Penalty Shoot-out Strategy for the RoboCup Standard Platform League

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***Abstract*—Penalty shoot-out is a 1v1 robot match in RoboCup Standard Platform League (SPL), where the performance of a single robot plays a significant role in the competition. In this paper, we design dedicated running strategies and special actions for the two robot roles in the penalty shoot-out on the open-source architecture of the international powerhouse B-human. For the striker, propose a two-stage penalty shot method, a high-speed ball kicking method, and a corresponding optimal shot angle. A forward stance method, a defensive anticipation algorithm, and a dive special action for the keeper are proposed. During the research process, data through repeated tests and experiments are collected using the NAO robot. The improved strategy version improved the goal-scoring rate by about 48.4%, and the defensive success rate increased to 93%.**

***Index Terms*—RoboCup, Penalty Shoot-out, Special Action**

I. Introduction

RoboCup is the highest level, largest, and most influential international robotics event with the most significant number of participants and has played an essential role in developing motion control and automation technologies for individual robots. The NAO humanoid robots are used uniformly in the RoboCup Standard Platform League (SPL), which has developed and used more than 5,000 units worldwide and in inter-university robotic soccer tournaments. In the matchup of teams of equal strength, the scores are very close in most cases because both teams have developed similar tools for robot game decision-making, motion, and computer vision. If the match ends in a tie, the winner of the match depends on a penalty shoot-out. The penalty shoot-out is suitable for multiple repetitive experiments to test performance improvement due to the fixed match scenario, short duration of a single game and single robot role. There are two main problems in the course of the penalty shoot-out match. One is the striker's missed touches problem on the ball before kicking. The other is the conflict between the keeper's defensive range and the reaction time left for the keeper. In the current academic research, a few papers study penalty shoot-outs, and many angles can be studied. Some scholars have proposed strategies for maximum goalie coverage and optimal striker kicking routes from goalie standing and striker kicking routes [1]. Some scholars also analyzed the range of high probability field goals from the perspective of goal zoning with a normal distribution model [2]. Some scholars have also proposed the theory of forwarding state transition for penalty kicks [3]. Some scholars propose to plan smooth motion trajectories in joint space with five times spline curves based on the dynamics model of the robot. [4]The above papers have a single research perspective, and there is still much room for improvement in each aspect. This paper further optimizes the strategy of the penalty kick battle based on a combination of the perspectives of strategy optimization in the above literature. This paper proposes an algorithm and dedicated action optimization scheme for striker's missed touches problem. Based on the forward-leaning stance method using the keeper, some methods are proposed to improve the defensive reaction speed of the keeper. Multiple SimRobot and real-world validation significantly reduce the striker's missed touches rate, improve goal scoring, and increase the keeper's defensive success rate.

II. Penalty shoot-out optimization

A. Rules

1) Field and Robots

In the standard platform group, all teams must use the NAO robot made by SoftBank Robotics and are not allowed to add or modify its robot hardware. As shown in Figure 1, the NAO robot has difficulty kicking curved balls or balls off the ground without modifying its feet, as the robot's front feet have a smooth curved shape, and the sides are perpendicular to the ground.

Fig. 1: The shape of NAO robot's feet

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2) Competition Process

In a penalty shoot-out, there is only one striker and one keeper. As shown in Figure 2, the referee places the ball, the striker, and the keeper. The referee places the ball on the penalty spot before the goal. Then places the striker 1 meter behind the penalty spot, facing the ball and the goal. And the keeper in the middle of the goal with his foot on the goal line. The striker must take the penalty kick within 30 seconds of the start of the penalty kick with only one shoot. The ball must shoot into the goal within 30 seconds for the goal and score. The keeper can only be in the penalty area or the goal during the penalty kick.

