DEEP INVERSE REINFORCEMENT LEARNING VIA ADVERSARIAL ONE-CLASS CLASSIFICATION

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ABSTRACT

Traditional inverse reinforcement learning (IRL) methods require a loop to find the optimal policy for each reward update (called an inner loop), resulting in very time-consuming reward estimation. In contrast, classification-based IRL methods, which have been studied recently, do not require an inner loop and estimate rewards quickly, although it is difficult to prepare an appropriate baseline corresponding to the expert trajectory. In this study, we introduced adversarial one-class classification into the classification-based IRL framework, and we propose a novel IRL method that requires only expert trajectories. We experimentally verified that the proposed method can achieve the same performance as existing methods.

1 INTRODUCTION

Inverse reinforcement learning (IRL) (Russell, 1998) refers to the problem of estimating rewards for reinforcement learning (RL) agents to acquire policies that can reproduce expert behavior. An RL algorithm learns a policy that maximizes the cumulative discounted reward under a given reward function. An IRL algorithm does the opposite; it estimates the reward from the given policies or trajectories to satisfy the condition under the assumption that the expert is maximizing the reward.

IRL has been used in two main applications (Ramachandran & Amir, 2007). The first is apprenticeship learning, which enables the learning of complex policies for which it is difficult to design a reward function. Compared to behavioral cloning, IRL is robust to the covariate shift problem (Ross et al., 2011) and achieves superior performance even when the amount of data is small. The second is reward learning, where IRL is used to estimate rewards from trajectory data of human and animal action sequences and to analyze the intention of the subject. In previous studies, IRL methods have been used to analyze human walking paths (Kitani et al., 2012) and the behavior of nematodes (Yamaguchi et al., 2018).

In traditional IRL methods, the IRL loop has an inner loop that computes the optimal policy for the reward being estimated until convergence. This inner loop presents a difficulty in applying IRL to tasks with a large state-action space because it requires a large amount of computation. As a solution to this, classification-based IRL methods transform the IRL problem into a problem of classifying the expert's trajectory and the trajectory to be compared. Notable methods include AIRL (Fu et al., 2017), LogReg-IRL (Uchibe, 2018), and T-REX (Brown et al., 2019).

These methods differ in the ways they are formulated, but they result in similar learning methods. Online methods, such as AIRL, collect trajectories to be compared from the environment. On the contrary, offline methods, such as LogReg-IRL and T-REX, which collect trajectories to be compared in advance, can further speed up and stabilize learning by not requiring access to the environment during training. However, the learning performance of current offline methods depends heavily on the properties of the trajectories to be compared or the ranking of the trajectories, which are difficult to collect.

In this study, we took advantage of the fact that the learning process of LogReg-IRL by binary classification is equivalent to the learning of a discriminator in adversarial learning, such as with a generative adversarial network (GAN) (Goodfellow et al., 2014). Then, we propose an innovative deep IRL method called **SOLO-IRL**, which replaces binary classification with adversarial one-class classification. Figure 1 shows a comparison between the traditional and proposed IRL methods. The proposed method does not require an inner loop and is an offline method, so it can be trained

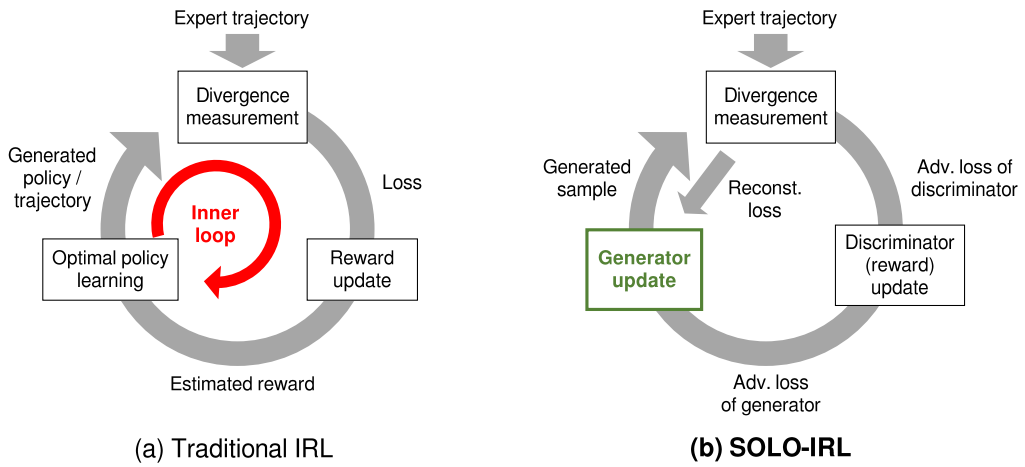

Figure 1: Comparison of traditional IRL and SOLO-IRL.

