Development of an Omnidirectional Kick for a NAO Humanoid Robot

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Abstract. This paper proposes a method to develop an omnidirectional kick behavior for a humanoid robot. The objective is to provide a humanoid with the ability to kick in different directions and to make kicks look more like those of a human player. This method uses a Path Planning module to create the trajectory that the foot must follow to propel the ball in the intended direction. Two additional modules are required when performing the movement: the Inverse Kinematics module computes the value of the joints to place the foot at a given position and the Stability module is responsible for the robot's stability. Simulation tests were performed using different ball positions, relative to the robot's orientation, and for various ball directions. The obtained results show the usefulness of the approach since the behavior performs accurately the intended motion and is able to kick the ball in all the desired directions.

Keywords: Robotics, Robotic Behaviors, Autonomous Agents, Human Behaviors, Robotic Soccer.

1 Introduction

Robotic soccer has been an area of constant evolution and of major driving for the development of Artificial Intelligence and Intelligent Robotics [1]. Being soccer a complex game where the environment is dynamic and in real time, it raises exciting challenges and covers a wide area of research, from which stands out research in robotics, physics, biology, electronics, computer science and mechanics. Fig. 1 shows two teams of robots playing a simulated soccer.

Fig. 1. Robots playing simulated 3d soccer.

This work is related to the development of a new human like behavior for a humanoid robot for Portuguese soccer team FC Portugal, to equip a robot with the ability to kick a ball in various directions. The need to create this behavior arises from the necessity to perform a kick or a pass without having a preparation phase (phase used to put the robot at a precise position to perform the old front/side kick), during which the ball can be intercepted by an opponent.

This behavior will be added to the list of all others previously developed in [2-3] and enable a team of robots (NAO robots from Aldebaran), real or virtual ones, capable of playing a soccer match at RoboCup 3D Simulation League and Standard Platform League, using similar rules to real soccer, following the strategic framework previously developed in several related works [4-8].

Section 2 describes the implementation of the kick behavior as well as its constituent modules, section 3 contains the practical results and experiments on the behavior, and finally, section 4 gives the conclusions and presents some future work.

2 Omnidirectional Kick Development

2.1 Omnidirectional Kick

In general, kick behavior development is based on the use of keyframes for defining the trajectory of the foot. This method defines motion as a series of static values for the joints and then interpolates them sequentially to perform the movement. The main disadvantages of this approach are the inflexibility and the need of a preparation phase, in which the robot positions itself in order to kick the ball forward in the desired direction.

The idea of developing an omnidirectional kick is to make the kick more flexible and to kick the ball in any direction. To perform this, the robot has to compute the trajectory in real time and then make the foot follow this trajectory and propel the ball in the intended direction. If, during the movement, the ball position changes, the trajectory is updated and the foot movement adapts to this change, but only if the ball is still reachable by the foot.

The omnidirectional kick behavior consists mainly of three modules: Inverse Kinematics module, Path Planning module and Stability module. The Inverse Kinematics module is responsible for calculating the value of the joints of the leg that will perform the kick, the Path Planning module is responsible to compute a trajectory for the foot to propel a ball in some direction and the Stability module is responsible to stabilize the robot while performing the movement.

Fig. 2 shows some of the parameters required to develop the movement. A description of all used parameters can be seen in Table 1.

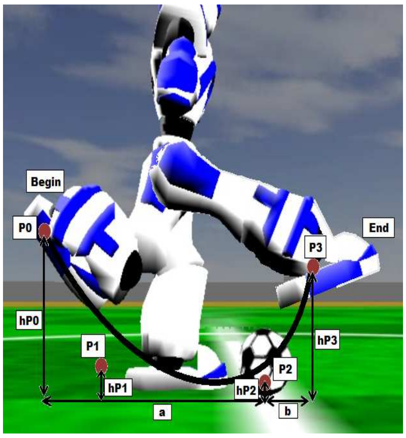

Fig. 2. Parameters used to create the movement.

Table 1. Parameters description.

Parameter	***Description***
a	Distance from ball to curve start
b	Distance from ball to curve end
hP0	Bézier cubic curve parameters (height coordinate only). Useful to shape the curve and try different kicks)
hP1	
hP2	
hP3	
Duration	Duration of the kicking phase (see Fig. 3)
footOrientation	Angle between foot orientation and vector Ball2Target. This parameter is important to kick with different sections of the foot, e.g. front, side (inner/outer) or heel.