Fig. 2: Penalty shoot-out robot placement

B. Striker Strategy

Since the striker can only touch the ball once during the whole process and the ball locates at the penalty spot, the rules fix the place where the striker kicks the ball. Therefore, the striker must carefully choose the angle of the kick for each kick and avoid touching by mistake the ball due to walking. This paper proposes a two-stage penalty shot method, which excludes the image recognition error caused by the robot's vibration during the motion and solves the case of touch by mistake the ball before kicking.

1) Scanning to determine the best angle phase

In the first phase, the striker walks to a point 0.4m away from the ball and chooses the best angle to kick the ball. This phase is the scanning phase, where SecterWheel tools scan the keeper's stance and choose which side the ball should be kicked to by whether the keeper is off to the side. After the scanning angle is selected, an optimal angle for the penalty kick is proposed in this paper to determine the actual angle of the kick.

Currently, in the study of choosing the best angle of the penalty kick, there are scholars in a proposed kick path selection algorithm. However, this algorithm ignores the time difference between the keeper's torso side down the process to each shading position and only studies the fastest path from the ball to the goal line. A striker's high-speed kicking action proposed in section 3.1 of this paper, in which case of a significant lift, the time difference between the keeper's side fall acting as a cover for each position becomes more critical. As shown in Figure 3, the keeper takes the longest dumping time for the most marginal area to play a defensive role. This paper obtains an optimal angle of 28° for kicking after analyzing the successful data through several real-world games.

Fig. 3: The keeper's dive action

Based on the SectorWheel corner parity kicking strategy used in the traditional strategy, this paper proposes a SectorWheel penalty-kick-select-side tool for penalty kicks. While retaining the weighted sector selection of the SectorWheel tool, change the selection angle from the best sector angle parity to the side to which the penalty kick is selected. This paper proposes combining the SectorWheel penalty-kick-select-side tool with the optimal angle and deriving the kick angle. Selecting the best kick angle in the first stage avoids spending unnecessary judgment and calibration time in the second stage of the kick.

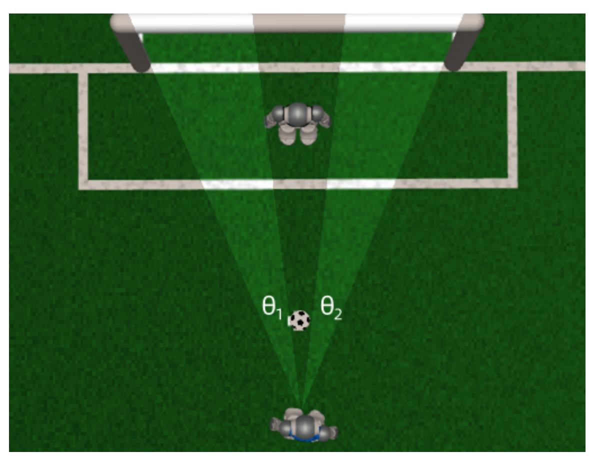

Fig. 4: Scan sector schematic

Algorithm 1: Selecting Angle for Shooting

Input :
The best angle for one side θ_b.

Output:
The best angle to shoot θ_s.

```
Initialize sector of left and right side as W1,W2.
Build one empty angly θs to store the return value
  and one empty sector obejct to record the sector
  blocked by the enemy.
Update object sector:object ← ObjectSector()
for each object ∈ W1 do
    W1 ← W1 − object
end
for each object ∈ W2 do
    W2 ← W2 − object
end
if W1 < W2 then
    θs ← object
else
    θs ← −object
end
return θs
```

2) Slow-speed moving kick phase

During the actual robot matches, many teams over-idealize the execution accuracy of the robot, resulting in the striker mistakenly touching the ball while moving towards it at high speed. This small error can cause a severe error during a penalty kick shoot-out. According to the rules, the striker can only touch the ball once. A missed touche by the striker can lead to a foul. Thus, the striker loses the chance to score. Currently, the academic community has no corresponding solutions for this phenomenon. To solve this problem, this paper gives a method to take a small span of high-frequency movement in the second phase. It eliminates the inertial error of high-speed movement. It makes the robot not take the problem of not being able to take the best angle selected in the previous stage because of the large movement span during the alignment process.

