

# P-HRL: An Adaptive and Flexible Prediction-based Hierarchical Reinforcement Learning for Robot Soccer

Anonymous submission

## Abstract

Robot soccer as a complex mixed cooperative-competitive task presents many challenges to multi-agent reinforcement learning (MARL). Firstly, due to the sparse rewards and the long-term credit assignment problem, it is difficult for MARL to learn to collaborate in robot soccer. Secondly, high-dimensional and continuous state-action spaces make it difficult for MARL to adapt to new opponents. Although MARL has made impressive achievements in many robot tasks, MARL has shown a limited ability to handle such complex and long-term tasks, especially where other opponents are present and rewards are sparse. To address these challenges, we propose Prediction-based Hierarchical Reinforcement Learning (P-HRL) for robot soccer. P-HRL consists of a coach for soccer tactics and a robot controller for robot motion control. To professionally evaluate the performance of P-HRL, we design various key performance indicators (KPIs) for robot soccer such as ball possession rate. Experimental results demonstrate that P-HRL has a better performance than the state-of-the-art baseline MATD3. In 50 matches against MATD3, P-HRL won 26 matches, tied 11 matches and lost 13 matches. P-HRL had an average ball possession rate of 70.25%, compared to 17.14% for MATD3. In 50 matches against the new opponent, P-HRL won 18 matches and tied 14 matches; while MATD3 won 15 matches and tied 15 matches.

## Introduction

Robot soccer have been developed to facilitate research in the field of robot control and to help deploy multi-agent systems (MAS) from virtual environments to the real world (Antonioni et al. 2021). In robot soccer, MAS controls the robots on the team to cooperate and score goals. Several leagues on robot soccer have been successfully organized in recent years, such as RoboCup, IEEE Very Small Size Soccer (IEEE VSSS) and many research problems based on robot soccer have received extensive attention, such as path planning (Cooksey and Veloso 2017; Macenski et al. 2020).

Multi-agent reinforcement learning (MARL) have achieved outstanding success on cooperative problems such as video games (Zhang et al. 2020; Wang et al. 2020) and robot control (Perrusquía, Yu, and Li 2021). MARL controls the actions of multiple agents based on reward to maximize the return by continuously interacting with the environment. MARL has achieved state-of-the-art performance in many

competitive video games (e.g., StarCraftII (Vinyals et al. 2017)) and defeated the top human professional players.

MARL has higher expressiveness and flexibility than other methods (Sutton and Barto 2018). Especially in real-time competitive tasks like soccer games, reinforcement learning-based approaches are more likely to be flexible and fast in handling unexpected situations.

Thus, the development of a MARL-based approach in robot soccer has the potential to outperform other non-reinforcement learning approaches (Akiyama et al. 2018; Chen et al. 2019). However, unlike video games, MARL needs to control real entities (i.e. robots) instead of virtual entities (i.e. units in video games) in robot soccer. We present the following challenges in robot soccer to MARL, which is commonly used to control robots (e.g., MADDPG (Lowe et al. 2017), MATD3 (Ackermann et al. 2019)).

First, the sparsity of rewards and the long-term credit assignment problem (Vezhnevets et al. 2017; Harutyunyan et al. 2019) make it difficult for MARL to learn to collaborate. Scoring goals in soccer games is highly sparse (e.g., in our experiments, scoring a goal occurred on average once every 500 time steps). MARL learns actions by using rewards to estimate expected returns (Mnih et al. 2013). Sparse rewards can cause MARL to misestimate the expected return and lead MARL to take inappropriate actions to control the robot.

Moreover, the scores does not explicitly show the contribution of each robot to the goal, which leads MARL to misestimate the impact of each robot's actions on the event of scoring a goal. This results in unpredictable variance between MARL's assignment of expected returns and the correct assignment.

Previous work (Abreu, Reis, and Cardoso 2019; de Medeiros, Marcos, and Yoneyama 2020) addressed the problem of reward sparsity by reward shaping. But reward shaping does not solve the problem of long-term credit assignment in robot soccer. The contribution of players to a goal is related to many factors such as possession and positions of the opposing players. Any inappropriate consideration of these factors also causes the reward to misestimate the contribution of each player to the goal.

Second, high-dimensional and continuous state-action spaces make it difficult for MARL to adapt to new opponents. Unlike other robot control tasks in stationary environ-

ments(Mordatch and Abbeel 2018; Todorov, Erez, and Tassa 2012), the transfer of state is caused by both MARL and the opponent, which resulting in the optimal policy being related to the opponent policy. This leads MARL to explore a larger state-action space to find the optimal policy.

Previous work(Vinyals et al. 2019; Berner et al. 2019) in video games guides MARL to find optimal policies by means of training with opponents with domain expertise (e.g., human players). This approach requires training with a large number of opponents to fully explore the state-action space. However, the state-action space in robot soccer is continuous, rather than the discrete state-action space in video games, which makes it difficult to use this approach in robot soccer.

This paper aims to design a *coach* to guide MARL for robot motion control at the level of soccer tactics and help MARL to adapt to new opponents. Hierarchical reinforcement learning (HRL) provides a framework for improving MARL through coach. HRL learns the same task at multiple time scales, and the policies at each time scales jointly determine the behavior of the agent(Pateria et al. 2021).

In this paper, we propose Prediction-based Hierarchical Reinforcement Learning (P-HRL), which consists of two hierarchical parts: a coach for soccer tactics and a robot controller for robot motion control. Coach decomposes the soccer game into a series of subtasks, and the robot controller controls the motions of robots to complete these subtasks. For the first challenge, P-HRL provide different goals and rewards for each robot. It compensates for the sparsity of rewards of goal scoring, and reduces the time scale of credit assignment. For the second challenge, the hierarchical structure of P-HRL allows the coach to focus only on learning soccer tactics and the robot controller to focus only on learning robot control. This allows the coach to train in a low-dimensional space, and the robot controller only needs to train for the subtasks assigned by the coach.

