boldsymbol{\phi}$ to match the source marginal $p^s(\boldsymbol{x})$ to the target known marginal $p^t(\boldsymbol{x}|\text{kn})$ and align the source class-conditional $p^s(\boldsymbol{x}|y)$ to the target known class-conditional $p^t(\boldsymbol{x}|y, \text{kn})$ under the MMD distance in the projection space. Furthermore, they also segregated the target unknown marginal $p^t(\boldsymbol{x}|\text{uk})$ from the source marginal $p^s(\boldsymbol{x})$, and separated the source and target class-conditionals $p^s(\boldsymbol{x}|y)$, and $p^t(\boldsymbol{x}|\tilde{y}, \text{kn})$ conditioned on different known classes, i.e., $y \neq \tilde{y}$. The optimization problem for learning the projection $\boldsymbol{\phi}$ is formulated as

$$\begin{aligned}\min_{\boldsymbol{\phi}} \Bigg(& \alpha \widehat{\text{MMD}}\left(p^s\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)\right), p^t\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)|\text{kn}\right)\right) \\ & + \alpha \sum_{y=1}^{c} \widehat{\text{MMD}}\left(p^s\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)|y\right), p^t\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)|y, \text{kn}\right)\right) \\ & - \lambda_1 \widehat{\text{MMD}}\left(p^s\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)\right), p^t\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)|\text{uk}\right)\right) \\ & - \lambda_2 \sum_{y \neq \tilde{y}}^{c} \widehat{\text{MMD}}\left(p^s\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)|y\right), p^t\left(\boldsymbol{\phi}\left(\boldsymbol{x}\right)|\tilde{y}, \text{kn}\right)\right) \Bigg), \end{aligned} \tag{26}$$

where α, λ_1, and $\lambda_2 (> 0)$ are three tradeoff parameters for balancing the four estimated MMD distances. In the objective function (26), the first and second terms are the losses for distribution matching, and the third and fourth terms are the losses for distribution segregation and separation. It is worth mentioning that since estimating the four MMDs in (26) requires the labels for the target data, the authors therefore utilized the open set nearest neighbor (OSNN) classifier [44] to generate the pseudo target labels of both the known classes and the unknown class. With the pseudo target labels, optimization problem (26) is solved to learn the optimal projection $\widehat{\boldsymbol{\phi}}$. Then, they used square loss as the classification loss and trained the classifier $\boldsymbol{g}$ to minimize the average source classification loss and the average classification loss computed on the pseudo-labeled target unknown data $\{(\boldsymbol{x}_i^{tu}, c+1)\}_{i=1}^{m_{tu}}$. The optimization problem for training the classifier $\boldsymbol{g}$ is formulated as

$$\min_{\boldsymbol{g}} \frac{1}{m_s} \sum_{i=1}^{m_s} \ell\left(\boldsymbol{g}\left(\boldsymbol{z}_i^s\right), y_i^s\right) + \frac{\gamma}{m_{tu}} \sum_{i=1}^{m_{tu}} \ell\left(\boldsymbol{g}\left(\boldsymbol{z}_i^{tu}\right), c+1\right), \tag{27}$$

where $\boldsymbol{z} = \widehat{\boldsymbol{\phi}}(\boldsymbol{x})$ and $\gamma (> 0)$ is a tradeoff parameter for balancing the two loss terms. In the objective function (27), the first term is the loss for the known classes and the second term is the loss for the unknown class. Specifically, computing the second term also requires the pseudo target labels generated by the OSNN classifier. With the pseudo labels, optimization problem (27) is solved to learn the optimal classifier $\widehat{\boldsymbol{g}}$. Finally, the authors updated the pseudo labels by using classifier $\widehat{\boldsymbol{g}}$ and conducted the update procedure until convergence or maximum iteration. Jang et al. [7] exploited the featurizer $\boldsymbol{h}$ to match the source marginal $p^s(\boldsymbol{x})$ to the average marginal $p^a(\boldsymbol{x}) = (p^s(\boldsymbol{x}) + \theta p^t(\boldsymbol{x}|\text{kn}) + (1-\theta) p^t(\boldsymbol{x}|\text{uk}))/2$ and also align the target known marginal $p^t(\boldsymbol{x}|\text{kn})$ to the average marginal $p^a(\boldsymbol{x})$ under the KL divergence in the feature space, where $\theta = p^t(\text{kn})$ is the prior probability for the known classes. Besides, they segregated the target unknown marginal $p^t(\boldsymbol{x}|\text{uk})$ from the average marginal $p^a(\boldsymbol{x})$. Concurrently, the authors used cross entropy as classification loss and trained the classifier $\boldsymbol{g}$ to minimize the average source classification loss and the average classification loss computed on the weighted unlabeled target

data. The optimization problem for training the neural network $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{g}(\boldsymbol{h}(\boldsymbol{x}))$ is formulated as

$$\begin{aligned}\min_{\boldsymbol{g},\boldsymbol{h}} \Bigg(& \frac{1}{m_s}\sum_{i=1}^{m_s} \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^s\right)\right), y_i^s\right) + \frac{1}{m_t}\sum_{i=1}^{m_t} w_i^t \ell\left(\boldsymbol{g}\left(\boldsymbol{h}\left(\boldsymbol{x}_i^t\right)\right), c+1\right) \\ & + \widehat{\mathrm{KL}}\left(p^s\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right), p^a\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right)\right) \\ & + \theta\widehat{\mathrm{KL}}\left(p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right)|\mathrm{kn}\right), p^a\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right)\right) \\ & - (1-\theta)\widehat{\mathrm{KL}}\left(p^t\left(\boldsymbol{h}\left(\boldsymbol{x}\right)|\mathrm{uk}\right), p^a\left(\boldsymbol{h}\left(\boldsymbol{x}\right)\right)\right)\Bigg), \end{aligned} \tag{28}$$

where $w_i^t \in (0, 1)$ is the weight learned via posterior inference. In the objective function (28), the first term is the loss for the known classes, the second term is the loss for the unknown class, the third and fourth terms are the losses for distribution matching, and the last term is the loss for distribution segregation. Similar to the adversarial domain adaptation works [5], [20], here the distribution matching and distribution segregation under the KL divergence are also performed via adversarial training.