extremely fast. In addition, the proposed method does not require any trajectories to be compared. With these advantages, the proposed method greatly advances the application of IRL methods to real-world problems.

2 Preliminaries

2.1 Markov decision process (MDP)

RL is a learning method based on the Markov decision process (MDP). The MDP consists of a tuple $M = \langle S, A, P, R, \gamma \rangle$, where S is the state space, A is the action space, P is the state-transition probability, R is the reward function, and γ is the discount factor indicating the degree of importance for future rewards. In the MDP, the state-value function for state s_t at time t is represented by the Bellman equation as follows:

$$V(s_t) = \max_a \left\{ R(s_t, a) + \sum_{s'} p(s'|s_t, a)\gamma V(s') \right\} \tag{1}$$

where $R(s_t, a_t)$ is the reward for taking action a_t in state s_t, and $p(s_{t+1}|s_t, a_t)$ is the probability of transitioning to the next state s_{t+1} when taking action a_t in state s_t.

2.2 Linearly-solvable MDP (LMDP)

The linearly-solvable MDP (LMDP) is an extension of the MDP. The agent in the LMDP directly determines the transition probability $u(s_{t+1}|s_t)$ from the current state s_t to the next state s_{t+1} as the control, instead of the action a_t in the MDP. Then, the Bellman equation is linearized under two assumptions. First, the state-transition probability $p(s_{t+1}|s_t, u)$ is assumed to be expressed as the product of the uncontrolled transition probability $\bar{p}(s_{t+1}|s_t)$ and u as follows:

$$p\left(s_{t+1}|s_t, u(s_{t+1}|s_t)\right) = \bar{p}(s_{t+1}|s_t) \exp\left\{u(s_{t+1}|s_t)\right\} \tag{2}$$

The uncontrolled transition probability $\bar{p}(s_{t+1}|s_t)$ indicates a transitional relationship between the states in the environment. When a transition is impossible, i.e., $\bar{p} = 0$, then $p = 0$.

The second assumption is that the reward $R(s_t, u)$ is composed of a state-dependent reward $r(s_t)$ and penalty term $D_{\mathrm{KL}}\left(u||\bar{p}\right)$ for control u over the divergence from the uncontrolled transition probability $\bar{p}$. This assumption can be formulated as follows:

$$R\left(s_t, u(s_{t+1}|s_t)\right) = r(s_t) - D_{\mathrm{KL}}\left(u(s_{t+1}|s_t)||\bar{p}(s_{t+1}|s_t)\right) \tag{3}$$

where $D_{\mathrm{KL}}(P_x||P_y)$ represents the Kullback–Leibler (KL) divergence of P_x and P_y. By rearranging Eq. (3) according to the definition of KL divergence, the following equation is obtained:

$$R\left(s_t, u(s_{t+1}|s_t)\right) = r(s_t) - \sum_{s'} p(s'|s_t, u(s'|s_t))u(s'|s_t) \tag{4}$$

Substituting Eq. (4) into the Bellman equation in Eq. (1) gives the following:

$$V(s_t) = r(s_t) + \max_u \left\{ \sum_{s'} p(s'|s_t, u(s'|s_t)) \Big[-u(s'|s_t) + \gamma V(s') \Big] \right\} \tag{5}$$

Then, substitute Eq. (2) into Eq. (5) and apply the Lagrange multiplier with $\sum_{s'} p(s'|s_t, u) = 1$ as a constraint. Finally, the $\max$ operator is removed, resulting in the linear Bellman equation as follows:

$$\exp\{V(s_t)\} = \exp\{r(s_t)\} \sum_{s'} \bar{p}(s'|s_t) \exp\{\gamma V(s')\} \tag{6}$$