We test the P-HRL by simulating 3x3 robot soccer games under IEEE VSS rules(Bassani et al. 2020). The results demonstrate that P-HRL has better performance than the state-of-the-art MARL methods. The main contributions of this paper can be summarized as follows:

- (1) To the best of our knowledge, this is the first work to use the HRL framework in robot soccer to control robot soccer in a more soccer tactically targeted way than MARL.
- (2) We design multiple key performance indicators(KPIs) for robot soccer such as ball possession rate. These KIPs are designed with reference to the relevant indicators of human soccer, which allow for a more professional and systematic evaluation of P-HRL performance in robot soccer.
- (3) In 50 matches against the state-of-the-art baseline MATD3, P-HRL won 26 matches, tied 11 matches and lost 13 matches. P-HRL had an average ball possession rate of 70.25%, compared to 17.14% for MATD3. In 50 matches against the new opponent, P-HRL played to a draw with the new opponent, in which P-HRL won 18 matches and tied 14 matches. MATD3 lost to the new opponent, in which MATD3 has only won 15 matches and tied 15 matches.

## Background

### Multi-agent Reinforcement Learning

### Hierarchical Reinforcement Learning

### Prediction-based Hierarchical Reinforcement Learning (P-HRL)

Figure 1 shows the temporal process of P-HRL. The key idea of P-HRL is to design a coach to guide the robot controller at the level of soccer tactics. To achieve this idea, we design two types of subtasks: offensive subtask and defensive subtask. Coach breaks the soccer game process into a combination of these two subtasks, and the robot controller is aimed to complete those subtasks.

### Problem Formalization

The entire process of robot soccer can be formalized as a partially observable, goal-conditioned Markov Decision Process (MDP)[?]. Specifically, it is formally defined as a tuple  $\langle \mathcal{S}, \mathcal{O}, \mathcal{G}, \mathcal{U}, P, R, \gamma \rangle$ , where  $\mathcal{S}$  is state space.  $s_t \in \mathcal{S}$  is the state at each time step  $t$ . These states usually consist of position vectors and speed vectors for robots and balls. Limited by the robot hardware, robots cannot observe all the information in the state (e.g., the speed vectors of the opposing robots is usually not available), so each robot can only receive the partially observable observations  $o_t^i \in \mathcal{O}$ , where  $i = 1, \dots, n$ ,  $n$  is the number of our robots. We define  $o_t = \bigcup_{i=1}^n o_t^i$  is all the observations that our robots obtain from the environment.  $g_t \in \mathcal{G}$  is the subtask.  $\mathbf{u} = (u_t^1, \dots, u_t^n)$  is the joint action, where  $u_t^i$  is the action of the  $i$ -th robot.  $P(s_{t+1}|s_t, \mathbf{u}_t)$  is the state transition function.  $\mathcal{R}$  is the reward function, which consists of the subtask reward  $r_{g_t}$  and the external reward  $r_t$ .  $\gamma$  is the discount factor. A complete robot soccer game is defined as:

$$P(\tau) = P(s_0) \prod_{t=0}^T P(\mathbf{u}_t|s_t) P(s_{t+1}|s_t, \mathbf{u}_t) \quad (1)$$

where  $\tau = \{s_0, \mathbf{u}_0, s_1, \mathbf{u}_1, \dots, s_T, \mathbf{u}_T\}$  is the trajectory of a game.  $s_0$  is the initial state. It is the state at the beginning of the game.  $s_T$  is the terminal state and defined as the state when a goal is scored or the state when the game reaches the end time step  $t = T_{max}$ . At each time step  $t$ , the coach starts (or continues) a subtask  $g_t$  according to the coach policy  $\pi^c(o_t)$  and gives a subtask reward  $r_{g_t}$ . The robot controller gives an joint action  $\mathbf{u}_t \sim \pi^r(\mathbf{u}_t | o_t^i, g_t, r_{g_t}, r_t)$  to control the robot movement. Then, the environment transfers to state  $s_{t+1}$  according to  $P(s_{t+1}|s_t, \mathbf{u}_t)$ . The aim of the robot soccer is to maximize goal scores, which is defined by maximizing discounted accumulated rewards  $E \left[ \sum_{t=0}^T \gamma r_t(s_t, \mathbf{u}_t) \right]$ .

### Coach

**Method Overview** Formally, coach is represented as a tuple  $\langle \mathcal{G}, r_g, I_g, \beta_g \rangle$ , where  $g \in \mathcal{G}$  is subtask.  $r_g$  is subtask reward, and it is used to train the agent in robot controller to complete the subtask  $g$ .  $I_g$  and  $\beta_g$  is the initiation condition and the termination condition of the subtask  $g$ , respectively. They are used to start or terminate a subtask  $g$ .