The behavior is divided into a computational part, in which all the computations needed to perform the movement are made, and an execution part, in which the actual movement is performed. Execution part consists of five phases:

- **Lean_Phase –** This is when the robot shifts is center of mass onto support leg.
- **Raise_Phase –** Phase where the robot raises the kick foot off the ground.
- **Kick_Phase –** When the robot kicks the ball. This is the main phase.
- **Return_Phase –** Phase when the robots returns it's kick leg to the base position, without putting the foot on the ground.
- **UnRaise_Phase –** This is when the robot shifts is center of mass to both legs while putting the kick foot on the ground.

Fig. 3 shows the building blocks of the behavior as well as the connections between them, inputs, outputs and generated data.

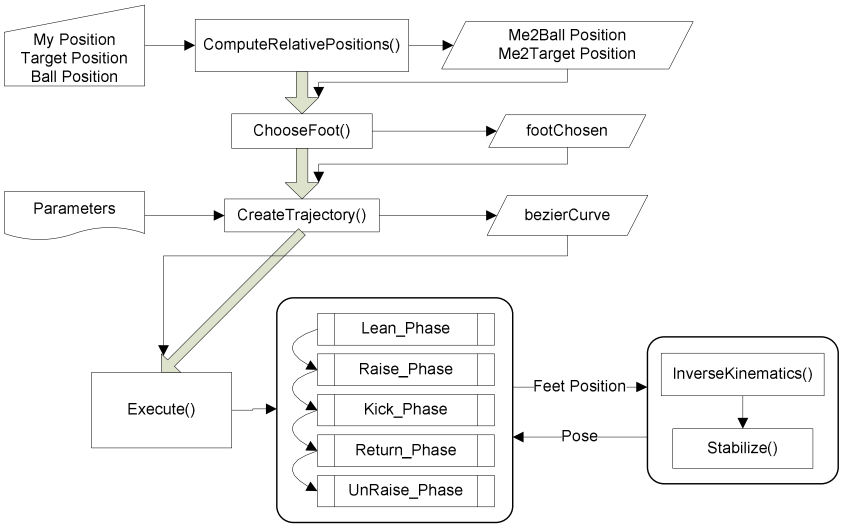

Fig. 3. Building blocks of the developed behavior.

2.2 Inverse Kinematics Module

The Inverse Kinematics problem is to determine the value of each joint in order to put a part of our object at a given location in space. Some mechanical characteristics associated with our object, such as the number of joints, joints rotation/translation limits, can make the calculation complex and often raise difficulties to obtain a unique solution [9]. In this study we used a method adapted from [10] in which the geometric approach method was used to determine each joint from the leg of the robot NAO. Two mechanical problems make the solving of Inverse Kinematics complicated:

- The axes of the hip yaw are rotated by 45 degrees;
- The hip yaw axes of each leg are mechanically connected.

The input data is a homogeneous transformation matrix that contains the position and orientation of the desired foot target relative to a frame located at the robot pelvis. This matrix is represented by H_{Foot}^{Pelvis} . Next we have to determine the foot relative to the hip rotated frame [6].

$$H_{Foot}^{HipRot} = Rot_x(\pi/4)\cdot Trans_y(l_{dist}/2)\cdot H_{Foot}^{Pelvis}\,{}^{1} \tag{1}$$

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[1] $Rot_K(v)$ and $Trans_K(v)$ represents rotation and translation of value v along axis K, respectively, and l_{legs} = distance between legs.

Assuming a triangle formed by the robot's thigh (lthigh) and lower leg (llowerleg), and the translational vector of $\mathrm{H}_{\mathrm{Foot}}^{\mathrm{HipRot}}$ (ltrans), and using law of cosines and atan2(), we can determine the value of the knee and ankle joints [6].

The pitch, roll and yaw of the hip are determined by simple manipulation of the elements of H_{HipRot}^{Thigh} as seen in (2).

