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Omni-directional Walking Gait and Path Planning for Biped Humanoid Robot

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Abstract: Omni-directional walking is a humanoid, flexible and efficient walking way for biped humanoid robot. A method based on motion decomposition, inverse kinematics, key-frame and cubic spline interpolation is proposed to realize Omni-directional gait and walking planning. The Omni-directional gait can be seen as an integration of the three independent movements, so each movement can be planned separately. It significantly reduces the complexity of implementation, as well increases the accuracy of gait. Base on the implementation of omni-directional gait, reinforcement learning is used to optimize the walking path while tracking dynamic target in order to be more stable and efficient. Experiment shows the method is valid and efficient.

Key words: Biped humanoid robots, omni-directional walking gaits, path planning, inverse kinematics, reinforcement learning

INTRODUCTION

Omni-directional movement of is a concept which the object can move in any direction in real time, it has been applied in the wheeled robot with many Omni-direction wheels firstly and provide superior maneuvering capability in dynamic environments and in restricted spaces. Because of the advantage to move into any direction, irrespective of the orientation of the vehicle and to control the rotational speed at the same time, it has been applied in many fields, such as in robotic soccer. Since, Omni-directional drives have been introduced in 2000 by Alur *et al*. (2005) in the Robo cup small size league, most teams in the wheeled leagues has adopted this approach. It is much easier to move to the allocated position, so the robot can control and kick the ball quickly. Omni-directional movement is not restricted to wheeled robot, for example, Pleite *et al*. (2000) described an approach to implement body and leg coordination of a hexapod robot for Omni-directional walking in rough terrain. Omni-directional movement is also generally used in the RoboCup Four-legged League by Fujita (2003). The Omni-direction gait is named of Omni-direction movement for biped humanoid robot. There are several approaches to implement Omni-directional gait of biped humanoid robot. For example, Xu and Tan (2007) proposed the layered Omni-directional walking gait controller for the humanoid soccer robot, but it cannot realize the adjustable walking speed. Tang and Er (2007) proposed an approach for online trajectory generation that produces fully parameterizable Omni-directional walking gait for biped robots, Chang *et al*. (2009) gave the method to realize the 3D walking gait generation based on inverted pendulum model for humanoid robot, the two above method can not turn body frequently in real time.

A novel Omni-directional walking gait for the biped robot is proposed in this study, the complex Omni-directional walking can be decomposed into three independent movements, so the walking planning became easy, but not reduce the accuracy of planning. Then reinforcement learning is used to optimize the parameter of gait and realize biped humanoid path planning. So, it can get the walking gait more quickly and steadily.

PLANNING OMNI-DIRECTION WALKING GAIT

In this study, the robot stands in the world coordinate system can be described in Fig. 1. The x-axis corresponds to the anterior axis, y-axis to the lateral axis and z-axis to the vertical axis. The frontal plane is defined by the lateral and vertical axis and the sagittal plane is defined by the anterior and vertical axis.

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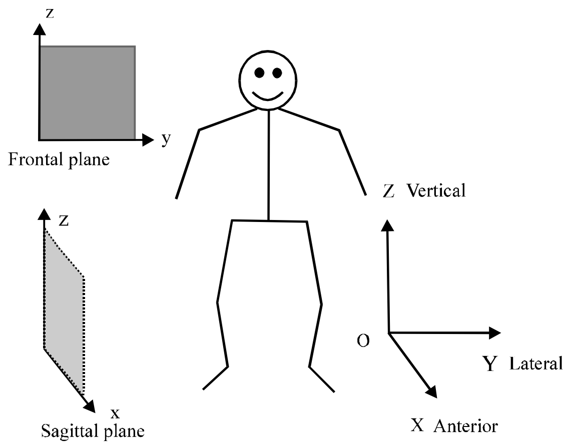

Fig. 1: Posture of the robot model in the 3D coordinate system

The Omni-direction walking gait means that the biped humanoid robot can move in both frontal plane and sagittal plane and turn body synchronously. By analyses characteristic of the human's movement, Chang *et al*. (2009) proposed the humanoid robot walking gait can be decomposed into the movements in the sagittal plane, the frontal plane and body turning. Then plan the movement in three movements, finally integrate the three movements into a walking gait.