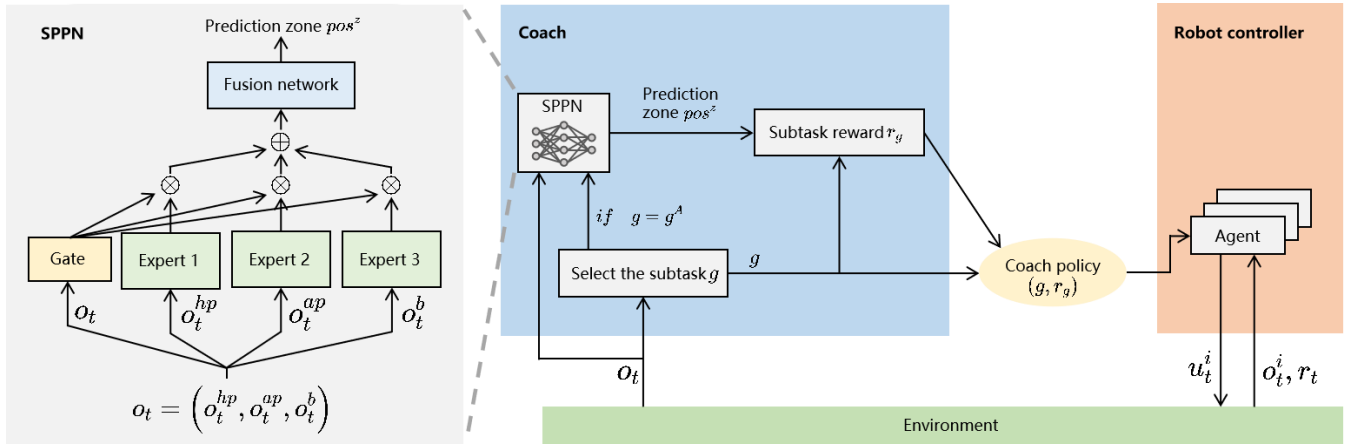


Figure 1: Illustration of the P-HRL. At each time step  $t$ , after coach receives observation  $o_t$ , it starts (or continues) a subtask  $g$  and calculates the subtask reward  $r_g$  according to subtask initiation condition  $I_g$  and termination condition  $\beta_g$ . Then, each agent in the robot controller will output an action  $u_t^i$  to control the corresponding robot based on coach policy  $\pi^c$ , observation  $o_t^i$  and reward  $r_t$ .

We divide subtasks into two types  $\mathcal{G} = \{g^A, g^D\}$ , where  $g^A$  is offensive subtask and  $g^D$  is defensive subtask. Considering the most general soccer tactics, when our robots are in possession, the optimal tactic is obviously to attack and shoot. When opposing robots are in possession, the optimal tactic is obviously to defend to prevent the opponent from scoring. Thus, we define the offensive subtask as the subtask that helps to score when our robots are in possession and defensive subtasks as the subtask that help reduce scores lost when opposing robots are in possession.

In offensive subtask, passing the ball is an effective way to secure possession to ensure that the opponent team does not have the opportunity to attack. Thus, coach encourage passing between robots to attack with more flexibility. To realize the this idea, we propose the soccer position prediction network (SPPN) which is described in following session. SPPN will predict the zone where the ball will come up after  $T_p$  time steps. Our robot closest to the ball is defined as an attacker, and the rest of our robots are defined as supporters. Attacker’s goal is to attack with the ball, and supporter’s goal is to go to prediction zone and wait to be passed. It is worth noting that in this process, once the ball is intercepted by the opposing robot (i.e. the opposing robots are in possession), the offensive subtask will be terminated immediately, and the defensive subtask will be started. In defensive subtask, because the opposing robots are in possession, we encourage all of our robots to intercept the ball. According to the process of the these subtasks, subtask reward  $r_g$  is defined as encouraging the robot to go to the target position (i.e. the position of the ball or the position predicted by the SPPN):

$$r_g = \frac{pos^r - pos^g}{\|pos^r - pos^g\|} \cdot v^r \quad (2)$$

$$\text{where } pos^g = \begin{cases} pos^b & \text{if } g = g^A \text{ and robot is attacker.} \\ pos^z & \text{if } g = g^A \text{ and robot is supporter.} \\ pos^b & \text{if } g = g^D \end{cases}$$

where  $\|\cdot\|$  is the euclidean distance,  $pos^r$ ,  $pos^z$  and  $pos^b$  is the position vectors of the robot, ball and centroid of the prediction zone respectively,  $v^r$  is the robot speed vector. Table ?? shows the definition of initiation conditions  $I_g$  and termination conditions  $\beta_g$ .

	Offensive subtask $g^A$	Defensive subtask $g^D$
Initiation condition $I_g$	Our robots are in possession.	Opposing robots are in possession.
Termination condition $\beta_g$	(1) Opposing robots are in possession. (2) After $T_p$ time steps.	Our robots are in possession.

Table 1: Definition of initiation and termination conditions

**Soccer Position Prediction Network** To achieve the soccer position prediction we mentioned in the previous section, we propose SPPN. SPPN is inspired by Mixture of Experts(MoE)(Eigen, Ranzato, and Sutskever 2013) and is a neural network for prediction.

Robot soccer presents many challenges to soccer position prediction. The data in the observation can be divided into three types: data related to the home team player (i.e. our robots), data related to the away team player (i.e. the opposing robots), and data related to the ball. In soccer games, the position of the soccer is determined by a combination of three types of data in the observation. However, a single network structure cannot effectively model the data under observation because the data of the home player and the data of the away player are independent. Moreover, the uncertainty in the opponent policies leads to variances between the training samples and test samples (i.e., real-time situations). To address these challenges, we propose soccer position predic-

tion network(SPPN). SPPN consists of the following three components:

**Expert network:** To effectively solve the problem of data independence in the observation, we use three expert networks in SPPN. Each expert focused on modeling only one type of data. We divided the data into the three types and input the divided data into three expert networks.

**Gating network:** Gating network is used to gate the output of expert networks. This allows modeling the complex relationship between the three types of data in the observation.

**Fusion network:** Fusion network is used to map the output features of the expert network with the soccer position prediction results. To reduce the influence of the opponent policies on the prediction results, we divide the soccer field into several equal rectangular zones, and fusion network output the prediction for the zone.

Formally, given a observation  $o_t = (o_t^{hp}, o_t^{ap}, o_t^b)$  obtained by coach at time step  $t$ , where  $o_t^{hp}$ ,  $o_t^{ap}$  and  $o_t^b$  is the part of the observation related to the home team players, away team players and ball, respectively. The prediction zone of SPPN can be formulated as below:

$$pos^z = h \left( \sum_{i=1}^3 g(o_t) f_i(o_t^i) \right) \quad (3)$$

where  $o_t^1 = o_t^{hp}$ ,  $o_t^2 = o_t^{ap}$ ,  $o_t^3 = o_t^b$

$g(o_t) = softmax(f(o_t))$

where  $f_i(\cdot)$  is the  $i$ -th expert network,  $g(\cdot)$  is the gating network,  $f(\cdot)$  is a single fully connected layer,  $h(\cdot)$  is the fusion network, and  $pos^z$  is the position vector of the centroid of the prediction zone. The expert networks and the fusion network are stacked by fully connected layers.