$$\begin{aligned}\mathrm{H}_{\mathrm{HipRot}}^{\mathrm{Thigh}} &= \mathrm{Rot}_z(\theta_{\mathrm{hipYaw}}) \cdot \mathrm{Rot}_x(\theta_{\mathrm{hipRoll}}) \cdot \mathrm{Rot}_y(\theta_{\mathrm{hipPitch}}) \\ &= \begin{bmatrix} c_y c_z - s_x s_y s_z & -c_x s_z & c_z s_y + c_y s_x s_z \\ c_z s_x s_y + c_y s_z & c_x c_z & -c_y c_z s_x + s_y s_z \\ -c_x c_y & s_x & c_x c_y \end{bmatrix}^{2} \end{aligned} \tag{2}$$

and $\mathrm{H}_{\mathrm{HipRot}}^{\mathrm{Thigh}}$ can be determined using

$$\mathrm{H}_{\mathrm{HipRot}}^{\mathrm{Thigh}} = \left(\mathrm{H}_{\mathrm{Thigh}}^{\mathrm{Foot}}\right)^{-1} \cdot \left(\mathrm{H}_{\mathrm{Foot}}^{\mathrm{HipRot}}\right)^{-1} \tag{3}$$

$$\begin{aligned}\mathrm{H}_{\mathrm{Thigh}}^{\mathrm{Foot}} = {} & \mathrm{Rot}_x(\theta_{\mathrm{ankleRoll}}) \cdot \mathrm{Rot}_y(\theta_{\mathrm{anklePitch}}) \cdot \\ & \mathrm{Trans}_z(l_{\mathrm{lowerleg}}) \cdot \mathrm{Rot}_y(\theta_{\mathrm{knee}}) \cdot \mathrm{Trans}_z(l_{\mathrm{thigh}}) \end{aligned} \tag{4}$$

2.3 Path Planning Module

This module is responsible for creating a trajectory for the foot to follow in order to impose a motion to the ball in the desired direction. It makes use of Bézier curves [11] to determine a path between two points. These type of curves are defined as parametric curves and is easy to determine any point of the curve without using complex math (a simple equation gives the point). For our study we used a Bézier cubic curve (n=3) and the point can be determined using (5).

$$b(t) = \sum_{i=0}^{n} \binom{n}{i} \cdot t^i \cdot (1-t)^{n-1} \cdot p_i, \quad t \in [0,1] \tag{5}$$

2.4 Stability Module.

The Stability module uses the center of mass equation [12] to determine if the ground projection of the center of mass (GCoM) is actually inside the polygon of the support foot. If not, it enters in a cycle where it will open one arm (on the same side of the supporting foot) until GCoM is in the desired location. In the extreme case where the arm movement is not enough a change in the hip and ankle roll angles of the supporting foot is also made to tilt the robot to a stable position.

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[2] c_x, c_y, c_z represents cos($\theta_{\mathrm{hipRoll}}$), cos($\theta_{\mathrm{hipPitch}}$), cos(θ_{hipYaw}), respectively.

3 Experiments and Results

In this section we show the results of several experiments performed to verify analytically the success of this work. We start by testing each module individually and then test the whole behavior. The tests to each individual module are of great importance since the final behavior depends strongly of their success.

All points representing positions in the individual module tests are relative to a frame located at the robot pelvis (see Fig. 4).

Fig. 4. Reference frame.

3.1 Inverse Kinematics Module Tests

The main objective when testing this module is to verify its functionalities and limitations. It is necessary for it to operate with the minimum error possible because it is the base of the motion. A small error when computing the joints values makes the foot perform a wrong trajectory and propel the ball in the wrong direction. Table 2 shows the results of this test.

Table 2. Results of the Inverse Kinematics module tests.

Target (x, y, z) (mm)	Average (x, y, z) (mm)	Standard Deviation (x, y, z) (mm)	Average-Target (x, y, z) (mm)
(0, -55, -150)	(3, -56, -148)	(1, 1, 3)	(3, -1, 2)
(-100, -55, -100)	(-89, -60, -99)	(1, 1, 0)	(11, -5, 1)
(100, -55, -100)	(100, -55, -105)	(7, 1, 3)	(0, 0, -5)
(0, -100, -100)	(7, -104, -108)	(2, 3, 3)	(7, -4, -8)
(500, -55, -10)	(214, -54, -16)	(1, 1, 2)	(-286, 1, -6)

3.2 Path Planning Module Tests

The main purpose when testing this module is to verify its trajectories creation. It is also necessary for it to operate with the minimum error possible because if the trajectory is miscalculated we will get a wrong movement, resulting in a wrong ball motion.

Fig. 5 shows 3 curves (linear, quadratic and cubic) created and the ability of the foot to follow these curves.