Our work is different from the works of Liu et al. [11] and Jang et al. [7] from the following two perspectives.

1) From the perspective of distribution matching regarding the known classes, we match joint distributions $p^s(\boldsymbol{x}, y)$, $p^t(\boldsymbol{x}, y|\mathrm{kn})$ in (25), rather than marginal distributions $p^s(\boldsymbol{x})$, $p^t(\boldsymbol{x}|\mathrm{kn})$ in (26) and (28), or class-conditional distributions $p^s(\boldsymbol{x}|y)$, $p^t(\boldsymbol{x}|y, \mathrm{kn})$ in (26). In particular, we match distributions under the TD distance in (25), rather than the MMD distance in (26), or the KL divergence in (28). In Section IV-C, we demonstrate that our known joint distribution matching under TD distance is superior to the distribution matching and segregation under MMD or KL in [7] or [11]. Again, as aforementioned in Section II-C, we select the TD distance because it is better suited for measuring the distance between two joint distributions and can free us from the unstable adversarial training. Like the MMD distance or KL divergence, the TD distance also needs to be estimated from data for practical application. In our research, we show that the estimation of TD distance can be elegantly cast into the familiar least squares classification problem that has an analytic solution.
2) From the perspective of unknown class recognition, we derive the classification loss regarding the unknown class in a theoretically justified manner, rather than the heuristic manner in [7] and [11]. In particular, thanks to the joint distribution matching and risk reformulation, our unknown loss can be directly computed on the unlabeled target and source data in (25). Unfortunately, the unknown loss in (27) should rely on the additional pseudo labels generated by the OSNN classifier, and the unknown loss in (28) should rely on the additional weights learned by posterior inference. In Section IV-C, we demonstrate that our theoretically justified unknown class recognition is superior to the heuristic unknown class recognition in [7] and [11].

IV. Experiments

A. Experimental Setup

1) Datasets: We conduct experiments on five benchmark image datasets commonly used in OSDA. **OfficeHome** [50] consists of 65 classes and 4 domains: RealWorld (**R**), Product (**P**), Clipart (**C**), and Art (**A**). For this dataset, following [7], [15], [16], [51], the first 25 categories in alphabetic order are selected as the known classes and the remaining 40 classes are treated as the unknown. **ImageCLEF**[1] has 12 classes and 4 domains: Pascal (**P**), ImageNet (**I**), Caltech (**C**), and Bing (**B**). For this dataset, following [16], [51], the first six categories are used as the known classes and the remaining six classes are combined as the unknown. **Office** [52] contains 31 classes and three domains: Amazon (**A**), DSLR (**D**), and Webcam (**W**). For this dataset, following [7], [15], [16], and [51], the first 10 classes are defined as the known classes and the last 11 classes are treated as the unknown. **DomainNet** [53] includes 345 classes and six domains. For this dataset, following [54] and [55], we use three domains: Painting (**P**), Real (**R**), and Sketch (**S**) in the experiments. Then, the first 150 categories in alphabetic order are selected as the known classes and the remaining classes are grouped as the unknown. **VisDA** [56] contains 12 classes and two domains: Real (**R**) and Synthetic (**S**). For this dataset, following [4], [51], and [57], the six classes: bicycle, bus, car, motorcycle, train, and truck are denoted as the known classes, and the remaining classes are denoted as the unknown. Apart from the benchmarks, we also conduct experiments on a real world image dataset. **SkinDisease** contains two domains: PAD-UFES-20[2] (**P**) and ISIC-SkinCancer[3] (**I**). PAD-UFES-20 includes clinical skin lesion images collected via smartphone devices and has six disease classes: actinic keratosis, ..., squamous cell carcinoma. ISIC-SkinCancer is the other skin disease dataset collected via professional equipment and has nine disease classes. These nine classes include the aforementioned six classes, and three additional classes: dermatofibroma, pigmented benign keratosis, and vascular lesion. For this dataset, PAD-UFES-20 is naturally regarded as the source domain, and ISIC-SkinCancer is the target domain, where the three additional classes in the target domain are grouped as unknown.

2) Evaluation Protocol: We select two different domains D1 and D2 from each dataset, and build the OSDA task as "D1→ D2." On each task, we follow [7], [15], and [16] and use three metrics, OS*, UNK, and HOS, to measure a method's performance on the target domain. OS* is the class-wise averaged classification accuracy (%) on known classes, UNK is the classification accuracy on unknown class, and $\mathrm{HOS} = 2(\mathrm{OS}^* \times \mathrm{UNK})/(\mathrm{OS}^* + \mathrm{UNK})$ is the harmonic mean of OS* and UNK. Among these three metrics, HOS is the core metric in mainstream OSDA literature [7], [15], [16] because it requires a method to perform well on both the known and unknown classes in an unbiased manner.