## Robot Controller

In robot controller, we modify MADDPG(Lowe et al. 2017) to be used in the hierarchy structure of P-HRL. This approach is also easy to use for the expansion of MATD3(Ackermann et al. 2019). Specifically, each agent controls the motion of one robot separately. Consider a game with  $N$  robots per team, where each agent  $i$  uses an actor network  $\mu_i$  with parameter  $\theta^{\mu_i}$  and a critic network  $Q_i$  with parameter  $\theta^{Q_i}$ . The aim of the robot controller is to complete subtask  $g$  and maximize goal scores. Thus, critic network  $Q_i$  is written as:

$$Q_i(o_t, \mathbf{u}_t) = \max \left( E \left[ \sum_{j=0}^T \gamma \left( r_{g_{t+j}}^i + r_t \right) \mid g_t, o_t, \mathbf{u}_t \right] \right) \quad (4)$$

We update the parameter  $\theta^{Q_i}$  of the critic network  $Q_i$  by using the tuple  $(o, g, r_g, \mathbf{u}, r, o')$  in the replay buffer  $\mathcal{D}$  to minimize the loss:

$$\mathcal{L}(\theta^{Q_i}) = E_{o, g, r_g, \mathbf{u}, r, o' \sim \mathcal{D}} \left[ (Q_i(o, \mathbf{u}, g \mid \theta^{Q_i}) - y)^2 \right], \quad (5)$$

where  $y = r + r_g^i + \gamma Q_i'(o', \mathbf{u}', g \mid \theta^{Q_i'}) \mid_{u'_j = \mu'_j(o^j)}$

where  $Q_i'(o', \mathbf{u}', g \mid \theta^{Q_i'})$  is the target critic network with parameter  $\theta^{Q_i'}$ , which is periodically updated by parameter  $\theta^{Q_i}$ . Each action  $u'_j$  in the joint action  $\mathbf{u}'$  is given by the target actor network  $\mu'_j(o^j)$ , respectively, and the target actor network with parameter  $\theta^{\mu_i'}$  is updated periodically by the parameter  $\theta^{\mu_i}$ . Using this critic network  $Q_i$ , the gradient of actor network  $\mu_i$  used to optimize the deterministic policy of agent  $i$  can be written as:

$$\begin{aligned} \nabla_{\theta^{\mu_i}} J(\theta^{\mu_i}) = \\ E_{o, u^j \neq i, g, r_g \sim \mathcal{D}} [\nabla_{u^i} Q_i(o, \mathbf{u}, g \mid \theta^{Q_i}) \mid_{u^i = \mu_i(o^i, g)}] \\ \nabla_{\theta^{\mu_i}} \mu_i(o^i, g \mid \theta^{\mu_i})] \end{aligned} \quad (6)$$

## Training Method

To allow the robot controller to focus on completing the subtasks assigned by the coach, P-HRL uses parallel training of the coach and robot controller. Although the prediction region of SPPN output in coach may be inaccurate at the beginning of training, and the training process of robot controller also affects the prediction accuracy of SPPN, this training method allows both hierarchical parts to adapt intermediately. Algorithm 1 describes the training parallel for P-HRL. To make the SPPN in coach and the robot controller can be trained simultaneously, we use two replay buffer  $\mathcal{D}_1$  and  $\mathcal{D}_2$ . In an episode, coach selects a subtask  $g$  (lines 5 to 12). Then, the robot controller controls robots to complete the subtask (lines 14 to 15). Every  $T_p$  time steps, P-HRL stores the observation  $o_t$  into replay buffer  $\mathcal{D}_1$  for the training of SPPN (lines 16 to 18). P-HRL uses the samples in  $\mathcal{D}_1$  to construct the training set and the labels to perform parameter updates on the SPPN (lines 20 to 21). P-HRL performs parameter updates on the robot controller using samples from  $\mathcal{D}_2$  and deterministic policy gradient (lines 22 to 23).

## Evaluation

Our experiments are based on rSoccer(Martins et al. 2022) - a framework for studying reinforcement learning for small and very small robot soccer. Specifically, we use the the IEEE VSSS (Very Small Size Soccer) multi-agent environment to simulate a robot soccer scenario (See Figure 2). IEEE VSSS is a robotic soccer competition in which two teams of three robots compete against each other. According to the rules, the robots are controlled remotely by computers without human intervention; The robot are fixed-size (0.08 m  $\times$  0.08 m) with wheels but no hardware to dribbling or kicking the ball. The size of the soccer field is 1.5 m  $\times$  1.3m.

In our experiments, we basically followed the reward shaping in rSoccer (Bassani et al. 2020). Exceptionally, we changed the reward for movement toward the ball to movement toward the target, and added a speed penalty to encourage continuous movement of the robot. The detailed reward settings are defined as follows:

---

**Algorithm 1: Parallel training for P-HRL**


---

```

1: Initialize replay buffer  $\{\mathcal{D}_1, \mathcal{D}_2\}$ , SPPN in coach, actor
   networks and critic networks in robot controller.
2: for episode = 1 to  $M$  do
3:   Rest the environment.
4:   for  $t = 0$  to  $T_{max} - 1$  and not occur_goal_scoring do
5:     if  $I_{g^A}$  is True then
6:        $g \leftarrow g^A$ 
7:        $\beta_g \leftarrow \beta_{g^A}$ 
8:       Use SPPN to predict zone  $pos^z$ .
9:     else
10:       $g \leftarrow g^B$ 
11:       $\beta_g \leftarrow \beta_{g^B}$ 
12:    end if
13:    while  $\beta_g$  is False do
14:      Sample a joint action  $\mathbf{u}$  from robot controller.
15:      Execute the joint action  $\mathbf{u}$ , calculate subtask re-
        ward  $r_g$  using Eq 2, observe the external reward
         $r$  and next observation  $o'$ .
16:      if  $t \bmod Tp=0$  then
17:        Store observation  $o$  in replay buffer  $\mathcal{D}_1$ .
18:      end if
19:      Store  $(o, g, r_g, \mathbf{u}, r, o')$  in replay buffer  $\mathcal{D}_2$ .
20:      Randomly sample mini-batches from  $\mathcal{D}_1$ .
21:      Update SPPN by samples and cross-entropy loss
        function.
22:      Randomly sample mini-batches from  $\mathcal{D}_2$ .
23:      Update robot controller by samples, Eq 5 and
        Eq 6.
24:    end while
25:  end for
26: end for

```

---

$R_g$  is the goal scoring rewards and is defined as:

$$R_g = \begin{cases} 1 & \text{if the team scores a goal.} \\ 0 & \text{if no goal scored.} \\ -1 & \text{if the opponent scores a goal.} \end{cases} \quad (7)$$

$R_m$  is a reward that encourages the robot to move to the target position.  $R_m$  in timestep  $ts$  is defined as:

$$R_m = \|r, t\|_{ts} - \|r, t\|_{ts-1} \quad (8)$$

where  $\|\cdot\|$  is the euclidean distance.  $r$  and  $t$  are the positions of the robot and target.

$R_{bd}$  is a reward for the direction of ball's movement. It is positive when the ball is taken toward the opponent's goal line and negative toward its own goal line.  $R_{bp}$  in timestep  $ts$  is defined as:

$$R_{bd} = bd_{ts} - bd_{ts-1} \quad (9)$$

$$bd = \frac{\|g_t, b\| - \|g_o, b\|}{l} - 1 \quad (10)$$

where  $g_t$  and  $g_o$  are the positions of the center of the team goalpost and opponent goalpost respectively,  $b$  is the position of the ball, and  $l$  is the total length of the field, which is 1.5 in our experiment.

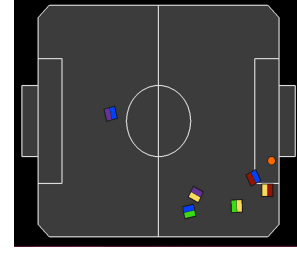


Figure 2: rSoccer VSSMA Environment

The energy penalty  $R_e$  is a negative reward used to penalize the robot's wheel speed, which is defined as:

$$R_e = -(|v_l| + |v_r|) \quad (11)$$

where  $v_l$  and  $v_r$  are the linear velocities of the left and right wheels respectively.

The speed penalty  $R_s$  is a negative reward when the robot is considered stationary, used to penalize the robot for being lazy or getting stuck, which is defined as:

$$R_s = \begin{cases} 0 & \text{if } s \geq ts \\ -1 & \text{if } s < ts \end{cases} \quad (12)$$

where  $s$  is the linear speed of the robot and  $ts$  is the threshold value that determines whether the robot is stationary or not, which is set to 0.01 in our experiment.

For each agent, the final reward at each time step is calculated as a weighted sum of the above rewards:

$$R = w_g R_g + w_m R_m + w_{bp} R_{bp} + w_e R_e + w_s R_s \quad (13)$$

where the weights are based on the default settings of rSoccer and, for those values that are not available, are determined by trial and error. In our experiments,  $w_g = 50$ ,  $w_m = 0.2$ ,  $w_{bp} = 0.8$ ,  $w_e = 2 \times 10^{-6}$ ,  $w_s = 0.5$ .

The evaluation focused on these questions:

- RQ1: How is P-HRL compared to baseline in terms of end-to-end performance?
- RQ2: How well does the P-HRL adapt to the new opponent compared to baseline?
- RQ3: How do the individual components (SPPN, dynamic subtask assignment) contribute to the overall system?

### Evaluation Metrics

The number of goals scored is undoubtedly the most direct indicator to victory. However, it could not be enough to evaluate simply by the score. In many cases, both teams have the same or a similar number of goals, or even no goals at all, making it impossible to compare the performance of the two teams. Based on the common metrics used in human soccer analysis, we defined the following key performance indicators (KPIs) applicable to robot soccer:

**Ball possession rate** The last robot to control the ball is defined as having possession of the ball. In particular, if at least one robot from both teams approach ball and compete

for the ball simultaneously, it is considered that no one has possession of the ball. Historically, it has been believed that higher possession is associated with scoring advantage (Lago and Martín 2007; Lago-Ballesteros and Lago-Peñas 2010; Parziale and Yates 2013). In particular, we use the clock time method to measure a team’s possession rate. For a team, possession rate can be calculated as the sum of the time that all robots on the team have possession of the ball as a percentage of the total time of the game.

**Number of Passes** Passing is defined as the transfer of possession from one player to another player of the same team. The number of passes made by a team is the sum of all passes made by all players. Passing brings an advantage in that the team secures possession of the ball while bringing the ball to a good position to attack. The number of passes is a key indicator of the coordination between players.

**Number of interception** Interception is defined as the transfer of possession from one player to an opponent’s player. For a team, the number of interceptions is counted as the sum of interceptions made by all players. Frequent interceptions mean that players are more motivated to compete for ball possession, bringing more scoring opportunities for the team.

## End-to-end Performance

To test the end-to-end performance, we use MATD3 (Ackermann et al. 2019), an state-of-the-art actor-critic-based algorithm that has been used in many multi-agent cooperative tasks similar to robot soccer. In the above environment, P-HRL controls one team of three robots and MATD3 controls another team of three robots for soccer matches. The results of the competition are used to evaluate the end-to-end performance of the P-HRL.