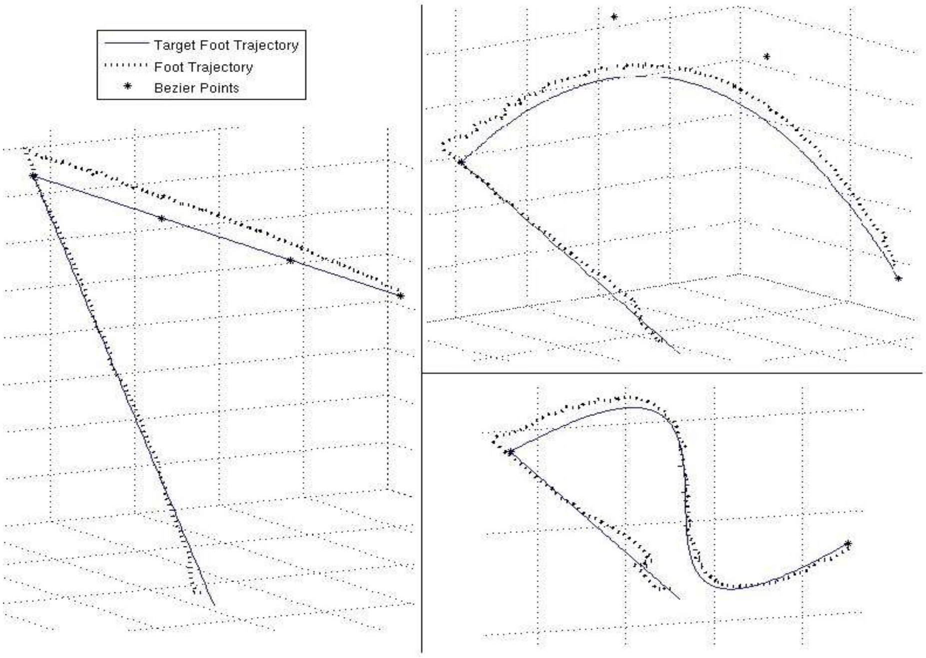

Fig. 5. Various curves created by Path Planning module and the trajectory executed by the foot.

3.3 Omnidirectional Kick Tests

For the tests of the complete behavior we will test for:

- 3 positions (#1, #2 and #3) of the ball relative to the robot orientation (see Fig. 6);
- 5 kick directions (-90, -45, 0, 45 and 90 degrees), when possible.

Fig. 6. Ball Positions for the tests. Left is 'Position #1', center ‘Position #2’ and right is 'Position #3'

For each direction we performed the movement 10 times and 10 samples of the final ball position. We proceeded to get the average and standard deviation of the 10 samples and in the end we determined the resulting direction. This data is shown in Table 3 and Fig. 7.

Table 3. Results from the performed tests.

		-90 **(x, y)**	**-45** **(x, y)**	**0** **(x, y)**	**45** **(x, y)**	**90** **(x, y)**
Pos. #1	**Average (mm)**	(24, -1009)	(719, -678)	(975, -2)	(701, 681)	(31, 962)
	Standard Deviation (mm)	(17, 38)	(37, 34)	(37, 22)	(23, 43)	(16, 45)
	Direction (º)	-88.60	-43.32	-0.15	44.18	88.12
Pos. #2	**Average (mm)**	(13, -989)	(758, -741)	(1082, 2)	(721, 676)	(31, 997)
	Standard Deviation (mm)	(7, 21)	(41, 40)	(44, 4)	(31, 40)	(26, 36)
	Direction (º)	-89.20	-44.37	0.12	43.15	88.19
Pos. #3	**Average (mm)**	(11, -991)	(693, -697)	(1053, -29)		
	Standard Deviation (mm)	(3, 23)	(22, 22)	(34, 18)		
	Direction (º)	-89.35	-45.15	-1.59		