3) Comparison Methods: We compare our KMUR approach against other OSDA methods, including OSBP [4],

[1] https://www.imageclef.org/2014/adaptation
[2] https://data.mendeley.com/datasets/zr7vgbcyr2/1
[3] https://www.kaggle.com/datasets/rajivaiml/isic-skin-cancer-dataset

TABLE I

OS* (%), UNK (%), AND HOS (%) ON BENCHMARK DATASET OFFICEHOME (RESNET50)

Method	A→C			A→P			A→R			C→A			C→P			C→R		
	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**
OSBP [4]	50.20	61.10	55.10	71.80	59.80	65.20	79.30	67.50	72.90	59.40	70.30	64.30	67.00	62.70	64.70	**72.00**	69.20	70.60
STA [5]	46.00	72.30	55.80	68.00	48.40	54.00	78.60	60.40	68.30	51.40	65.00	57.40	61.80	59.10	60.40	67.00	66.70	66.80
ROS [15]	50.60	74.10	60.10	68.40	70.30	69.30	75.80	77.20	76.50	53.60	65.50	58.90	59.80	71.60	65.20	65.30	72.20	68.60
JACS [11]	57.65	75.32	65.31	66.73	74.50	70.40	71.39	69.09	70.22	56.24	69.66	62.23	60.15	70.43	64.89	64.11	74.53	68.93
UADAL [7]	54.90	74.70	63.20	69.10	72.50	70.80	81.30	73.70	77.40	53.50	80.50	64.20	62.10	**78.80**	**69.50**	69.10	78.30	73.40
ANNA [16]	61.40	78.70	69.00	68.30	**79.90**	73.70	74.10	79.70	76.80	58.00	73.10	64.70	64.20	73.60	68.60	66.90	80.20	73.00
PSDC [58]	**65.50**	71.40	68.30	78.60	68.20	73.60	76.20	67.50	71.60	52.80	68.60	59.70	**67.80**	69.00	68.40	69.00	68.60	68.80
WDAN [59]	50.30	66.50	57.30	71.80	59.80	65.20	78.70	75.20	76.90	59.40	70.30	64.30	67.00	62.70	64.70	**72.00**	69.20	70.60
LIWUDA [60]	52.40	69.30	59.70	65.20	65.00	65.00	68.20	66.90	67.50	56.20	**91.90**	**69.80**	65.30	70.00	67.60	61.10	73.10	66.60
RTA [51]	55.50	74.20	63.50	67.20	77.60	77.00	**85.30**	74.50	79.60	59.70	72.50	65.50	59.90	75.80	66.90	70.00	72.80	71.40
KMUR (ours)	59.90	**86.46**	**70.77**	**84.59**	74.45	**79.20**	73.19	**92.45**	**81.70**	**60.43**	79.59	68.70	66.01	70.36	68.12	67.80	**81.30**	**73.94**

Method	P→A			P→C			P→R			R→A			R→C			R→P			Avg		
	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**
OSBP	59.10	68.10	63.20	44.50	66.30	53.20	76.20	71.70	73.90	66.10	67.30	66.70	48.00	63.00	54.50	76.30	68.60	72.30	64.16	66.30	64.72
STA	54.20	72.40	61.90	44.20	67.10	53.20	76.20	64.30	69.50	67.50	66.70	67.10	49.90	61.10	54.50	77.10	55.40	64.50	61.83	63.24	61.12
ROS	57.30	64.30	60.60	46.50	71.20	56.30	70.80	78.40	74.40	67.00	70.80	68.80	51.50	73.00	60.40	72.00	80.00	75.70	61.55	72.38	66.23
JACS	61.55	69.10	65.11	52.22	70.66	60.06	67.25	75.74	71.24	62.88	72.15	67.20	61.80	70.25	65.75	71.00	78.25	74.45	62.75	72.47	67.15
UADAL	50.50	**83.70**	63.00	43.40	81.50	56.60	71.60	83.10	76.90	66.70	78.60	72.10	51.10	74.50	60.60	77.40	76.20	76.80	62.56	78.01	68.71
ANNA	**63.00**	70.30	66.50	54.60	74.80	63.10	74.30	78.90	76.60	66.10	77.30	71.30	59.70	73.10	65.70	76.40	81.00	**78.70**	65.58	76.72	70.64
PSDC	61.80	65.30	63.50	**64.70**	64.10	64.40	77.50	63.20	69.60	60.30	65.00	62.50	**66.60**	69.10	**67.80**	82.20	74.20	78.00	**68.60**	68.00	68.00
WDAN	62.20	64.60	63.40	44.70	63.90	52.60	78.80	71.50	75.00	66.30	78.50	71.90	48.40	66.60	56.10	74.40	79.10	76.70	64.50	68.99	66.23
LIWUDA	57.70	71.80	63.90	52.80	70.90	60.50	64.60	76.80	70.20	64.50	70.90	67.50	61.50	72.20	66.40	70.60	71.40	71.00	61.70	72.60	66.30
RTA	58.60	80.90	68.00	51.60	78.60	62.30	**82.10**	77.20	79.50	**72.50**	77.80	75.00	55.00	70.70	61.70	**84.40**	72.40	77.90	66.70	75.60	70.90
KMUR	60.12	81.61	**69.23**	53.11	**83.49**	**64.92**	78.35	**85.74**	**81.88**	70.98	**81.98**	**76.09**	50.32	**87.17**	63.81	70.61	**85.53**	77.35	66.28	**82.51**	**72.98**

TABLE II

OS* (%), UNK (%), AND HOS (%) ON BENCHMARK DATASET IMAGECLEF (RESNET50)

Method	B→C			B→I			B→P			C→B			C→I			C→P		
	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**
OSBP [4]	87.00	81.00	83.90	85.30	65.70	74.30	66.30	66.70	66.50	**62.00**	58.00	59.90	89.00	80.00	84.30	**87.70**	53.70	66.70
STA [5]	93.30	51.70	66.50	86.00	60.70	71.20	77.70	48.70	59.80	61.30	69.70	65.20	91.70	66.70	77.20	84.00	54.00	65.70
ROS [15]	78.30	90.00	83.80	73.00	76.30	74.60	59.00	67.30	62.90	59.00	68.30	63.30	78.30	83.00	80.60	68.70	78.70	73.30
JACS [11]	96.30	82.30	88.80	**88.30**	84.70	86.50	75.00	**75.30**	75.10	54.00	**95.30**	**68.90**	90.00	**97.00**	93.40	65.70	**89.30**	75.70
UADAL [7]	85.34	92.44	88.75	76.40	83.39	79.74	67.10	73.80	70.29	55.20	77.00	64.30	78.00	88.60	82.96	72.40	75.00	73.68
ANNA [16]	95.30	**98.30**	96.80	81.30	84.70	83.00	74.00	75.00	74.50	58.00	83.00	68.30	87.00	93.00	89.90	78.70	84.00	81.20
RTA [51]	95.00	96.30	95.70	79.00	92.70	85.30	73.30	72.00	72.60	57.30	85.70	68.70	86.00	94.00	89.80	75.30	88.30	81.30
KMUR (ours)	**97.66**	97.00	**97.33**	83.66	**95.00**	**88.97**	**84.66**	72.00	**77.82**	**62.00**	67.33	64.55	**92.66**	**97.00**	**94.78**	78.33	87.66	**82.73**