We trained P-HRL and MATD3 respectively in the above environment, using rSoccer built-in algorithm as the opponent. Unless otherwise specified, all RL-related training parameters in this evaluation section are consistent, see Table 2. The training lasts until the average episode reward does not rise with the episode (about  $1 \times 10^6$  steps), and the changes in the reward and goal difference of the two methods during the training process are shown in Figure 3(a),3(b).

We do further training to ensure that the model is adequately trained in case the build-in opponents in rSoccer might not be competitive enough to reach the full potential of the model. Inspired by Robust Adversarial Reinforcement Learning (RARL) proposed by Pinto et al.(2017), we further train P-HRL with MATD3 in a mutual confrontation using a RARL-like approach. Based on the converged model output from the previous experiment as the starting point, the two sides of the competition are set to P-HRL and MATD3 respectively, alternately training two sets of agents: In the first stage, P-HRL is trained and parameters are updated, including the coach and the agents, while keeping the MATD3 strategy unchanged; In the next stage, P-HRL’s policies remain unchanged and MATD3’s policies are learned. Repeat this sequence until convergence.

For evaluation, the robots controlled by both algorithms play 50 matches in the environment as described above, each

Table 2: Hyperparameters

<i>Name</i>	<i>Value</i>
Critic hidden layers size	64
Critic learning rate	$1 \times 10^{-4}$
Actor hidden layers size	64
Actor learning rate	$1 \times 10^{-4}$
Batch size	1024
Discount Factor (gamma)	0.95
Soft Update (tau)	0.01
Initial Noise	0.2
Noise decay rate	$5 \times 10^{-7}$
Minimum noise	0.05

match lasting 2000 time steps. The results of the matches are shown in Figure 3. Out of the total 50 matches, P-HRL won 26 matches, MATD3 won 13 matches and tied 11 matches. Figure 3(c) show that P-HRL scored more goals than MATD3. Figure 3(d), 3(e), 3(f) show the differences in KPIs. P-HRL outperform MATD3 in ball possession rate and number of passes. P-HRL has an average of 70.25% possession and 14.32 passes per game; MATD3 has an average of 17.14% possession and 1.92 passes per game. In terms of interceptions, P-HRL and MATD3 averages 14.40 and 14.44 respectively, with no significant difference found.

## Ability against new opponents

We investigated the performance of the model against new opponents. This simulates that in real robot training, the opponent’s strategy is unknown during the training phase. Once on the field, the robots are supposed to fine-tune their strategies to counter their opponents.

We use MADDPG (Lowe et al. 2017), a commonly used MARL algorithm, as the new opponent. Use the P-HRL and MATD3 models trained in the previous chapter as starting points. Let the two play against MADDPG separately to evaluate their adaptability. Note that neither model has been trained with MADDPG as the opponent, therefore, it is safe to say that they both play against a new opponent.

A total of 50 matches were played, each lasting 2000 timesteps. In this process, MATD3 got the entire network trained, while P-HRL got only the coach trained, with the robot controllers unchanged. In the respective 50 matches, P-HRL won 18 and tied 14; MATD3 won 15 and tied 15. The results in Figure 4(a) show that the goal difference of P-HRL is higher than MATD3 and tends to increase slightly over the 50 episodes, while no significant trend is seen for MATD3. One possible reason for the increase could be the convergence of SPPN. Figure 4(e), 4(f) show the loss and accuracy of SPPN during training. It can be observed that the loss decreases rapidly in the first period and converges approximately within 20000 time steps. The accuracy of prediction increases within 50 matches and reaches a maximum of 66.17% top1 accuracy and 82.35% top2 accuracy, which is close to the model tested in end-to-end performance experiment with long training time (average of 67.49% top1

