

Flexible Movement Planning in Humanoid Soccer

Bruno Pimentel^{#1}, Nuno Lau^{#2}, Luís Paulo Reis^{*3}

[#]DETI/UA - Department of Electronics, Telecommunications and Informatics, University of Aveiro
 IEETA - Institute of Electronics and Telematics Engineering of Aveiro
 Campus Universitário de Santiago, Aveiro, Portugal

¹brunopimentel@ua.pt

²nunolau@ua.pt

^{*}DEI/FEUP - Department of Informatics Engineering, Faculty of Engineering of the University of Porto
 LIACC - Artificial Intelligence and Computer Science Laboratory of the University of Porto, Portugal

Rua Dr. Roberto Frias s/n, 4200 465 Porto, Portugal

³lpreis@fe.up.pt

Abstract— This paper presents a set of techniques for developing flexible skills for humanoid robots on the basis of movement planning with forward and inverse kinematics. The developed methods are especially applicable in the fields of humanoid robot soccer. The kicking motion has been considered the most important motion in robotic soccer. A flexible skill was developed for robust ball-kicking under a relatively wide range of conditions and thus overcoming the disadvantages of the commonly used predefined skills. A set of experimental simulations were carried out using fixed and random parameters in order to obtain evidence of the skill’s flexibility.

I. INTRODUCTION

The development of skills for humanoid robots has different fields of application. The RoboCup international event [1] contains several of such fields and probably the most popular one is robotic soccer. The simulation league comprises both 2D and 3D variants. While 2D competitions are particularly suitable to develop strategies and high-level coordination among team members, the 3D environment allows researchers to work on the challenges which a physical “world” poses to humanoid movement and stability.



Fig. 1 – Screenshot of the Simspark simulator with virtual NAO robots

RoboCup 3D competitions used the Simspark Simulation Environment [2][3], in which 2 teams of virtual NAO robots [4] compete against each other (see Fig. 1). Until RoboCup’2009 [5] held in Graz, Austria, each team was composed of 3 players, whereas in 2010 the number will double. The most relevant physical characteristics of all the 23 body parts and all the 22 joints (see Fig. 2, from [4]) of a real NAO are accurately modelled, allowing for a realistic simulation. Dynamic walking, running and kicking the ball while maintaining balance, self-localization, and team play are among the many research issues which can be investigated in this context, and the high level of realism renders results very useful for applications in real scenarios.

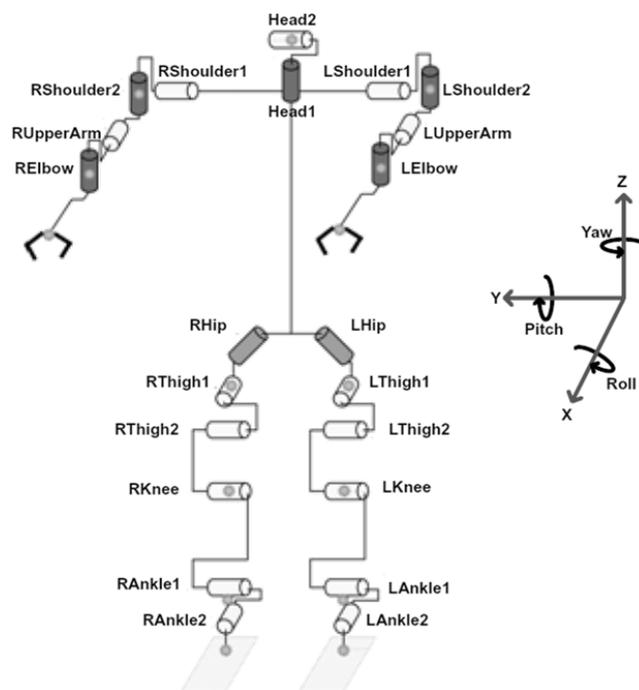


Fig. 2 – Map of joints of NAO, from [4]

In the context of humanoid skill development, bipedal walking has been receiving significant attention [6][7] due to not only its importance, but also its complexity. Walking gaits must often be adapted to the physical characteristics of the robot's body and those of the surface, but they can also differ when changing speed or direction. When factors like these are not taken into account, stability becomes an issue. Different generic strategies to address this particular issue have been put forth and some of the most popular are Centre of Mass (COM) [8], Zero Moment Point (ZMP) [9], and Centre of Pressure (COP) [10]. Although these strategies have appeared in the context of gait development, they can have application in the development of other humanoid skills.

II. DEVELOPING FLEXIBLE SKILLS

Many of the skills used by simulated and real humanoid robots are, to a very high extent, predefined. Using such skills, the ability to adapt to particular situations is bound to the decision of which sequences of skills to perform. The use of those predefined skills often poses very specific requirements. The latter must be previously satisfied by means of performing additional actions based on other predefined skills which, in turn, have their own set of requirements to be fulfilled. This fact often leads to excessive amounts of time to complete simple actions.