The optimal control u^* in the LMDP is given by

$$u^*(s_{t+1}|s_t) = \frac{\bar{p}(s_{t+1}|s_t) \exp\{\gamma V(s_{t+1})\}}{\sum_{s'} \bar{p}(s'|s_t) \exp\{\gamma V(s')\}} \tag{7}$$

2.3 Logistic Regression-Based IRL (LogReg-IRL)

Logistic regression-based IRL (LogReg-IRL) (Uchibe, 2018) is a deep IRL method in the LMDP. The following is an overview of the IRL framework in LogReg-IRL. By rearranging the linear Bellman equation in Eq. (6), the following is obtained:

$$\exp\{V(s_t) - r(s_t)\} = \sum_{s'} \bar{p}(s'|s_t) \exp\{\gamma V(s')\} \tag{8}$$

Then, substitute Eq. (8) into Eq. (7) and rearrange to obtain

$$\begin{aligned} u^*(s_{t+1}|s_t) &= \frac{\bar{p}(s_{t+1}|s_t) \exp\{\gamma V(s_{t+1})\}}{\exp\{V(s_t) - r(s_t)\}} \\ \frac{u^*(s_{t+1}|s_t)}{\bar{p}(s_{t+1}|s_t)} &= \exp\{r(s_t) + \gamma V(s_{t+1}) - V(s_t)\} \\ \log \frac{u^*(s_{t+1}|s_t)}{\bar{p}(s_{t+1}|s_t)} &= r(s_t) + \gamma V(s_{t+1}) - V(s_t) \end{aligned} \tag{9}$$

Apply Bayes' theorem to Eq. (9) to obtain

$$\log \frac{u^*(s_t, s_{t+1})}{\bar{p}(s_t, s_{t+1})} = \log \frac{u^*(s_t)}{\bar{p}(s_t)} + r(s_t) + \gamma V(s_{t+1}) - V(s_t) \tag{10}$$

The left-hand side and the first term on the right-hand side of Eq. (10) are the density ratios. The density ratio p_a/p_b can be estimated by assigning the label $\eta = 1$ to the samples from the probability distribution p_a, assigning $\eta = -1$ to the samples from p_b, and training a classifier using logistic regression (Qin, 1998; Cheng et al., 2004; Bickel et al., 2007). First, by Bayes' theorem, the following is obtained:

$$\begin{aligned} \frac{p_a(x)}{p_b(x)} &= \frac{p(\eta = 1|x)}{p(\eta = -1|x)} \frac{p(\eta = -1)}{p(\eta = 1)} \\ \log \frac{p_a(x)}{p_b(x)} &= \log \frac{p(\eta = 1|x)}{p(\eta = -1|x)} + \log \frac{p(\eta = -1)}{p(\eta = 1)} \end{aligned} \tag{11}$$

Next, the first discriminator $D_1(x)$ is defined by the sigmoid function $\sigma(x) = 1/\{1 + \exp(-x)\}$ and a neural network $f(x)$:

$$D_1(x) = p(\eta = 1|x) = \sigma(f(x)) \tag{12}$$

where the second term on the right-hand side of Eq. (11) can be approximated by calculating the sample number ratio N_{p_a}/N_{p_b} and taking its logarithm. For the first term, the following equation can be obtained from the definition of the discriminator in Eq. (12):

$$\begin{aligned}\log \frac{p(\eta=1|x)}{p(\eta=-1|x)} &= \log \frac{D_1(x)}{1-D_1(x)} \\ &= \log \frac{1+\exp\{f(x)\}}{1+\exp\{-f(x)\}} \\ &= \log \exp\{f(x)\} \\ &= f(x) \end{aligned} \tag{13}$$

From Eq. (13), when $N_{p_a} = N_{p_b}$,the following holds:

$$\log \frac{p_a(x)}{p_b(x)} = f(x) \tag{14}$$

Therefore, the density ratio of the first term in Eq. (10) can be estimated by sampling the states $s_t^* \sim \tau^*$ and $\bar{s}_t \sim \bar{\tau}$ from the expert trajectory τ^* according to the optimal control u^* and the baseline trajectory $\bar{\tau}$ according to the uncontrolled transition probability $\bar{p}$, followed by training with the following cross-entropy loss:

$$L_1(D_1) = -\mathbb{E}_{\bar{s}_t \sim \bar{\tau}}[\log(1-D_1(\bar{s}_t))] - \mathbb{E}_{s_t^* \sim \tau^*}[\log(D_1(s_t^*))] \tag{15}$$