Method	I→B			I→C			I→P			P→B			P→C			P→I			Avg		
	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**
OSBP	55.70	60.70	58.10	80.70	92.70	86.30	66.30	74.30	70.10	52.30	61.00	56.30	94.00	68.00	78.90	66.00	80.70	72.60	74.40	70.20	71.50
STA	**62.30**	54.00	57.90	94.00	53.70	68.40	80.70	59.00	68.20	61.30	43.70	51.00	93.70	47.70	63.20	90.00	51.00	65.10	**81.30**	55.10	65.00
ROS	58.00	59.70	58.80	88.70	92.70	90.60	78.00	76.00	77.00	47.30	59.30	52.70	71.30	90.30	79.70	79.70	81.30	80.50	69.90	76.90	73.10
JACS	56.30	75.30	64.40	96.70	96.70	96.70	82.70	78.30	80.40	53.00	82.70	64.60	95.30	74.30	83.50	**92.00**	**92.00**	**92.00**	78.80	85.20	80.80
UADAL	55.02	69.30	61.34	87.73	95.00	91.22	74.40	85.70	79.65	51.50	64.87	57.42	86.53	78.88	82.53	84.66	80.12	82.33	72.86	80.34	76.18
ANNA	56.00	78.00	65.20	94.30	**97.70**	96.00	80.70	82.70	81.70	**54.00**	73.70	62.30	94.00	**93.70**	93.80	85.00	83.30	84.20	78.20	85.60	81.40
RTA	58.00	79.30	67.00	95.40	98.00	96.70	79.00	**86.00**	82.40	52.00	78.30	62.50	95.30	89.70	92.40	86.70	84.70	85.70	77.70	87.10	82.10
KMUR	52.66	**94.33**	**67.59**	**97.00**	97.00	**97.00**	**85.00**	81.33	**83.12**	49.33	**94.00**	**64.70**	**95.33**	93.00	**94.15**	90.66	85.33	87.91	80.75	**88.42**	**83.39**

STA [5], ROS [15], JACS [11], UADAL [7], ANNA [16], PSDC [58], WDAN [59], MTS [57], LIWUDA [60], and RTA [51]. Since our experimental setup aligns with the comparison methods, we directly cite their experimental results reported in the original articles. For the comparison methods that do not provide results on a certain dataset, we conduct experiments by using their released source codes and report their best results.

4) Implementation Details: We run the experiments on the Pytorch platform and implement our neural network as the ResNet50 model for all datasets except VisDA, for which we follow [51] and use VGGNet. In the network, the featurizer is pretrained on ImageNet and the classifier $\boldsymbol{g}$ is trained from scratch. To train the neural network, we use the Adam optimizer [35] and set the learning rate to 10^{-5}. Again, see Algorithm 2 for the training procedure. As defined in objective function (25), our KMUR approach has two parameters: θ and λ_{TD}. For parameter θ associated with the classification loss, we utilize the class prior estimation technique from [61] to estimate it from the source and target data. As a result, θ is, respectively, set to 0.36, 0.47, 0.50, 0.45, 0.52, and 0.68 for OfficeHome, ImageCLEF, Office, DomainNet, VisDA, and SkinDisease. In Section IV-C, we study the sensitivity of our approach to this parameter. For parameter λ_{TD} associated with the joint distribution matching loss, following the common strategy in [20], [31], [33] and [34], we change it from 0 to 1 during the training procedure by using the formula $\lambda_{\text{TD}} = 2/(1+\exp(-10i/I)) - 1$, where $i \in [0, I]$ is the current iteration and I is the total iteration. In [20], [31], [33] and [34], this strategy has proven effective for balancing the distribution matching loss.

B. Experimental Results

1) Results: We report the performance metrics (OS*, UNK, and HOS) of the OSDA methods in Tables I–V for the five benchmark datasets OfficeHome, ..., VisDA, and in Table VI for the real world dataset SkinDisease, where the best results are highlighted in **bold** and the second best are underlined. It is important to emphasize that HOS is the most critical metric, as it requires a method to achieve balanced performance on both the known and unknown classes without bias. In Table I for the benchmark dataset OfficeHome, our KMUR significantly

TABLE III
OS* (%), UNK (%), AND HOS (%) ON BENCHMARK DATASET OFFICE (RESNET50)