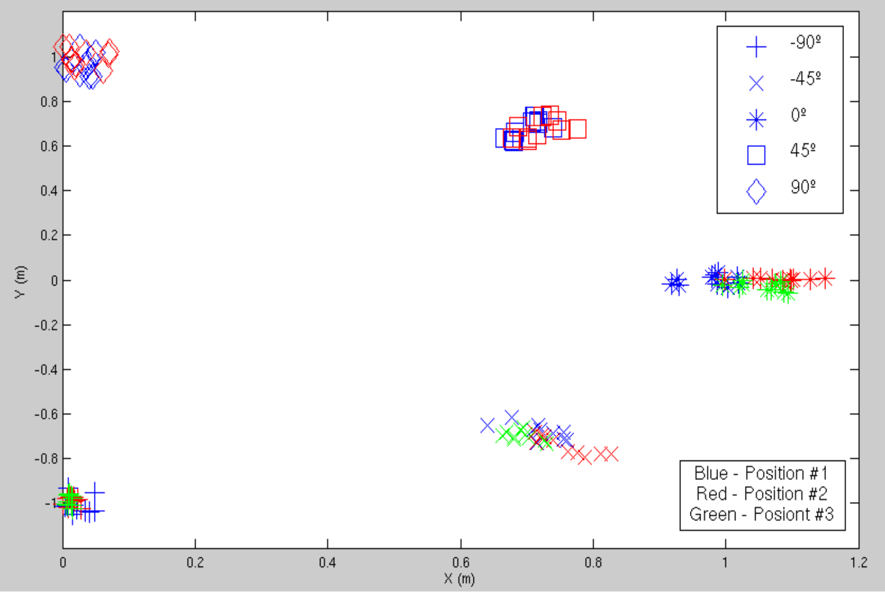

Fig. 7. Samples location for Positions #1, #2 and #3.

By examining the results obtained from this test we can see that the behavior can perform the movement and propel the ball in various directions. From the table we can see the average final position of the ball of the 10 samples as well as the standard deviation, and from the average we determined the direction. The determined direction value, of each direction, only differs a few degrees from the intended target direction, which confirms the accuracy propelling the ball. The accompanying graphic serves only to have a visualization of the ball's final position of the 10 samples for each target direction. The samples are grouped by target direction. The parameters used on these tests were hand tuned. We can control the kick power by adjusting both the kick duration and the initial and final position.

To test the sensibility of the kick against different positions of the ball, relative to the robot, another test was made. This test consists of kicking the ball with a desired direction, using always the same values for the parameters, and only changing the ball initial position.

The results obtained are shown in Fig. 8, where it is represented the distance and direction of the ball with a gradient value and the (x, y) coordinates refers to the ball's initial position relative to the kick foot.

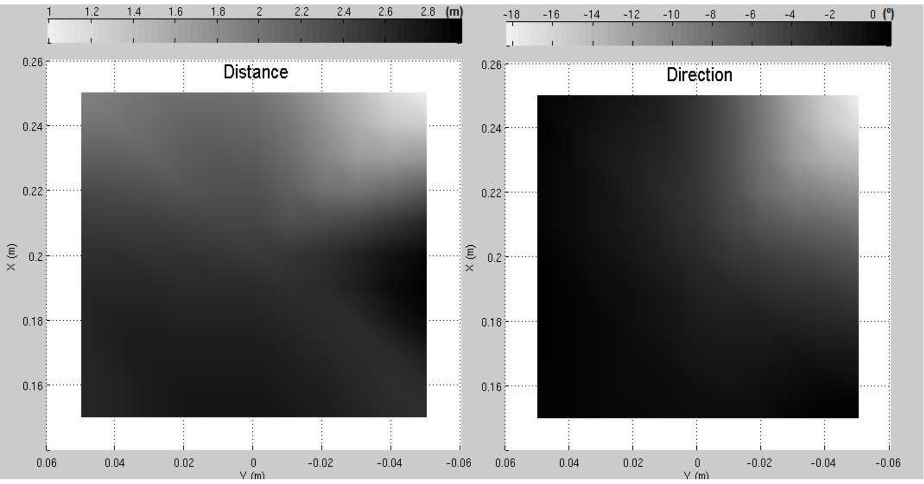

Fig. 8. Differences on the distance and direction due to different ball positions, for the same kick (forward kick, direction=0º).

The conclusion we take from these tests is that: if we configure the parameters of the behavior with some accuracy, we can get very good results. The problem is that, sometimes, it is not so easy to get the best parameters, becoming necessary the use of optimizers.

From Fig. 8 we can see that, if the ball is within a certain area relative to the kick foot, in almost 80% of that area it can kick the ball without losing accuracy.

4 Conclusions and Future Work

In this study we developed a behavior in order to provide a humanoid robot with the ability to perform an omnidirectional kick. The modularity of this behavior makes it perfect for future improvements or modifications.

The results obtained proved that the behavior performs accurately the desired motion. The Inverse Kinematics module, being the base of the behavior and with errors in the order of millimeters, is responsible for these satisfactory results. If it was not for the joints limitations it could reach any point within the working volume.

The Path Planning module proved to be very valuable when creating trajectories. With it, one can calculate any kind of trajectory easily, quickly and accurately.

Future work will be focused on improving the behavior, by optimizing it in order to perform faster and to drive the ball farther. This will be based on previous work developed on the area of machine learning and optimization applied to robotic soccer [13-16]. It will also be interesting to expand the behavior to perform heel kicks and to incorporate the kick in a walk/run motion.

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