The density ratio on the left-hand side of Eq. (10) is defined as follows using the trained $f(x)$, reward-estimating neural network $\tilde{r}(x)$, and state-value-estimating neural network $\tilde{V}(x)$:

$$\log \frac{u^*(s_t, s_{t+1})}{\bar{p}(s_t, s_{t+1})} = f(s_t) + \tilde{r}(s_t) + \gamma \tilde{V}(s_{t+1}) - \tilde{V}(s_t) \tag{16}$$

The second discriminator D_2 for the state-transition pair is defined as

$$D_2(x, y) = \sigma(f(x) + \tilde{r}(x) + \gamma \tilde{V}(y) - \tilde{V}(x)) \tag{17}$$

As with D_1, the discriminator D_2 is trained by cross-entropy loss L_2, given as

$$L_2(D_2) = -\mathbb{E}_{(\bar{s}_t, \bar{s}_{t+1}) \sim \bar{\tau}}[\log(1-D_2(\bar{s}_t, \bar{s}_{t+1}))] - \mathbb{E}_{(s_t^*, s_{t+1}^*) \sim \tau^*}[\log(D_2(s_t^*, s_{t+1}^*))] \tag{18}$$

In the original LogReg-IRL, an L2 regularization term is added to the loss function. Following the process described above, LogReg-IRL estimates the reward and state-value by classifying the expert and baseline trajectories. Unlike traditional IRL methods, LogReg-IRL does not require RL in the reward estimation process, and thus, it can be trained very quickly.

2.4 Difficulty in collecting baseline trajectories

LogReg-IRL showed that IRL in LMDP can be formulated by learning two discriminators. However, LogReg-IRL has a problem in that its learning performance is greatly affected by the baseline trajectory. For the baseline trajectory, it is desirable to collect data that follow uncontrolled transition probability $\bar{p}$, such as trajectories obtained under a random policy, for a wide range of states.

However, for some tasks, the number of states that can be transitioned by a random policy may be limited. For example, in a game task, such as an Atari game, the game does not progress, and in a driving simulator task such as TORCS, the car crashes into a wall immediately. In such a case, data according to a random policy cannot cover a wide range of states.

Several methods have been proposed to collect the baseline trajectory in LogReg-IRL. For Atari games, a method using state-transition pairs from random policy in any state in the expert trajectory was proposed (Uchibe, 2018). For TORCS, a method using the trajectory recorded by driving with noise added to the action output of the expert agent was proposed (Kishikawa & Arai, 2021). These methods are task-specific, and there is no well-established generalized method for collecting baseline trajectories.

An inappropriate baseline trajectory leads to inappropriate reward estimation. The density ratios diverge with respect to the states that the agent can reach and those for which there is no baseline trajectory, and high rewards are estimated where there are no experts. Therefore, an agent that learns according to the estimated reward may acquire a different action from the expert as the optimal policy.

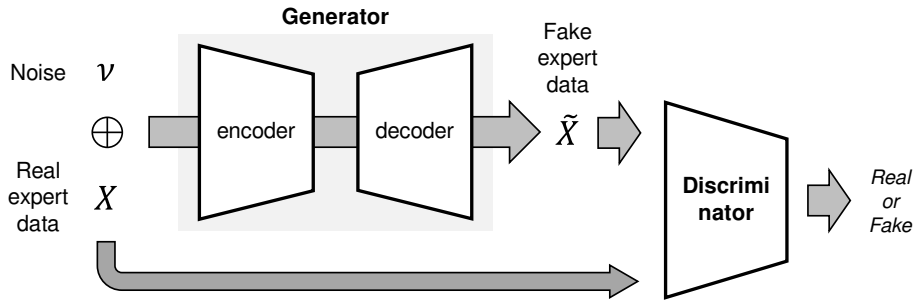

Figure 2: Proposed SOLO-IRL.