Method	A→D			A→W			D→A			D→W			W→A			W→D			Avg		
	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**
OSBP [4]	90.50	75.50	82.40	86.80	79.20	82.70	76.10	72.30	75.10	97.70	96.70	97.20	73.00	74.40	73.70	99.10	84.20	91.10	87.20	80.40	83.70
STA [5]	91.00	63.90	75.00	86.70	67.60	75.90	83.10	65.90	73.20	94.10	55.50	69.80	66.20	68.00	66.10	84.90	67.80	75.20	84.30	64.80	72.60
ROS [15]	87.50	77.80	82.40	88.40	76.70	82.10	74.80	81.20	77.90	99.30	93.00	96.00	69.70	86.60	77.20	**100.00**	**99.40**	**99.70**	86.60	85.80	85.90
JACS [11]	90.20	88.60	89.40	88.10	90.30	89.20	88.20	**96.90**	**92.30**	97.20	99.60	98.40	90.60	**95.00**	**92.70**	**100.00**	92.60	96.20	92.40	93.80	93.00
UADAL [7]	85.60	90.40	87.90	85.50	**95.10**	90.10	74.20	87.80	80.50	98.70	97.70	98.20	65.60	87.80	75.10	99.30	**99.40**	99.40	84.82	93.03	88.53
ANNA [16]	93.20	76.10	83.80	82.80	88.40	85.50	75.40	91.10	82.50	99.40	99.60	99.50	76.00	87.90	81.60	**100.00**	96.80	98.40	87.80	89.98	88.55
PSDC [58]	94.60	81.70	87.70	97.80	85.90	91.50	**94.20**	88.80	91.40	**100.00**	99.90	**99.90**	**94.90**	86.00	90.20	99.00	98.90	99.00	**96.80**	90.20	93.30
LIWUDA [60]	99.20	83.10	90.40	89.80	86.70	88.20	70.30	85.20	77.00	94.40	91.60	93.00	84.10	71.60	77.30	94.90	86.20	90.30	88.80	84.10	86.10
RTA [51]	94.70	91.20	92.90	92.20	93.80	93.00	87.90	94.10	90.90	98.00	**100.00**	99.00	89.00	92.50	90.70	98.50	99.10	98.80	93.40	**95.10**	**94.20**
KMUR (ours)	**100.00**	**91.48**	**95.55**	**99.52**	90.26	**94.66**	87.40	90.31	88.83	**100.00**	94.38	97.11	85.00	93.77	89.17	99.33	93.08	96.11	95.21	92.21	93.57

TABLE IV
OS* (%), UNK (%), AND HOS (%) ON BENCHMARK DATASET DOMAINNET (RESNET50)

Method	P→R			P→S			R→P			R→S			S→P			S→R			Avg		
	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**	OS*	UNK	**HOS**
OSBP [4]	55.07	65.80	59.96	29.47	63.44	40.24	40.41	67.44	50.54	29.60	68.25	41.29	32.71	64.56	43.42	49.67	66.01	56.69	39.49	65.92	48.69
STA [5]	35.33	69.96	46.95	21.16	69.72	32.47	35.62	63.14	45.54	28.39	61.56	38.86	23.08	55.24	32.55	33.39	77.70	46.71	29.49	66.22	40.51
UADAL [7]	32.40	83.20	46.64	28.60	69.70	40.56	36.00	85.50	50.67	24.30	**94.90**	38.69	28.40	55.40	37.55	50.44	88.50	64.26	33.36	79.53	46.39
ANNA [16]	55.17	85.75	67.14	34.98	72.56	47.21	38.91	73.69	50.93	37.11	68.79	48.21	**40.02**	60.96	48.32	50.76	88.63	64.55	42.82	75.06	54.39
RTA [51]	51.30	88.80	65.03	30.80	**90.90**	46.01	34.00	85.40	48.64	**37.70**	93.40	**53.72**	33.20	84.50	47.67	48.10	**92.40**	63.27	39.18	89.23	54.06
KMUR (ours)	**57.90**	**90.75**	**70.70**	**36.75**	88.85	**51.99**	**41.26**	**90.50**	**56.68**	35.66	85.43	50.32	38.76	**89.90**	**54.17**	**56.80**	91.01	**69.95**	**44.52**	**89.41**	**58.97**

TABLE V
OS* (%), UNK (%), AND HOS (%) ON BENCHMARK DATASET VISDA WITH OSDA TASK $S \rightarrow R$ (VGGNET)

Method	Bicycle	Bus	Car	Motorcycle	Train	Truck	OS*	UNK	**HOS**
OSBP [4]	51.10	67.10	42.80	84.20	81.80	28.00	59.20	85.10	69.80
STA [5]	52.40	69.60	59.90	87.80	86.50	27.20	63.90	84.10	72.60
PSDC [58]	75.50	84.40	60.50	88.20	73.20	28.60	68.40	85.40	76.00
MTS [57]	55.60	68.40	65.50	88.20	85.30	31.50	65.60	**88.00**	75.17
RTA [51]	67.20	77.90	89.60	86.60	84.90	35.80	73.60	83.70	78.30
KMUR (ours)	72.80	86.30	79.50	90.20	81.40	33.60	**74.00**	86.40	**79.72**

TABLE VI
OS* (%), UNK (%), AND HOS (%) ON REAL WORLD DATASET SKINDISEASE WITH NATURAL OSDA TASK $P \rightarrow I$

Metric	OSBP [4]	STA [5]	ROS [15]	JACS [11]	UADAL [7]	ANNA [16]	KMUR (ours)
OS*	29.56	22.28	17.97	28.11	24.10	**42.27**	40.87
UNK	22.54	33.55	46.58	22.92	36.10	26.43	**50.32**
HOS	25.58	26.78	25.93	25.25	28.90	32.52	**45.11**

TABLE VII
AVERAGE RANKS OF THE METHODS

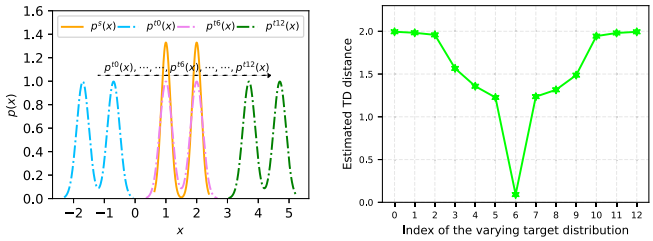
Method	OSBP [4]	STA [5]	UADAL [7]	ANNA [16]	RTA [51]	KMUR (ours)
Avg rank	4.89	5.78	3.81	2.61	2.42	1.50