Huang *et al*. (2001) proposed the Omni-direction walking gait of humanoid is also a periodic phenomenon. It alternates between the single-support phase and the double-support phase. The walking process of biped humanoid robot can be seen as repeating the both two phases. During the single-support phase, while one foot is stationary on the ground, the other foot swings from the rear to the front. During the double-support phase, both feet are in contact with the ground. This phase begins with the heel of the forward foot touching the ground and ends with the toe of the rear foot leaving the ground.

In the humanoid walking, every joint of biped humanoid robot should drive its steering to rotate a certain angle. It is too complex to plan trajectories for every joint of biped robot. But we only need to specify trajectories for hip and feet and all the other joint trajectories will be determined by robot 3D inverse kinematic constraints. The walking gait can therefore be denoted uniquely by both foot trajectory and the hip trajectory.

In each step of humanoid walking, every trajectory for every joint should be continuous and sequential, so we can steady posture. The number of trajectories is very huge and the key trajectories should be founded. The

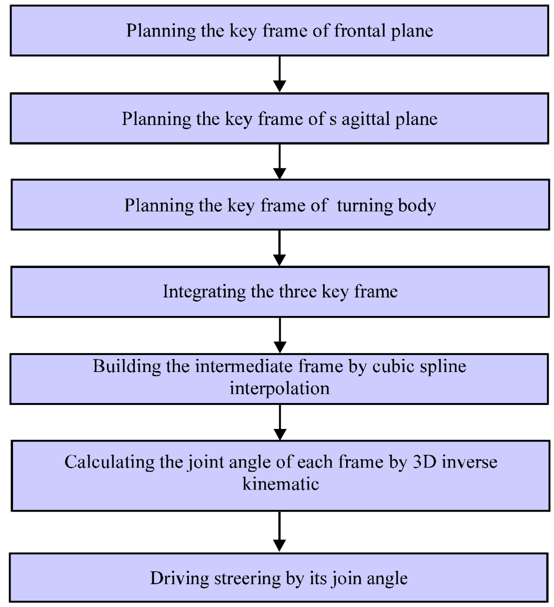

Fig. 2: Implementation steps for Omni-directional walking

key-frames have been introduced by Mellmann and Xu (2010). The key-frames of trajectories usually are corresponding to the key motions, which indicate the characterized posture. For example, the top point posture of humanoid raise its foot is the key motion. Though the key frame can't describe all details of humanoid robot walking gait, but it is very useful and we can get a total walking gait by linking lots key frames and inserting some intermediate frames. Intermediate frames are represented by a differentiable function about time t, so we can ensure the smooth transition between each frame. To get intermediate frame, interpolation method is used usually.

Bica (2012) proposed cubic spline interpolation can well fit the target function when the number of known data points is less and it approximates the real value by increasing the numbers of known data points. Cubic spline interpolation is used to build the intermediate frame. In this study, The key frame is designed as a function about time t and we set the interpolation conditions as $<(t_1, keyframe_1), (t_2, keyframe_2), ..., (t_n, keyframe_n)>$, then, get the differentiable interpolation function get frame (t), so the intermediate frame can be got.

The humanoid walking gait algorithm can be described as Fig. 2.

Walking planning in sagittal plane: The parameter of humanoid robot is showed in Fig. 3 and 4. Parameter l_{tr}, l_{th} and l_{sh} are the length of body, thigh and stank. A rod