C. *keeper strategy*

1) Defensive range analysis

Since it is currently difficult for the NAO robot to kick curved balls or balls that fly off the ground, this paper only discusses the case of rolling close to the ground. Half of the goal width is 75cm, and the maximum range of the keeper's unilateral dive is 62.6cm. The difference between the two is 12.4cm which is larger than the diameter of the ball itself, 10cm. As shown in Figure 5, theoretically, there is a certain shooting angle that the keeper cannot defend. Therefore, many teams choose the shot's angle to be in the dead center of the goal. The keeper can adopt a forward-leaning position to eliminate the dead angle. As shown in Figure 6, if the goalkeeper moves forward more than Δd, the keeper can cover the entire goal. Δd has the following formula

$$\frac{L_{gate}}{H} = \frac{L_{protect}}{h} \tag{1}$$

$$\Delta d = H - h \tag{2}$$

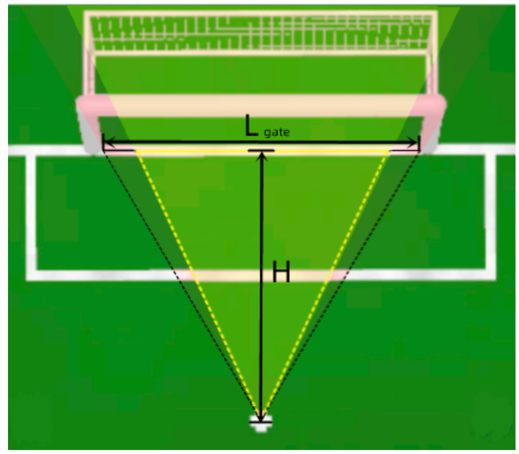

Fig. 5: Keeper's defensive range at the midpoint of the baseline

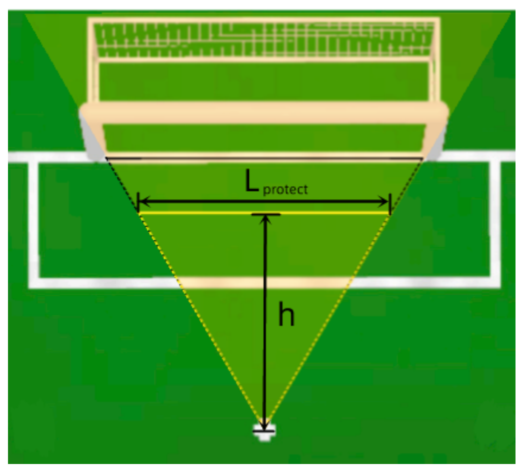

Fig. 6: Keeper's defensive range at forward standing place

2) Dive direction determination and speed enhancement

Adopting the strategy described above can extend the defensive range to the whole goal area, but there are still defensive failures in the actual experiment. There are two general reasons for the failure, but both are due to the reduced time left for the keeper to react due to the forward movement d. One is due to the misjudgment of the ball speed direction by the keeper, and the other is due to the shorter time left for the keeper to tackle the ball, resulting in the ball breaking through the keeper's defense before the keeper's arm is fully down. There is no academic solution to the failure of diving defense caused by this phenomenon. This paper will innovatively propose a solution that combines a weighted dive strategy algorithm with defensive special action optimization. A detailed description of special action optimization appears in section 3.2 of this paper, and this section only describes the weighted dive decision algorithm.

The traditional strategy determines the defense's direction by identifying the ball movement's y-axis velocity direction. Based on this, this paper comes out with an algorithm that predicts the direction of the kick by identifying the enemy striker's standing position. Since the maximum ball speed of the robot kick is generated by the striker kicking the ball forward, the ball kicked by the striker during the penalty shoot-out moves in a straight line.