TABLE VIII
HOLM'S STEP-DOWN TEST RESULTS

i	Method	z value	p value	$\alpha/(k-i)$	Reject
1	STA [5]	9.7011	0.0000	0.0100	✓
2	OSBP [4]	7.6853	0.0000	0.0125	✓
3	UADAL [7]	5.2285	0.0000	0.0167	✓
4	ANNA [16]	2.5198	0.0117	0.0250	✓
5	RTA [51]	2.0788	0.0376	0.0500	✓

outperforms the comparison methods on the majority of the 12 tasks, achieving the highest average UNK of 82.51% and the highest average HOS of 72.98%. For the comparison with JACS and UADAL, which perform marginal distribution matching and segregation under MMD or KL and design heuristic mechanisms for unknown recognition, the outperformance proves that our joint distribution matching under TD distance and risk reformulation for unknown recognition indeed better solve the OSDA problem. For the comparison with ROS and ANNA, which perform self-supervised learning and causal alignment, the outperformance again testifies that our KMUR is more advantageous than the other strategies in improving the OSDA performance. In Table II for the benchmark dataset ImageCLEF, our KMUR again outperforms the comparison methods, achieving the best average UNK of 88.42% and the best average HOS of 83.39%. In Table III for the benchmark dataset Office, our KMUR is among the top performing methods and obtains the second best average HOS of 93.57%, next to the latest method RTA. Since RTA is featured by its exploitation of the interclass relations as a prior to separate the unknown, we conjecture that incorporating such strategy into our approach may improve its performance in this specific Office dataset. In Tables IV and V for the benchmark datasets DomainNet and VisDA, our KMUR outperforms its counterparts and achieves the best average HOS of 58.97% and 79.72%, proving its suitability for complex and large-scale datasets with large domain shifts. Finally, in Table VI for the real world dataset SkinDisease, our KMUR is also more effective than its competitors in recognizing the known and unknown skin diseases and achieves the highest HOS of 45.11% on the natural OSDA task. To further reinforce the advantage of our approach, in Section IV-C, we demonstrate that compared with other methods, our KMUR better matches the cross-domain distributions regarding the known classes and is more robust against the varying number of known classes.

2) Statistical Tests: We validate the superiority of our approach in a statistical sense by conducting the Friedman test followed by Holm's step-down procedure [62]. The Friedman test uses statistic $F_F = ((N-1)\chi_F^2)/(N(k-1)-\chi_F^2)$, where N denotes the number of OSDA tasks and k is the number of methods. χ_F^2 is a statistic defined as $\chi_F^2 = 12N/(k(k+1))\left(\sum_{i=1}^{k} R_i^2 - (k(k+1)^2)/4\right)$, where R_i is the average rank of



(a) (b)

Fig. 3. TD distance estimated by our LSTDE technique. (a) Fixed source distribution $p^s(x)$ and varying target distributions $p^{t0}(x), \ldots, p^{t6}(x), \ldots, p^{t12}(x)$. (b) Estimated TD distance between source and target distributions.

TABLE IX

ABLATION STUDY FOR OUR KMUR APPROACH ON THE IMAGECLEF TASKS. $\mathcal{L}_{\text{known}}$ AND $\mathcal{L}_{\text{unknown}}$ ARE THE CLASSIFICATION LOSSES FOR KNOWN AND UNKNOWN CLASSES. $\mathcal{L}_{\text{TD}}$ IS THE JOINT DISTRIBUTION MATCHING LOSS FOR KNOWN CLASSES

$\mathcal{L}_{\text{known}}$	$\mathcal{L}_{\text{unknown}}$	$\mathcal{L}_{\text{TD}}$	B→C			C→I		
			OS*	UNK	**HOS**	OS*	UNK	**HOS**
✓	✓	✓	97.66	97.00	**97.33**	92.66	97.00	**94.78**
×	✓	✓	0.00 ↓	100.00	0.00 ↓	0.00 ↓	100.00	0.00 ↓
✓	×	✓	98.00	44.33 ↓	61.05 ↓	95.67	45.00 ↓	61.21 ↓
✓	✓	×	85.67 ↓	78.67 ↓	82.02 ↓	82.33 ↓	77.00 ↓	79.58 ↓

the ith method. Based on the HOS results from Tables I to IV, we compute the average ranks of the methods and report them in Table VII. Since our calculated $F_F = 106.60$ exceeds the critical value $F(k-1,(k-1)(N-1)) = 2.27$ at a significant level of $\alpha = 0.05$, we conclude that the methods have significantly different performance on the datasets. The subsequent Holm's step-down procedure uses test statistic $z = (R_i - R_j)/((k(k+1))/6N)^{1/2}$ to compute the p-values. We report the test results in Table VIII. The results suggest that all the null hypotheses can be rejected since the corresponding p values are below $\alpha/(k-i)$. This implies that our KMUR approach significantly outperforms the comparison methods.

C. Experimental Analysis

1) TD Distance Estimation: We verify the reliability of our LSTDE technique for estimating the TD distance. To this end, we prepare in Fig. 3(a) the fixed source distribution $p^s(x)$ and the varying target distributions $p^{t0}(x), \ldots, p^{t6}(x), \ldots, p^{t12}(x)$, and plot in Fig. 3(b) the estimated TD distance between the source distribution and each target distribution. From Fig. 3(a), we know that as the target distribution varies from left to right, the distance between the source and target distributions should first decrease, then reach a minimal value, and finally increase. From Fig. 3(b), we observe that the TD distance estimated by our LSTDE technique exactly reflects such trend. The estimated TD distance first decreases from the maximal value of 2, then reaches the minimal value close to 0, and finally increases again to the maximal value. Interestingly, the maximal and minimal values also coincide with the fact that the TD distance is upper bounded by 2 and lower bounded by 0. These results effectively confirm that our LSTDE can yield a reliable estimated value for the TD distance.