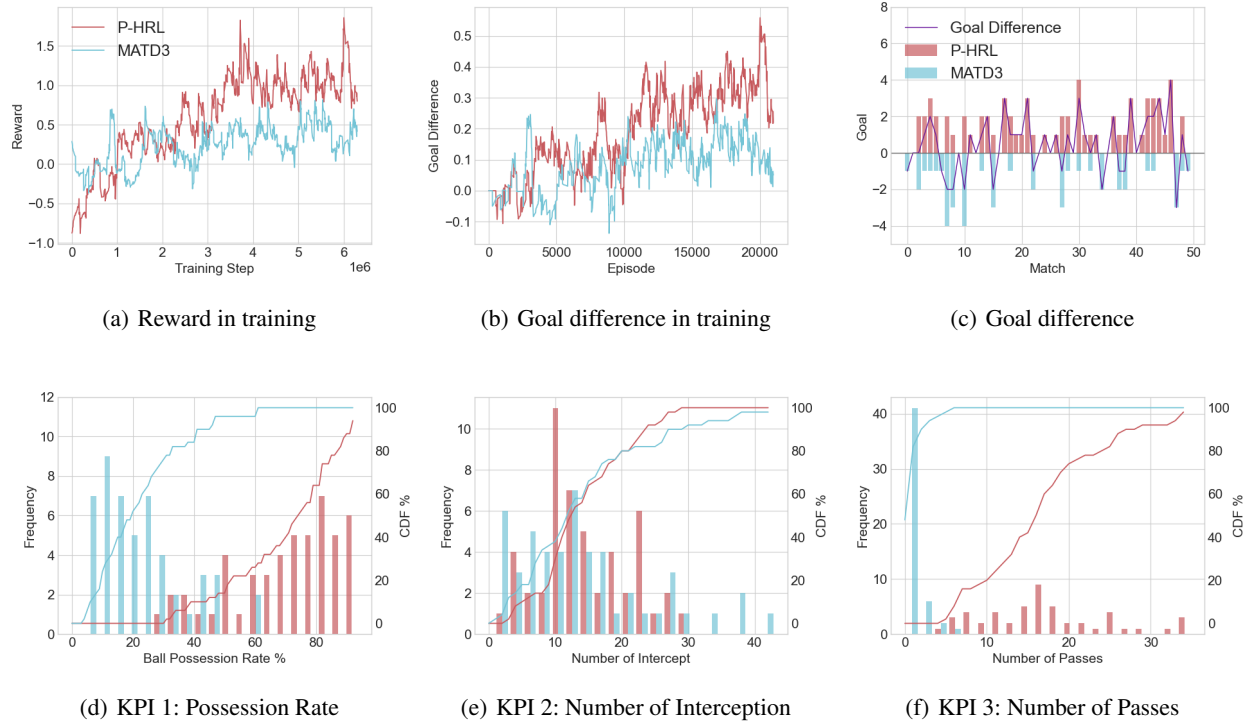


Figure 3: (a-b) Change of reward and goal difference with training. Smoothed by exponential moving average (EMA) with exponential smoothing constant  $K=0.95$ . (c) Results of P-HRL vs. MATD3 over 50 matches. The purple dash line represents the difference between the two (P-HRL minus MATD3). (d-f) Histogram shows the distribution of the average KPI per match; the dash line is the cumulative distribution function (CDF).

accuracy and 83.00% top2 accuracy over 50 matches). Figure 4(b), 4(c), 4(d) show that P-HRL has better overall performance than MATD3 in ball possession rate, the number of interceptions and the number of passes. P-HRL had an average of 73.18% possession, 13.16 interceptions and 14.32 passes per match; MATD3 had an average of 23.10% possession, 7.72 interceptions and 1.28 passes per match.

## Conclusion

## References

- Abreu, M.; Reis, L. P.; and Cardoso, H. L. 2019. Learning high-level robotic soccer strategies from scratch through reinforcement learning. In *2019 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*, 1–7. IEEE.
- Ackermann, J.; Gabler, V.; Osa, T.; and Sugiyama, M. 2019. Reducing overestimation bias in multi-agent domains using double centralized critics. *arXiv:1910.01465*.
- Akiyama, H.; Nakashima, T.; Fukushima, T.; Zhong, J.; Suzuki, Y.; and Ohori, A. 2018. Helios2018: Robocup 2018 soccer simulation 2D league champion. In *Robot World Cup*, 450–461. Springer.
- Antonioni, E.; Suriani, V.; Riccio, F.; and Nardi, D. 2021. Game strategies for physical robot soccer players: a survey. *IEEE Transactions on Games*, 13(4): 342–357.
- Bassani, H. F.; Delgado, R. A.; Junior, J. N. d. O. L.; Medeiros, H. R.; Braga, P. H.; Machado, M. G.; Santos, L. H.; and Tapp, A. 2020. A Framework for Studying Reinforcement Learning and Sim-to-Real in Robot Soccer. *arXiv preprint arXiv:2008.12624*.
- Berner, C.; Brockman, G.; Chan, B.; Cheung, V.; Debiak, P.; Dennison, C.; Farhi, D.; Fischer, Q.; Hashme, S.; Hesse, C.; et al. 2019. Dota 2 with large scale deep reinforcement learning. *arXiv:1912.06680*.
- Chen, Z.; Zhang, H.; Guo, D.; Jia, S.; Fang, X.; Huang, Z.; Wang, Y.; Hu, P.; Wen, L.; Chen, L.; et al. 2019. Champion team paper: Dynamic passing-shooting algorithm of the RoboCup soccer SSL 2019 champion. In *Robot World Cup*, 479–490. Springer.
- Cooksey, P.; and Veloso, M. 2017. Intra-robot replanning to enable team plan conditions. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 1113–1118. IEEE.
- de Medeiros, T. F.; Marcos, R. d. A.; and Yoneyama, T. 2020. Deep Reinforcement Learning Applied to IEEE Very Small Size Soccer Strategy. In *2020 Latin American Robotics Symposium (LARS), 2020 Brazilian Symposium on*