The ball's velocity is used in traditional decision-making to determine the direction of the dive. By connecting the striker with the ball, it is possible to predict the ball's movement along this ray line, as shown in Figure 7. So the keeper can predict the ball's direction by analyzing the relationship between the coordinates of the striker and the ball. The weighted dive determination algorithm proposed in this paper can be obtained by combining this prediction angle with the ball movement direction. After the ball movement is detected, the dive operation takes place by the result of the algorithm. The specific algorithm is as follows:

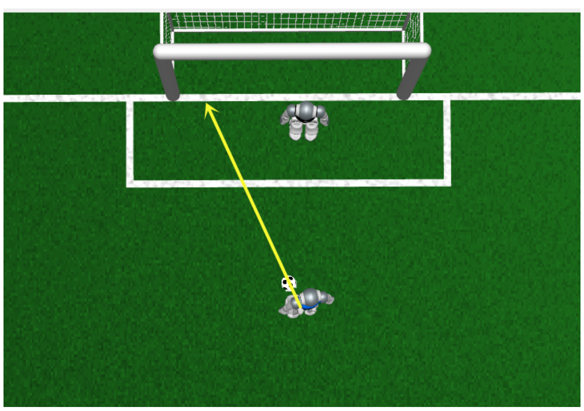

Fig. 7: Predicting the direction of the ball

This algorithm is the first in the field of penalty kicks that can play a pre-determining role before the striker kicks the ball. The algorithm not only solves the problem of incorrect dive direction due to unclear recognition of the y-axis velocity of the ball but also generates an initial tendency to dive in the direction of the ball before the striker kicks the ball through the prediction algorithm. Before diving, this required judgment time reduces the delay at the software level.

Algorithm 2: Selecting Side to Diving

Input :
The position of Ball P.
The weight of prediction algorithm Wei_p.
The weight of velocity angle Wei_v

Output:
Which side to prevent S.

Initialize sector of left and right side as W_1,W_2.
Build three empty angly θ_l,θ_r,θ_v,one empty sector $object$ to record the sector blocked by the enemy.
: Update object sector:$object \leftarrow$ ObjectSector()
for *each* $object \in W_1$ **do**
    $W_1 \leftarrow W_1 - object$
end
for *each* $object \in W_2$ **do**
    $W_2 \leftarrow W_2 - object$
end
Update left angle:$\theta_l \leftarrow angleinW_1$.
Update right angle:$\theta_r \leftarrow angleinW_2$.
if *ball is kicked* **then**
    $\theta_v \leftarrow Ball'sVelocityAngle()$
    if $\theta_v * Wei_v + (\theta_l - \theta_r) * Wei_p$ *¿ 0* **then**
        $S \leftarrow Left$
    else
        $S \leftarrow Right$
    end
    return S
end

III. Special action for kick and defensive moves

A. Striker's high-speed ball

In a penalty shoot-out, the speed and direction of the striker's kick are two critical indicators. In previous studies of penalty kicks, only optimize the direction of the kick. In this paper, a high-speed ball action improves the probability of the striker's goal by optimizing the kicking action. As shown in TABLE I, the high-speed ball action contains 5 phases. Each phase contains data such as duration, 3-D coordinate points of limbs, trajectory points of the head, and body center of gravity. The total duration of the 5 phases is 2500 ms.

Since the maximum ball speed of the present robot kick is generated by the striker kicking the ball forward, the ball kicked by the striker can approximate a rolling, uniformly decelerating linear motion with the following kinematic model.