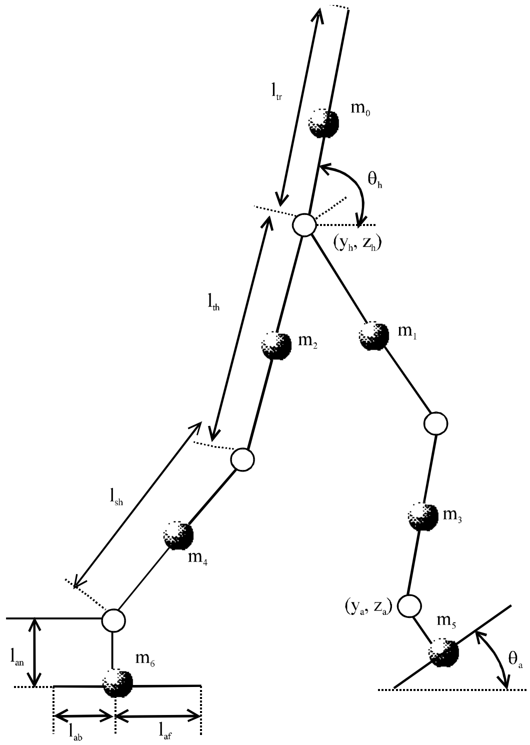

Fig. 3: Parameter names of each steering gears of humanoid robot

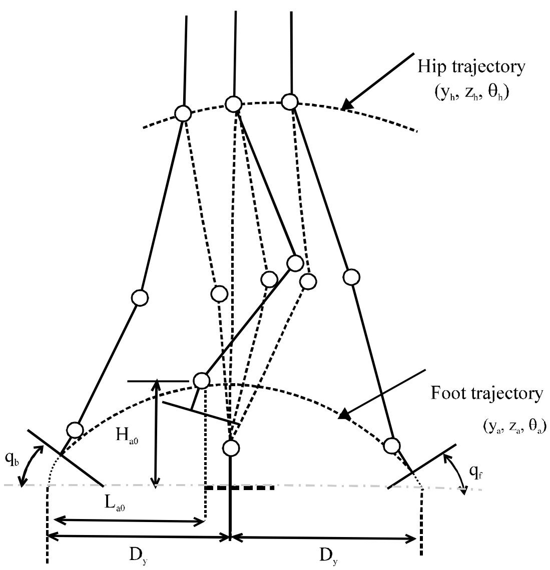

Fig. 4: Walking parameters of each walk step of humanoid robot

connects ankle and sole and the parameter l_{an} is the length of the rod. The parameter l_{ab} is length of the heel to the joint between the rod and foot. The parameter l_{af} is length of the tiptoe to the joint between the rod and sole. Set θ_h and θ_a are the angles of body and foot between ground. Let q_b and q_f be the designated angles of foot as it leaves and lands on the ground, respectively. When the swinging foot reaches its highest point, the ankle height is H_{a0} and L_{a0} is the horizontal displacement. The parameter D_y is the distance of a walking step.

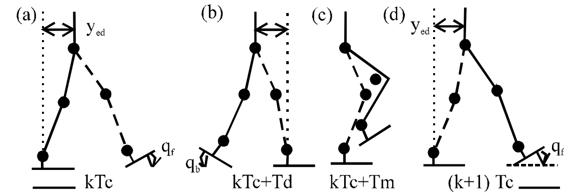

Fig. 5: Walking cycle of walking forward

Assuming that the period necessary for one walking step is T_c, the time of the kth step is from kT_c to $(k+1)\ T_c$, k is the number of steps. We define the kth walking step to begin with the heel of the right foot leaving the ground at $t = kT_c$ and to end with the heel of the right foot making first contact with the ground at $t = (k+1)\ T_c$. Td is the interval of the double-support phase. kT_c+T_m corresponds to the point when the swinging foot reaches its highest point. y_{sd} and y_{ed} denote the distances along t horizontal from the hip to the ankle of the support foot at the start and end of the single-support phase, respectively which is described in the study (Mitchell, 1997). Figure 5 gives the four frames of a walking cycle in sagittal plane. So, we only need plan the parameters of body and ankle joint in the time of kT_c, kT_c+T_m, kT_c+T_m and $(k+1)T_c$, then, get the other parameters of body and ankle of intermediate frames by using cubic spline interpolation.

Walking planning in frontal plane: Relative to walking in sagittal plane, robot needs two steps to finish the motion in frontal plane. So, the time for a cycle is 2^*T_c. First step is to stretch out one leg and touch the ground. In second step, the other leg should keep up with the first leg. The time for each step is 2^*T_c.