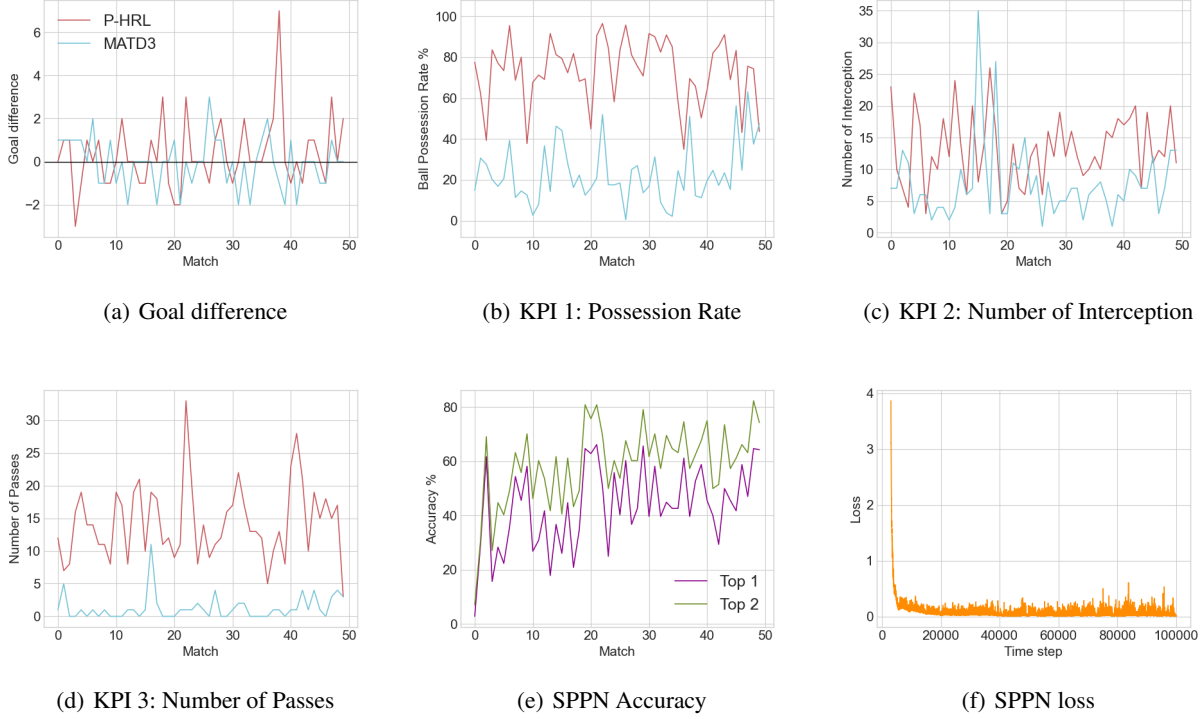


Figure 4: Results of P-HRL and MATD3 against MADDPG in 50 matches with learning. In (a-d), the red and blue lines represent the goal difference(P-HRL minus MADDPG, MATD3 minus MADDPG) and three KPIs of P-HRL and MATD3 against MADDPG over the number of matches. (e-f) show the prediction accuracy and loss of the SPPN module of P-HRL.

*Robotics (SBR) and 2020 Workshop on Robotics in Education (WRE)*, 1–6. IEEE.

Eigen, D.; Ranzato, M.; and Sutskever, I. 2013. Learning factored representations in a deep mixture of experts. arXiv:1312.4314.

Harutyunyan, A.; Dabney, W.; Mesnard, T.; Gheshlaghi Azar, M.; Piot, B.; Heess, N.; van Hasselt, H. P.; Wayne, G.; Singh, S.; Precup, D.; et al. 2019. Hindsight credit assignment. *Advances in neural information processing systems*, 32.

Lago, C.; and Martín, R. 2007. Determinants of possession of the ball in soccer. *Journal of sports sciences*, 25(9): 969–974.

Lago-Ballesteros, J.; and Lago-Peñas, C. 2010. Performance in team sports: Identifying the keys to success in soccer. *Journal of Human kinetics*, 25(1): 85–91.

Lowe, R.; Wu, Y. I.; Tamar, A.; Harb, J.; Pieter Abbeel, O.; and Mordatch, I. 2017. Multi-agent actor-critic for mixed cooperative-competitive environments. *Advances in neural information processing systems*, 30.

Macenski, S.; Martín, F.; White, R.; and Clavero, J. G. 2020. The marathon 2: A navigation system. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2718–2725. IEEE.

Martins, F. B.; Machado, M. G.; Bassani, H. F.; Braga, P. H.;

and Barros, E. S. 2022. rSoccer: A Framework for Studying Reinforcement Learning in Small and Very Small Size Robot Soccer. In *Robot World Cup*, 165–176. Springer.

Mnih, V.; Kavukcuoglu, K.; Silver, D.; Graves, A.; Antonoglou, I.; Wierstra, D.; and Riedmiller, M. 2013. Playing atari with deep reinforcement learning. arXiv:1312.5602.

Mordatch, I.; and Abbeel, P. 2018. Emergence of grounded compositional language in multi-agent populations. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 32.

Parziale, E. J.; and Yates, P. A. 2013. Keep the ball! The value of ball possession in soccer. *Reinvention: an International Journal of Undergraduate Research*, 6(1): 1–24.

Pateria, S.; Subagdja, B.; Tan, A.-h.; and Quek, C. 2021. Hierarchical reinforcement learning: A comprehensive survey. *ACM Computing Surveys (CSUR)*, 54(5): 1–35.

Perruquía, A.; Yu, W.; and Li, X. 2021. Multi-agent reinforcement learning for redundant robot control in task-space. *International Journal of Machine Learning and Cybernetics*, 12(1): 231–241.

Pinto, L.; Davidson, J.; Sukthankar, R.; and Gupta, A. 2017. Robust adversarial reinforcement learning. In *International Conference on Machine Learning*, 2817–2826. PMLR.



- Sutton, R. S.; and Barto, A. G. 2018. *Reinforcement learning: An introduction*. MIT press.
- Todorov, E.; Erez, T.; and Tassa, Y. 2012. Mujoco: A physics engine for model-based control. In *2012 IEEE/RSJ international conference on intelligent robots and systems*, 5026–5033. IEEE.
- Vezhnevets, A. S.; Osindero, S.; Schaul, T.; Heess, N.; Jaderberg, M.; Silver, D.; and Kavukcuoglu, K. 2017. Feudal networks for hierarchical reinforcement learning. In *International Conference on Machine Learning*, 3540–3549. PMLR.
- Vinyals, O.; Babuschkin, I.; Czarnecki, W. M.; Mathieu, M.; Dudzik, A.; Chung, J.; Choi, D. H.; Powell, R.; Ewalds, T.; Georgiev, P.; et al. 2019. Grandmaster level in StarCraft II using multi-agent reinforcement learning. *Nature*, 575(7782): 350–354.
- Vinyals, O.; Ewalds, T.; Bartunov, S.; Georgiev, P.; Vezhnevets, A. S.; Yeo, M.; Makhzani, A.; Küttler, H.; Agapiou, J.; Schrittwieser, J.; et al. 2017. Starcraft ii: A new challenge for reinforcement learning. arXiv:1708.04782.
- Wang, T.; Gupta, T.; Mahajan, A.; Peng, B.; Whiteson, S.; and Zhang, C. 2020. Rode: Learning roles to decompose multi-agent tasks. arXiv:2010.01523.
- Zhang, T.; Xu, H.; Wang, X.; Wu, Y.; Keutzer, K.; Gonzalez, J. E.; and Tian, Y. 2020. Multi-agent collaboration via reward attribution decomposition. arXiv:2010.08531.