I. Rolling linear motion model of approximately uniform deceleration:

$$\mathrm{a} = \mathrm{uV} \tag{3}$$

$$\mathrm{x_{stop}} - \mathrm{x_{ball}} = -\frac{\mathrm{V_{ball.x}}}{\mathrm{u}} + \frac{\mathrm{V_{ball\cdot x}}}{\mathrm{u}}\mathrm{e^{ut}} \tag{4}$$

TABLE I: Five phases of the high-speed ball action

Variate	Phase1	Phase2	Phase3	Phase4	Phase5
duration	850	300	100	400	850
leftFootTra1	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220
leftFootTra2	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220	x = 0; y = 65; z = -220	x = 0; y = 65; z = -230
leftFootRot1	x = 0.24; y = 0; z = 0	x = 0.3; y = 0; z = 0	x = 0.3; y = 0; z = 0	x = 0.3; y = 0; z = 0	x = 0; y = 0; z = 0
leftFootRot2	x = 0.24; y = 0; z = 0	x = 0.3; y = 0; z = 0	x = 0.3; y = 0; z = 0	x = 0.3; y = 0; z = 0	x = 0; y = 0; z = 0
rightFootTra1	x = 0; y = -50; z = -235	x = -82; y = -50; z = -141	x = 80; y = -50; z = -200	x = 40; y = -120; z = -220	x = 0; y = -65; z = -230
rightFootTra2	x = 0; y = -50; z = -235	x = -69; y = -50; z = -141	x = 80; y = -50; z = -200	x = 0; y = -80; z = -220	x = 0; y = -65; z = -230
rightFootRot1	x = -0; y = 0; z = -0	x = 0.1; y = 0; z = -0	x = 0.1; y = 0; z = -0	x = 0.1; y = 0; z = -0	x = 0; y = 0; z = -0
rightFootRot2	x = -0; y = 0; z = -0	x = 0.1; y = 0; z = -0	x = 0.1; y = 0; z = -0	x = 0.1; y = 0; z = -0	x = 0; y = 0; z = -0
leftArmTra1	x = 0; y = 140; z = 80	x = -39; y = 180; z = 80	x = 120; y = 190; z = 80	x = -30; y = 160; z = 80	x = -30; y = 120; z = 80
leftArmTra2	x = 0; y = 140; z = 80	x = -80; y = 180; z = 80	x = 120; y = 190; z = 80	x = -30; y = 160; z = 80	x = 0; y = 120; z = 80
leftHandRot1	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0
leftHandRot2	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0	x = -1.6; y = 0; z = 0
rightArmTra1	x = 0; y = -140; z = 80	x = 55; y = -120; z = 80	x = -50; y = -145; z = 80	x = -50; y = -145; z = 80	x = -50; y = -120; z = 80
rightArmTra2	x = 0; y = -140; z = 80	x = 100; y = -140; z = 80	x = -50; y = -145; z = 80	x = -50; y = -145; z = 80	x = 0; y = -120; z = 80
rightHandRot1	x = 1.6; y = 0; z = 0	x = 1.6; y = 0; z = 0	x = 1.6; y = 0; z = 0	x = 1.6; y = 1; z = 1.57	x = 1.6; y = 1; z = 1.57
rightHandRot2	x = 1.6; y = 0; z = 0	x = 1.6; y = 0; z = 0	x = 1.6; y = 0; z = 0	x = 1.6; y = 1; z = 1.57	x = 1.6; y = 0; z = 0
comTra1	x = 10; y = 10	x = 10; y = 14	x = 5; y = 14	x = 5; y = 14	x = 10; y = 14
comTra2	x = 10; y = 10	x = 10; y = 14	x = 5; y = 14	x = 10; y = 14	x = 10; y = 14
headTra1	x = 0.2; y = -0.3	x = 0.2; y = -0.3	x = 0.2; y = -0.3	x = 0.1; y = -0.15	x = 0; y = 0
headTra2	x = 0.2; y = -0.3	x = 0.2; y = -0.3	x = 0.2; y = -0.3	x = 0; y = 0	x = 0; y = 0
odometryOffset	x = 0; y = 0; z = 0	x = 0; y = 0; z = 0	x = 0; y = 0; z = 0	x = 0; y = 0; z = 0	x = 0; y = 0; z = 0