Figure 6 shows walking to the right side. Assuming the robot need D_x displacement in right side. The first step is from time kT_c to $(k+1)T_c$. After first step is finished the left leg becomes the support leg. The right leg only touches the ground. Center of gravity (COG) of robot locates at the left leg. And from time $(k+1)T_c$ to $(k+1)T_c+T_d$ COG moves from left leg to the right leg. At time $(k+2)T_c$, displacements in y-axis of legs and feet are zero. COG moves to the center of two feet. Assuming the displacement for a cycle is Y_m. Parameter Y_s and Y_d are the displacement of hip at time $(k+1)T_c$ and $(k+1)T_c+T_d$ when both the speed and acceleration of hip are zero,

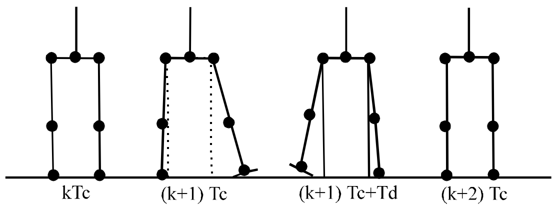

Fig. 6: Walking cycle of walking right side

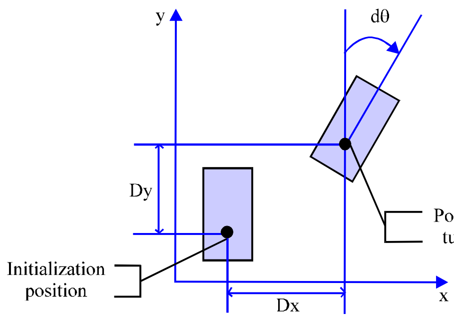

Fig. 7: Turning body while walking

respectively. At time $(k+2)T_c$ the motion of hip in a walking step is finished, so the displacement reaches Y_m. The position of left foot has not changed before $t = (k+1)T_c+T_d$. And the right foot has not moved since t = k*Tc. Ys and Yd are much important to the stability of motion. And they are always related to each other and Y_m. Y_m should be limited to an optimized value. The optimized value of them can be summarized through simulation experiments.

Planning turning body: The humanoid robot can turn the body while walking. Not only the legs should move, but also the feet should rotate. The swinging foot in z-axis should be rotated during single support phase after the foot reaches the highest point. When a foot is on the ground and center of gravity is on the foot, it can not implement the rotation and the robot will rotate the opposite direction if it rotates the ankle and the robot is also stay where it is. Fig. 7 shows the right process of turning body.

In the single support phase, the moving leg can swing freely, so the planning of turning body is designed. At the time $t = kT_c+T_m$, which the swinging foot reaches the highest point in z-axis, then the robot start to rotate the swinging foot around z-axis. And at the time $t = (k+1)T_c$, both of robot feet are on the ground, so robot ends the rotation. For rotation of feet, Following constraints should be satisfied:

$$\theta_f(t) = \begin{cases} \theta_s & t = kT_c + T_m \\ \theta_e & t = (k+1)T_c \end{cases} \tag{1}$$

where, θ_s is the angle of foot which is rotated in z-axis when it is at the highest point. And θ_e is the angle when it touches the ground. It is not necessary to change the position of foot at this time. The two key frames of the start and end of rotation are selected, so the final function is a line by cubic spline interpolation. For getting the higher steady, the speed should be zero when it reaches the expected angle. That is to say, the following condition should be satisfed:

$$\begin{cases} \dot{\theta}(kT_c + T_m) = 0 \\ \dot{\theta}(kT_c + T_c) = 0 \end{cases} \tag{2}$$

Walking planning in sagittal plane and frontal plane will decide where the foot should be put. After rotating the foot, the angles of all the joints can be got through robot 3D inverse kinematics constraints by Behnke (2006).

METHODOLOGY

Three planning method: In gaits and walking path planning of humanoid robot, not only the robot should reach the target position, but also it should be the right posture. There are many routes in the gaits and walking path planning, so they need different gait parameter sequences. Robot steady and consumption time is different in such sequences and gait planning sequences should be optimized. In Fig. 8, there are three typical planning methods for gait and walking planning from position A to position B.