2) Ablation Study: We conduct an ablation study on the ImageCLEF tasks to evaluate the contribution of each loss in our objective function (25). As shown in Table IX, removing loss $\mathcal{L}_{\text{known}}$ (classification loss for known classes) disables our approach's ability to learn the functional relationship between input features and known class labels and severely degrades its OS* performance (from 97.66% to 0.00% for B→C and from 92.66% to 0.00% for C→I). Removing loss $\mathcal{L}_{\text{unknown}}$ (classification loss for unknown class) weakens our approach's ability to classify the unknown class and deteriorates its UNK performance to a large extent (from 97.00% to 44.33% for B→C and from 97.00% to 45.00% for C→I). Finally, removing loss $\mathcal{L}_{\text{TD}}$ (joint distribution matching loss for known classes) disables our approach's ability to match the source to the target known and degrades its OS* (from 97.66% to 85.67% for B→C and from 92.66% to 82.33% for C→I) and UNK (from 97.00% to 78.67% for B→C and from 97.00% to 77.00% for C→I). These findings suggest that all the three losses $\mathcal{L}_{\text{known}}$, $\mathcal{L}_{\text{unknown}}$, and $\mathcal{L}_{\text{TD}}$ are indispensable for the superior performance of our approach.

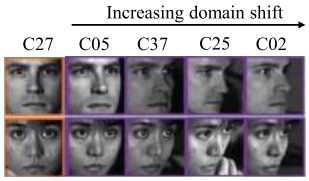


Fig. 4. Sample images from the PIE-Multiview dataset, where C27 is used as the source domain and C05, C37, C25, and C02 are used as the target domains to simulate the increasing domain shift.

TABLE X

OS* (%), UNK (%), AND HOS (%) ON FACE RECOGNITION DATASET PIE-MULTIVIEW (1HLNN)

Method	C27→C05			C27→C37			C27→C25			C27→C02		
	OS*	UNK	**HOS**	OS*	UNK	HOS	OS*	UNK	**HOS**	OS*	UNK	**HOS**
KMUR-Pretrain	66.03	63.83	64.91	51.26	46.51	48.77	28.88	46.07	35.51	27.77	43.75	33.98
KMUR	**78.41**	**71.94**	**75.03**	**67.77**	**50.90**	**58.14**	**32.38**	**50.96**	**39.60**	**33.65**	**47.87**	**39.52**

3) Pseudo Labels Under Increasing Domain Shift: We study the performance of our approach relative to the initial pseudo labels generated under increasing domain shift. To this end, we conduct experiments on the face recognition dataset PIE-Multiview [63] in Fig. 4, and choose looking forward (C27) as the source domain and looking toward left in an increasing angle (C05, C37, C25, C02) as the target domains to simulate the increasing domain shift. To measure the shift, we calculate the TD distance between the fixed source C27 and each target and obtain $\widehat{\text{TD}}(\text{C27},\text{C05}) = 0.47 < \widehat{\text{TD}}(\text{C27},\text{C37}) = 0.95 < \widehat{\text{TD}}(\text{C27},\text{C25}) = 1.10 < \widehat{\text{TD}}(\text{C27},\text{C02}) = 1.20$. These values confirm a controlled, monotonic increase in domain shift. We treat the first 30 classes as known and the remaining 37 classes as unknown and use a one-hidden-layer neural network (1HLNN) as the model. Results for both the pretraining (KMUR-Pretrain) and formal training (KMUR) phases are presented in Table X. We observe that as the domain shift increases: $\widehat{\text{TD}}(\text{C27},\text{C05}) < \cdots < \widehat{\text{TD}}(\text{C27},\text{C02})$, the HOS of KMUR-Pretrain keeps declining from 64.91% to 33.98%, indicating that the initial pseudo labels become increasingly noisy with larger shifts. Nevertheless, the formal training phase (KMUR) still improves

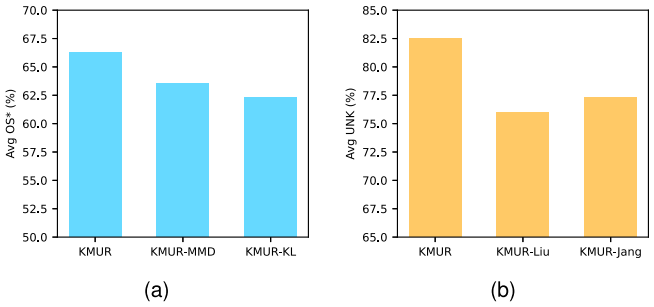


Fig. 5. Comparison of known distribution matching and comparison of unknown class recognition on OfficeHome. (a) Comparison of our known joint distribution matching under TD against the distribution matching and segregation under MMD and KL in [11] and [7]. (b) Comparison of our unknown classification risk reformulation against the strategies in [11] and [7] for recognizing the unknown class.

the HOS across all four tasks despite the degraded initial pseudo labels. This suggests that our approach does not excessively rely on the quality of initial pseudo labels, and that the optimization process in the formal training phase remains stable and robust even when starting from low-quality labels. We attribute the stability and robustness to the iterative refinement of pseudo labels and model parameters, which mitigates the effect of initial inaccuracies. However, we note that in some extreme cases of large shifts where transfer learning is rather difficult or even infeasible, our approach may not succeed since the initial pseudo labels may be too noisy to refine.

4) Known Joint Distribution Matching: We compare our known joint distribution matching under TD distance against the distribution matching and segregation under MMD distance [11] and KL divergence [7] by analyzing their impact on classifying the known classes. For this purpose, we replace our original TD-based known joint distribution matching by the MMD-based and the KL-based distribution matching and segregation, and derive two variants of our approach: KMUR-MMD and KMUR-KL. Fig. 5(a) plots the average OS* of KMUR and its two variants on OfficeHome. We observe that the average OS* of KMUR is higher than KMUR-MMD and KMUR-KL. This indicates that our known joint distribution matching under TD distance is better than the distribution matching and segregation under MMD or KL in [11] or [7].