After actual combat to obtain data, multiple measurements of the ball kicked out of the distance respectively: traditional action kicked out of the distance of about 4.6m, high-speed ball kicked out of the distance of about 7.1m. Kinematic equations show that the ball's initial velocity has increased by about 24

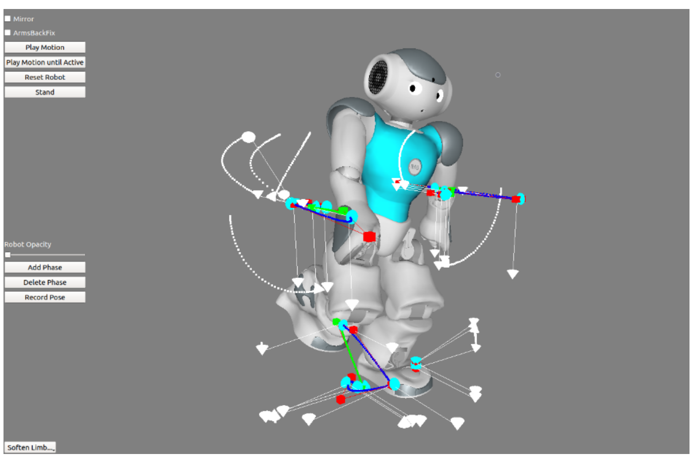

Fig. 8: 3-D view of high speed ball

B. Special defensive actions of keeper

In the b-human motion control system, there are seven executable actions. In addition to some common vital actions such as robot's walking, standing, and kicking, some static actions with small body amplitude, which achieve by interpolating between predefined joint positions, are called special action. The goalkeeper's action quality determines whether the keeper can successfully keep the ball out of the goal in the penalty shoot-out. The following is the analysis of the preparation and pouncing phase for the penalty shoot-out. After the pre-set action, the goalkeeper defends by analyzing the information of the incoming ball and choosing one of the two special actions of lunging to the left and lunging to the right. The special actions of the two phases are connected to achieve a fast and stable left and right dive, which showed excellent results in the game verification.

Preliminary phase: As in Figure 9, this phase contains three keyframes for 2000 ms. In 500 ms, a squatting motion lowers the center of gravity; in 1500 ms, the hands are opened and raised flat, and then the motion is maintained in the second keyframe. Prepare for the left and right dive to shorten the reaction time of the action.

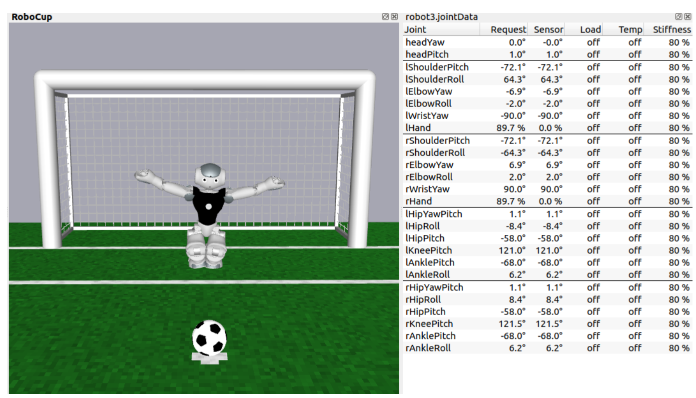

Fig. 9: Special movements in the preparatory phase

Leftward dive action phase: this phase contains one keyframe for 700 ms. As shown in Figure 10, in 700 ms, the robot shifts its center of gravity to the left through the downward movement of the right leg so that the robot falls left quickly. It maintains the left arm and retracts the right arm based on the upward movement of the arms in preparation for the penalty shoot-out so that the stance at the moment of landing can achieve the maximum interval width. This paper optimized left dive action has a wide dive range and fast reaction time, significantly improving the keeper's defensive effectiveness. The following is implementing the special action of pouncing the ball to the left. Due to the mirror symmetry of the left and right pounces, this paper does not analyze the right pounces here.