Planning method 1:
Figure 8(b) shows the process:

Step 1: Humanoid robot moves forward to position. During the walking process, it does not change its body direction. That is to say, the parameter dθ is always zero in the first planning phase

Step 2: Humanoid robot goes along right side to position B in the second planning phase and the parameter dθ is always zero yet

Step 3: Humanoid robot turns its body to the target posture at position B in the third phase. In the phase, the parameters of D_x and D_y are zero and parameter dθ is the change angles of each step/period

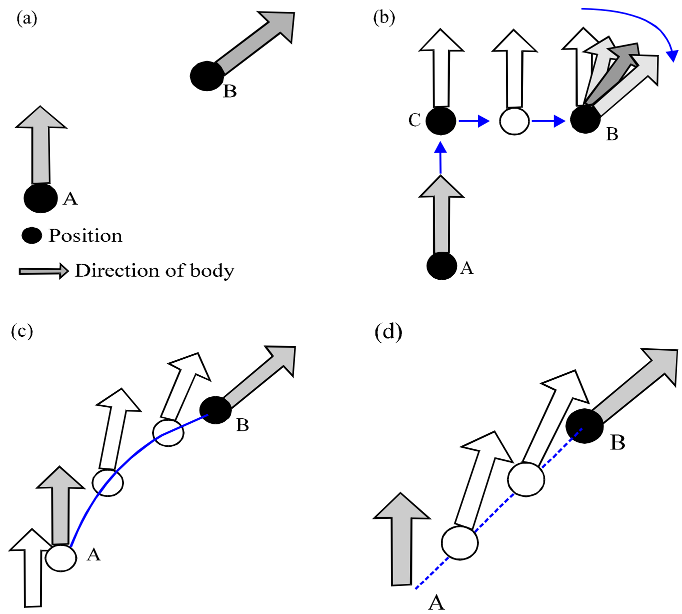

Fig. 8: Turn while walking: (a) Initial position and target position, (b) Planning method 1, (c) Planning method 2, (d) Planning method 3

Planning method 2: Figure 8 (c) shows the process:

Step 1: Construct an arc, which ensure the initial position and target position is on the arc and the tangential direction of which is the direction of robot in position A and position B

Step 2: Make the robot walk along the arc and ensure the direction of robot is the tangential direction of the arc. the next step of state can be got easily by the current state and target state of robot and it can be calculated by following formula:

$$\theta = a\tan\left(\frac{B.Pos.y - currentPos.y}{B.Pos.x - currentPos.x}\right) - B.Pos.\theta \quad (3)$$

$$x = B.Pos.x - \frac{\sqrt{(B.Pos.x - currentPos.x)^2 + (B.Pos.y - currentPos.y)^2}}{2*\cos\theta / \cos(B.Pos.\theta)} \quad (4)$$

$$y = B.Pos.y - \frac{\sqrt{(B.Pos.x - currentPos.x)^2 + (B.Pos.y - currentPos.y)^2}}{2*\cos\theta / \sin(B.Pos.\theta)} \quad (5)$$

θ is the direction of the robot and parameters of x and y are the position coordinate of the robot

Step 3: The state is the target state when the robot reaches position B

Planning method 3: Fig. 8 (d) shows the process:

Step 1: Make a line from position A and position B and the robot walk along the line

Step 2: Set the step parameters of D_x and D_y in each step

Step 3: Calculate the number n of total steps according to the step parameter. Then, calculate the direction change $d\theta$ of robot in each step by the direction difference of robot in each step. The calculation formula is as following:

$$n = \frac{(currentPos - B.Pos).length}{\sqrt{Dx^2 + Dy^2}} \quad (6)$$

$$d\theta = \frac{B.Pos.\theta - currentPos.\theta}{n} \quad (7)$$

Optimize method based on reinforcement learning: Reinforcement learning is an adaptive online learning style, which is used to get the optimized gait and walking planning route in one or more respects. The aim of reinforcement leaning is to learn the value $V^\pi(s_t)$ of $states_t$ in strategy π. t is the period of time and the state s_t represents the position and body angle of robot. The reward r of learning can be defined as following:

$$r_{t+i} = \begin{cases} \dfrac{balance}{t_i(t_{i+1} - t_i)} & \text{(in the state of walking process)} \\ 1 & \text{(in the target state)} \end{cases} \quad (8)$$

The parameter balance is the robot steady degree which can be observed by the robot sensor.