3 State-Only Learned One-class Classifier for IRL (SOLO-IRL)

We propose a novel IRL method called **state-only learned one-class classifier for IRL** (SOLO-IRL), which estimates the reward given only the expert. SOLO-IRL is a combination of an IRL framework based on LMDP, a transition generator based on adversarial one-class classification, and least-squares loss. Each of these is explained below.

3.1 Solution by adversarial one-class classification

Classification-based IRL methods are equivalent to learning a discriminator in adversarial learning frameworks, such as GANs (Goodfellow et al., 2014), which are binary classification problems. This means that the IRL problem can be solved by learning a discriminator that classifies the trajectory as expert or not.

When we broaden our perspective to other fields, the anomaly detection problem also requires a binary classifier to distinguish between normal and abnormal samples. However, in real problems, we often encounter situations in which we can obtain many normal samples but few abnormal samples. Therefore, one-class classification is a method for obtaining a binary classifier using only normal samples.

Recently, the adversarially-learned one-class classifier (ALOCC) (Sabokrou et al., 2018) was proposed as a one-class classification method. In the ALOCC, the discriminator is adversarially trained with a denoising autoencoder that generates fake normal samples. As a result, the discriminator is trained as a binary classifier that identifies normal and abnormal samples using only normal samples.

SOLO-IRL is an IRL method that combines a classification-based IRL method with the ALOCC. The structure of SOLO-IRL is illustrated in Figure 2, and its algorithm is given as Algorithm 1. In the following, we describe the learning process and features of SOLO-IRL as well as the objective function used for learning SOLO-IRL.

3.2 Learning process of SOLO-IRL

The training of SOLO-IRL consists of two stages. In the first stage, we learn a discriminator D_1 that classifies whether a state is sampled from expert data or not. The generator G_1 is composed of an encoder–decoder network and generates a fake current state $\bar{s}_t$ from the true current state s_t^* plus noise ν_1, as shown in Eq. (19). Then, the generator learns such that the generated $\bar{s}_t$ and s_t^* are close, and D_1 judges $\bar{s}_t$ to be the true current state.

$$\bar{s}_t \leftarrow \mathcal{R}_1(s_t^* + \nu_1) \tag{19}$$

Meanwhile, the discriminator D_1 is defined by Eq. (12) and outputs the probability that a given state is sampled from the expert. D_1 learns to distinguish between states sampled from a true expert and a fake expert from a generator. Here, the density ratio representing the expertness of each state is obtained in D_1.

In the second stage, the generator G_2 learns to generate a state-transition pair that is close to the sampled expert data and that the discriminator D_2 judges as expert. The generator G_2 uses two

encoder–decoder networks $\mathcal{R}_2$ and $\mathcal{R}_3$ to generate a fake state-transition pair $(\bar{s}_t, \bar{s}_{t+1})$ from the expert's current state s_t^* plus noise ν_2, as given by Eqs. (20) and (21). Then, the generator learns such that the generated $(\bar{s}_t, \bar{s}_{t+1})$ and (s_t^*, s_{t+1}^*) are close to each other, and the discriminator D_2 judges the generated data to be a true state-transition pair.

$$\bar{s}_t \leftarrow \mathcal{R}_2(s_t^* + \nu_2) \tag{20}$$

$$\bar{s}_{t+1} \leftarrow \mathcal{R}_3(s_t^* + \nu_2) \tag{21}$$

The training of D_2 is the same as that of D_1 in the first stage. Here, the discriminator D_2 contains a reward network $\tilde{r}$ and state-value network $\tilde{V}$, as shown in Eq. (17). Finally, it works as an IRL algorithm to estimate the reward and state-value.

By introducing a generator and training the discriminator in an adversarial manner, the decision boundary around the expert can be refined, and the appropriate reward can be estimated. This will make it unnecessary to prepare the baseline trajectory by trial and error. In addition, because SOLO-IRL is an offline method, it can learn quickly without executing RL or interacting with the environment. To the best of our knowledge, SOLO-IRL is the only method that estimates the reward and state-value from expert trajectories alone.