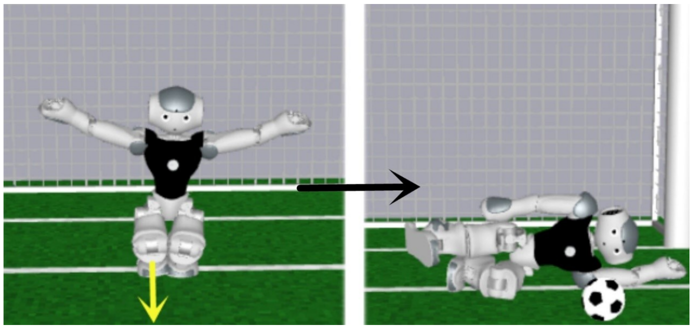

Fig. 10: Conversion of leftward pouncing action

IV. Real-world repeatability check

The project's modified version used the entire penalty shoot-out code decision and special action optimization. After testing the traditional striker-traditional keeper group, the modified striker-traditional keeper test group, and the traditional striker-improved keeper test group, every three groups performed 60 tests each. The following table counts the data of these 180 real-world tests.

TABLE II: Offensive optimization comparison

Group	Goal Success Rate	Mis-touch rate
Traditional	43.3%	93.3%
Modified Striker	91.7%	3.3%

TABLE III: Defensive optimization comparison

Group	Defensive Success Rate	Correct punt rate
Traditional	56.7%	95%
Modified Keeper	93%	96.6%

According to the data in TABLE II, the improved version of the striker improved the goal-scoring rate by about 48.4%. The rate of missed touches due to movement decreased to 3.3%. In TABLE III, it can reduce that the defensive success rate increased to 93%, and the punt errors caused by adopting the forward stance method decreased to a similar level as in the traditional group.

Conclusion

This paper gives a series of algorithm optimization and action optimization for defensive decision-making. Compared with the traditional defence strategy, the defence algorithm optimization in this paper has significantly improved the defence effect. The role conversion algorithm breaks the inherent identity of the robot so that each role can be converted to the most suitable robot, significantly reducing the robot's running time. The role defence algorithm of defender and keeper puts forward corresponding solutions to various situations, which hinders the opponent's goal in the path and can clear the ball out of the dangerous area in time. In this paper, the keeper's defensive action optimization increases the defensive range of the keeper's pounce and improves the rising speed of the keeper's sitting action. The defensive decision-making system optimized in this paper shows more flexible teamwork, more effective defensive decision-making and better defensive actions. In the SimRobot simulation, the probability of successful enemy shooting is significantly reduced. The defensive decision-making system proposed in this paper performed well compared with other teams in the competition and achieved third place in the country in Robocup China. Even if good results have been achieved in practical application, the defensive decision-making proposed in this paper still has a direction that can be further improved. The following aspects are presented for subsequent research to improve.

1. The role change will affect the original defensive layout of the defender and may cause a defender in the ideal defensive position to switch to a striker to compete for the ball. In future articles, the role conversion algorithm can be optimized to make the occurrence of role conversion more conducive to team defence.

2. Although the keeper and defender play a good role in blocking the shooting football, there is no cooperation based on each other's position. In the following article optimization, the keeper can shift to the position that needs to be blocked more through the blocking effect of the defender, or the defender can adjust the defender's position through the keeper's defensive dead corner.

3. Defensive action can only prevent the ball from rolling against the ground, not the ball shooting above the goal. Although no upward-angled kicking action has been developed, the defensive action is temporarily useless in RoboCup matches. However, based on RoboCup's ultimate goal: to realize the football match between robots and humans, keeper jumping defence is still a difficult problem on the way forward.

Acknowledgment

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