So, the $V^{\pi}(s_t)$ can be calculated:

$$V^{\pi}(s_t) = r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \ldots = \sum_{i=0} \gamma^i r_{t+i} \quad (9)$$

The parameter γ ($\gamma \in (0,1)$) is constant value, which determines proportion of the immediate reward and delay reward by Mitchell (1997). For the robot reach the target state by many transition periods, the immediate reward have no great significance, so γ is defined a constant close to 1. V^{π} can measure the performance of the current state by calculate the steady of gait and consumption of time.

The reward r_{t+i} is directly proportional about robot steady degree and inversely proportional to the consumption of time. The robot steady degree can be got by the angular rate gyroscope and pressure sensor equipped on the bottom of robot feet. The angular rate gyroscope can get the rotational velocity which rotates around its x-y-z axis based on its body coordinate system. The pressure sensor can get the resultant vector of all forces acted on the feet and also get the coordinate of the origin of resultant. The coordinate is the local coordinate based on the ankle and its axis and forward directions are the same as the body coordinates.

In this study, there are 50 simulation experiments in different initial and target states is trained for each planning method, the robot walk to the target position with different paths and step parameters and calculate their rewards, so we can get the optimal gait and walking planning with high steady and lower time consumption. The learning result is shown in Table 1. The planning methods always get the highest reward in each experiment. There are 49, 48 and 31 times succeed movements in the planning method 3, method 2 and method 1 separately in all 50 times. And the method 3 has the average consumption time with 6s which is the least. According the result, we can get the conclusion that the planning method 3 is the optimal gait and walking planning, it consider both the robot steady and walking time consumption.

Table 1: Comparison of the three planning method

	Planning method 1(π_1)	Planning method 2 (π2)	Planning method 3 (π3)
Reward	6.33	10.65	12.78
Success rate	00.62	0.96	0.98
Average time consumption (s)	15.08	7.06	6.09

The robot need change its action frequently and have low steady and long time to reach the target state in the planning method 1. Using planning method 2 and 3, the robot have high steady. The robot need move along a curved path in the method 2, so it spends more time than method 3. Usually, the planning method 3 is the best, which the experiment also proves. In fact, method 2 is very useful and it can avoid obstacles, when there is an obstacle between the initial and target points and the distance is far enough away.

SIMULATION AND EXPERIMENT

To verify the validation of above proposed gait and walking planning methods, we apply it to the RoboCup soccer simulation 3D and produce and optimize the walking gait to control the movement of simulation biped humanoid robot named Nao. The experiment platform is SimSpark.

The robot and ball are put in the soccer field randomly and then the robot need approach the ball and kick the ball to goal. It repeats the process of approach and kick until it is goal. Because the robot cannot control its suitable kick power in the Simpark platform, the ball only moves along the direction of the current movement direction of robot. The robot should face the goal when it has reached the position of ball, so the ball will move to the goal directly.

According to the position of robot and ball given by the Simpark platform, the kick movement track of robot can be got which is shown in Fig. 9. The power and direction of kick is random, so the track of ball is irregular. Robot need adjust its position and pose based on the ball position and reach the position which located on the extension line of goal center and ball and then it can kick the ball to the goal, so the target position is always a dynamic position, the omni-directional walking gait and path optimize method based on reinforcement