5) Unknown Classification Risk Reformulation: We contrast our unknown classification risk reformulation against the strategies in Liu et al. [11] and Jang et al. [7] for recognizing the unknown class. For this purpose, we replace our original unknown classification loss by the unknown classification losses in [11] and [7] and derive two variants of our approach: KMUR-Liu and KMUR-Jang. Fig. 5(b) plots the average UNK of KMUR and its variants on OfficeHome. We find that KMUR clearly outperforms its variants. This suggests our unknown classification risk reformulation is more advantageous than the strategies in [11] and [7] for classifying the unknown.

6) Feature Visualization: We demonstrate that our approach can well match the cross-domain distributions regarding the known classes. Fig. 6(a)–(d) plots the t-SNE [64] visualization results of source data (blue), target known data (red), and

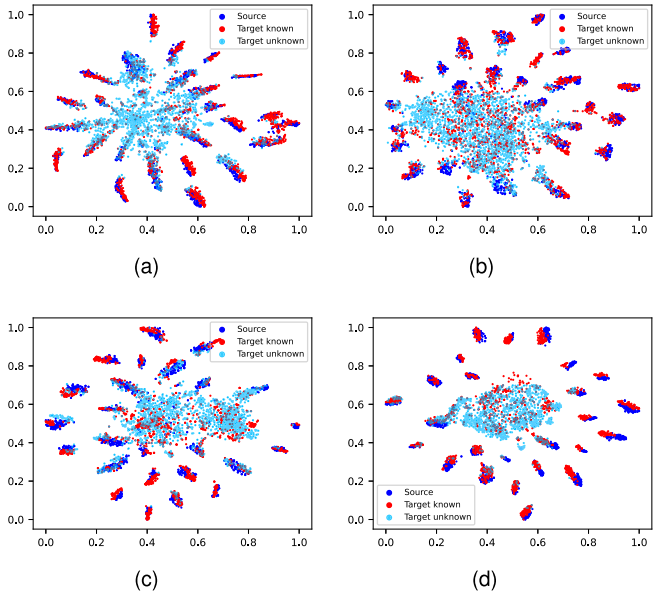


Fig. 6. Visualization of source data (blue), target known data (red), and target unknown data (skyblue) in the network's feature spaces of (a) OSBP, (b) UADAL, (c) ANNA, and (d) KMUR on the task "P→R" (OfficeHome).

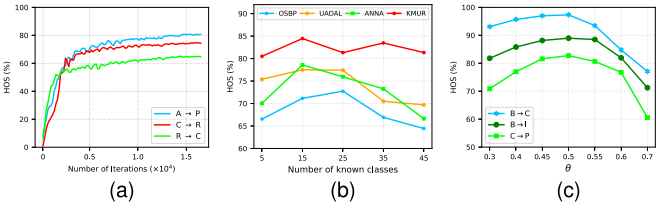


Fig. 7. Convergence, robustness, and sensitivity analysis of our approach. (a) Convergence on the tasks from OfficeHome. (b) Robustness on the task "A→R" (OfficeHome). (c) Sensitivity on the tasks from ImageCLEF.

target unknown data (skyblue) in the network's feature spaces of OSBP, UADAL, ANNA, and KMUR on the task "P→R" (Office-Home). By comparing with the visualization results of other methods, we find that our KMUR approach aligns the source data to the target known data in a better way and also leaves the target unknown data alone in the center. This proves that in the network's feature space, our approach can well match the cross-domain distributions of the known classes.

7) Convergence Analysis: We study the convergence behavior of our approach. Fig. 7(a) plots the convergence of the HOS of our approach on the OfficeHome tasks. We find that as the iteration proceeds, the HOS first rapidly increases, then gradually slows down, and finally reaches a plateau after 1.5×10^4 iterations. This implies that our Algorithm 2 for training the neural network is convergent.

8) Robustness Analysis: We analyze the robustness of our approach to different settings of the number of known classes. Fig. 7(b) plots the HOS of our approach and the comparison methods on the task "A→R" (OfficeHome) by varying the number of known classes. From Fig. 7(b), we observe that our approach consistently outperforms the comparison methods over all the cases. This suggests that our approach is robust to the change in the number of known classes.

9) Parameter Sensitivity: We analyze the sensitivity of our approach to parameter θ, which is the prior probability of known classes in the target domain, i.e., $\theta = p^t(\text{kn})$. This parameter is associated with the classification loss in our objective function. Fig. 7(c) illustrates the HOS performance of our approach under different values of θ on ImageCLEF tasks. Note that under our experimental setup, the true prior probability of known classes for this dataset is 0.5. As illustrated in Fig. 7(c), our approach achieves the highest HOS when θ is set to 0.5. Performance begins to decline when $\theta < 0.45$ or $\theta > 0.55$, highlighting the importance of setting an appropriate value for θ. As described in the experimental setup, we use the class prior estimation technique from [61] to estimate θ from the source and target data. The estimated value obtained is 0.47, which is close to the true value of 0.5. Therefore, our approach achieves superior HOS results in the main experiments.

V. Conclusion

In this article, we propose the KMUR approach to address the fundamental challenges in OSDA. Our approach matches the source joint distribution to the target known joint distribution under the TD distance to reduce the distribution difference, and reformulates the unknown classification risk to derive the classification loss for the unknown class. In addition, we also propose the LSTDE technique to estimate the TD distance from data and express the estimated distance as an objective function of the featurizer. The experiments on benchmark and real world datasets demonstrate the superiority of our approach over its competitors, and the experimental analysis on benchmark and synthetic datasets testifies the effectiveness of our proposed KMUR and LSTDE. In the future, we plan to explore the related multisource OSDA and universal DA problems. We also plan to apply the LSTDE technique to solving other machine learning problems, including clustering and representation learning.

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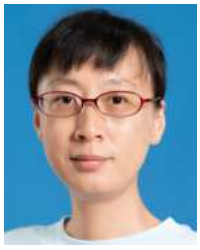

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