3.3 Least-squares loss as adversarial objective

To train the generator and discriminator, we propose the use of least-squares loss as an adversarial objective. The least-squares loss is represented by the following equations:

$$L_{adv}(D) = \frac{1}{2}\mathbb{E}_{x\sim d^*}[(D(x)-1)^2] + \frac{1}{2}\mathbb{E}_{\tilde{x}\sim \bar{d}}[(D(\tilde{x}))^2] \tag{22}$$

$$L_{adv}(G) = \frac{1}{2}\mathbb{E}_{\tilde{x}\sim \bar{d}}[(D(\tilde{x})-1)^2] \tag{23}$$

where d^* and $\bar{d}$ denote the true and fake state or state-transition pair, respectively. The least-squares loss was proposed alongside LSGAN (Mao et al., 2017), which solved the learning instability and mode collapse problems of previous GANs. In SOLO-IRL, this least-squares loss is used instead of the cross-entropy loss to address the problems of learning stability and mode collapse.

3.4 Reconstruction objective

Meanwhile, the generators G_1 and G_2 must be trained to be close to the true expert data in addition to training by the adversarial objective. The reconstruction objective is trained by the least-squares loss given by the following equations, as in the original ALOCC:

$$L_{rec}(G_1) = ||s_t^* - \mathcal{R}_1(s_t^* + \nu_1)||_2 \tag{24}$$

$$L_{rec}(G_2) = ||s_t^* - \mathcal{R}_2(s_t^* + \nu_2)||_2 + ||s_{t+1}^* - \mathcal{R}_3(s_t^* + \nu_2)||_2 \tag{25}$$

Finally, the objective of the discriminators D_1 and D_2 becomes $L_{adv}(D)$, and the objective of the generators G_1 and G_2 becomes $L_{adv}(G) + L_{rec}(G)$. Using these objectives, SOLO-IRL estimates the reward and state-value by training each neural network using the gradient descent method.

4 Experiment

We validated the performance of the proposed method in the OpenAI Gym environment (Brockman et al., 2016). For the expert trajectory, we used a trajectory generated by an agent that has learned the optimal action for the true reward as an expert. As RL algorithms, we used PPO (Schulman et al., 2017) for tasks with a discrete action space and TD3 (Fujimoto et al., 2018) for tasks with a continuous action space. In SOLO-IRL, a three-layer multilayer perceptron was used as both the encoder and decoder in the generator, and a three-layer multilayer perceptron was used as the discriminator. Adam (Kingma & Ba, 2014) was used to optimize the neural network. The noise input to the generator follows a Gaussian distribution and was tuned for each task.

Pendulum and CartPole. Pendulum (Gym, c) and CartPole (Gym, b) are basic reinforcement learning tasks. In Pendulum, the agent must hold a pendulum connected to a pivot point straight

Algorithm 1 SOLO-IRL: State-Only Learned One-class Classifier for IRL

Require: Expert trajectories τ^*, discount factor γ, noise ν_1 and ν_2, numbers of iterations n_1 and n_2
Ensure: Reward network $\tilde{r}(s)$, state-value network $\tilde{V}(s)$
Initialize neural network $f(x)$, $\mathcal{R}_1(x)$
Define discriminator $D_1(s_t) = \sigma(f(s_t))$
for $i = 0, \cdots, n_1$ **do**
  Sample expert state s^* from τ^*
  $\bar{s} \leftarrow \mathcal{R}_1(s^* + \nu_1)$
  Train D_1 according to the loss $L_{adv}(D)$ in Eq. (22)
  Train $\mathcal{R}_1$ with loss $L_{adv}(G) + L_{rec}(G_1)$ in Eqs. (23) and (24)
end for
Initialize neural network $\tilde{r}(x)$, $\tilde{V}(x)$, $\mathcal{R}_2(x)$, $\mathcal{R}_3(x)$
Define discriminator $D_2(s_t, s_{t+1}) = \sigma(f(s_t) + \tilde{r}(s_t) + \gamma\tilde{V}(s_{t+1}) - \tilde{V}(s_t))$
Disable f updates
for $i = 0, \cdots, n_1$ **do**
  Sample expert current state s_t^* and next state s_{t+1}^* from τ^*
  $\bar{s}_t \leftarrow \mathcal{R}_2(s_t^* + \nu_2)$
  $\bar{s}_{t+1} \leftarrow \mathcal{R}_3(s_t^* + \nu_2)$
  Train D_2 according to the loss $L_{adv}(D)$ in Eq. (22)
  Train $\mathcal{R}_2$ and $\mathcal{R}_3$ according to the loss $L_{adv}(G) + L_{rec}(G_2)$ in Eqs. (23) and (25)
end for