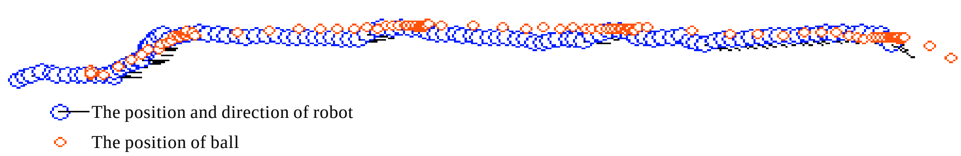

Fig. 9: The track of robot and ball

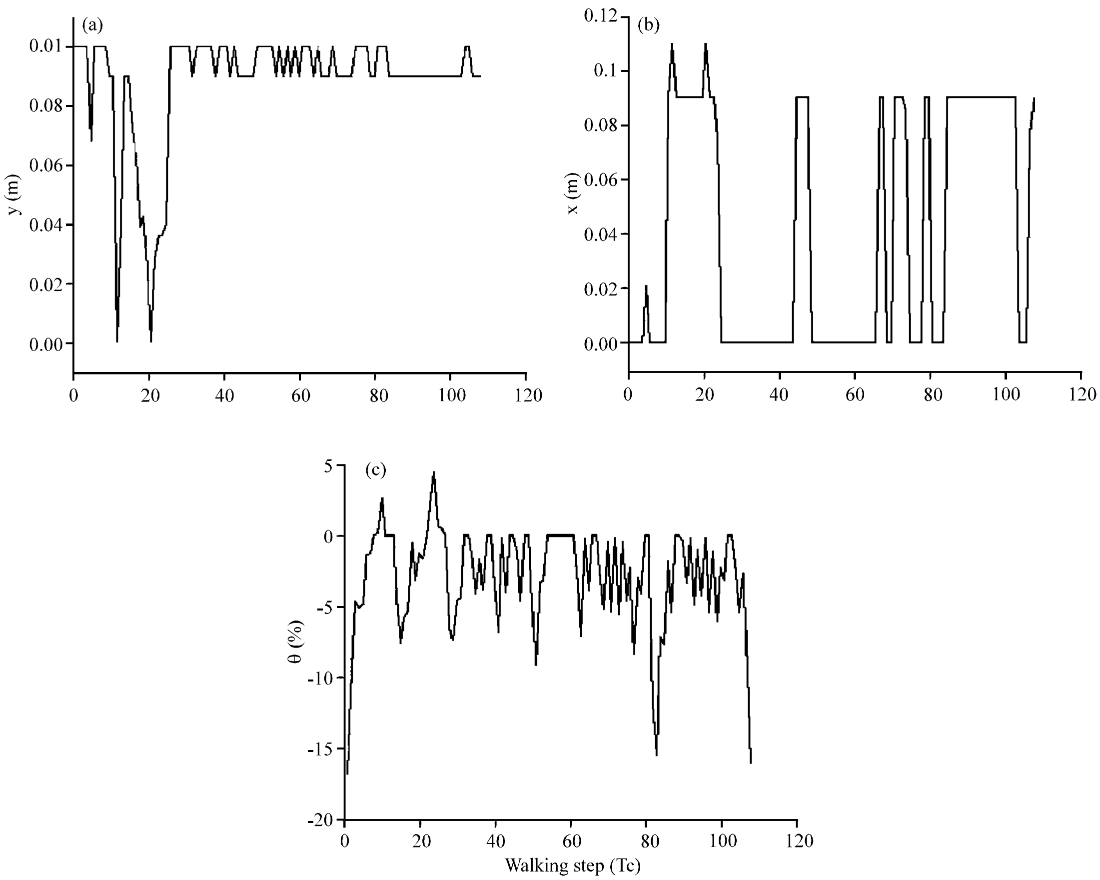

Fig. 10: Walking parameters of robot, (a) Displacement in y-axis, (b) Displacement in x-axis and (c) Turn angle 8

learning is applied in the approach and kick process. The robot is very flexible and steady from the track.

Figure 10 shows the gait walking parameter. The gait of robot is continuously varying, which is high flexible and adaptive and the robot is always move but not stop in real environment and adjust its walking gait according to the changing target position.

CONCLUSION

An omni-direction walking gait algorithm is proposed in this study. In the algorithm, the omin-direction walking gait is divided into three independent movements, which is analyzed and planned by inverse kinematics, key-frame and cubic spline interpolation separately, then the movements is integrated. Then reinforcement learning is applied to realize the optimized walking path planning. The robot can get high steady and low time consumption in approaching and kick ball. Experiment proves the feasibility of omni-direction walking gait and the effectiveness of walking path planning method based on reinforcement learning.

The road is usually rough and there are obstacles, to research omni-direction walking gait and walking path planning in such condition is urgent work in future. Three-dimensional linear inverted pendulum will be an important method to solve such problem.

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