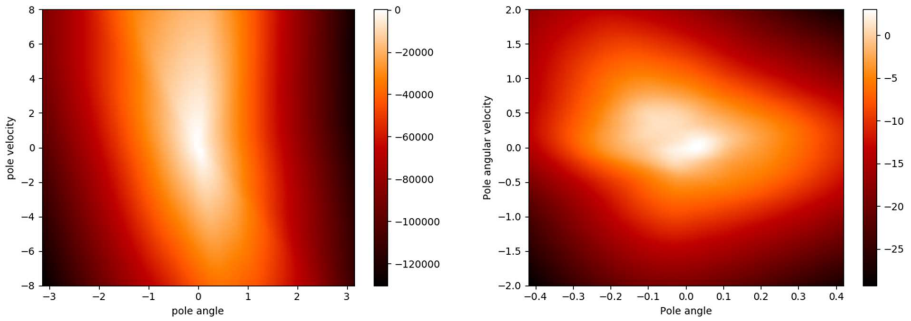

Figure 3: Visualized results of estimated rewards for (left) Pendulum and (right) CartPole.

up and upright. In CartPole, the agent must keep the pendulum connected to a cart upright by controlling the cart. A high reward is given to the upright state in Pendulum, and a survival reward is given to the pendulum in CartPole as long as it remains upright.

The estimation results for the rewards are presented in Figure 3. The visualized values are the rewards for the angle and velocity in Pendulum and the rewards for the angle and angular velocity of the pendulum when the position and velocity of the cart are zero in CartPole. For both tasks, the highest reward was estimated when the pendulum was fixed at the center.

BipedalWalker. BipedalWalker (Gym, a) is a task in which a robot with four joints learns a bipedal walking task. The agent is required to output the velocities of its two hips and knees as actions, taking the state given by virtual sensor inputs as the input. The true reward consists of a bonus for speed and penalty for magnitude of the action or a fall. The results are presented in 1. Here, expected value difference (EVD) (Levine et al., 2011) is one of the performance metrics of IRL, and the smaller the EVD, the closer it is to the expert. The proposed method obtained a walk that was closer to the expert's than LogReg-IRL.

Table 1: EVD values in the BipedalWalker task.

Methods	EVD
LogReg-IRL	17.02
Proposed method	13.59

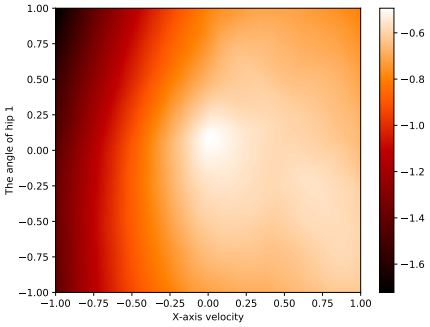

Figure 4: Visualized results of estimated rewards for BipedalWalker.

On the one hand, LogReg-IRL requires an appropriate baseline trajectory, and collecting the baseline trajectory often requires careful tuning. On the other hand, the reward estimated by the proposed method is improved by the data from the generator. This is because the discriminator in the proposed method is trained to focus on more expert-like features to distinguish the generator data accurately.

5 Conclusion

In this study, we took advantage of the fact that the classification-based IRL framework is equivalent to training a discriminator in adversarial learning. Based on this, we proposed a novel IRL algorithm called SOLO-IRL, which introduces a generator to generate fake expert data. This algorithm can be trained quickly without the need for an inner loop and can easily estimate rewards with high performance from expert trajectories alone, without the need for baseline trajectories.

However, although it is simpler than collecting baseline trajectories, the noise used for reconstruction by the generator still requires adjustment. In future work, we would like to develop a method that does not require noise adjustment. We will also consider application to more advanced image-based control tasks and the incorporation of recent advances in GANs.

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