To overcome this limitation, it is important that the skills themselves are flexible, so as to be more accurate, to be applicable in a wide range of circumstances, and consequently to avoid unwanted delays. In robotics, passing from predefined skills to flexible ones can correspond to passing from forward kinematics to inverse kinematics. So, instead of forcing the robot joints to make predefined angles and let body part positions to be the result of those angles, one may first calculate the joint angles which will allow some body part to reach as close to a target position as possible, and then apply those angles.

Our approach to solve this optimization problem is based on a multi-stage search implemented using the hill climbing optimization algorithm. Because only some joints have influence on the position of each body part, the search can be based on a short kinematic chain which is composed of relevant joints only.

Let N be the number of relevant joints, and S_1, S_2, \dots, S_N the angles that must be determined so as to be assigned to those joints. On the other hand, let A_1, A_2, \dots, A_N be the angles that are actually applied to those joints when we perform the search. In each stage $C = 1, 2, \dots, N$, the value of angle S_C varies along its assignable range with short intervals. For each different value of S_C , we calculate the distance between the body part and the target using forward kinematics on the basis of the following joint angle values:

- S_1 to S_{C-1} , i.e., the joint angles already assigned in previous stages;
- the angle we are testing for the current joint;
- A_{C+1} to A_N , i.e., the angles currently applied to the joints whose assignments will be set in future stages.

At each stage the angle which leads to the smallest distance is assigned to the corresponding joint and this assignment (S_C) will be considered during all the following stages.

Let us consider the very simple 2D example of Fig. 3, in which angles for joints J_1 and J_2 must be found in order to make body part P reach as close to target T as possible. In the first stage of the search process, five different angles are tested for joint J_1 . In each of these tests, the distance between P and T is calculated considering the angle actually applied to J_2 . The thick line connecting J_1 and J_2 in Fig. 3 reveals the angle A_1 which is chosen and assigned to J_1 . Thus, in the second stage, the angle for joint J_1 used in the calculus of the distance between P and T is A_1 , while five angles are tested for joint J_2 . The thick line connecting J_2 and P in Fig. 3 reveals the angle A_2 which is chosen and assigned to J_2 .

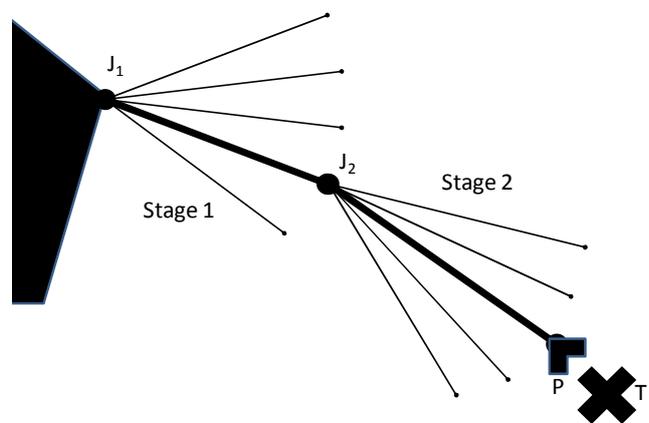
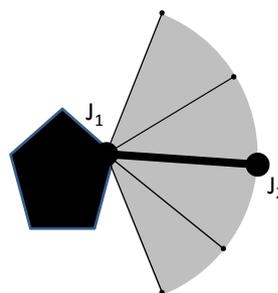


Fig. 3 – An approach to inverse kinematics

In order to enhance performance, the search can also be broken down to different resolution levels; using bigger angle intervals for a coarse search over the entire angle range, and then tightening both the angle range and the angle intervals for more refined searches over the angle area which gave the best results (see Fig. 4).

Starting resolution:



Enhanced resolution:

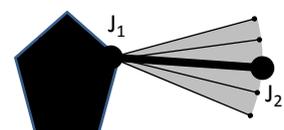


Fig. 4 – Using different resolution levels

In general, this strategy may cause good solutions to be missed because bigger intervals of joint angle combinations are skipped. Although we acknowledge this risk, we consider

that the achieved compromise can be, in general, advantageous because the time that is saved is then used to refine the search over the most promising area. This leads to fine-tuned solutions which start from joint angle combinations with high probability of neighbouring the optimal one.

Achieving optimal solutions usually requires too much time, compromising its use online [11]. Our approach leads to relatively good solutions rather than optimal ones, but most importantly, it will guarantee that we will reach them within a reasonable amount of time. Thus the search can be carried out online and, as a consequence, the specificity of the different scenarios which the robot might find itself in can be taken into consideration. In other words, it provides for adaptability, which is a characteristic of major importance in robotics.

After determining the angles which allows a body part to reach the position closest to the desired target, getting the robot to apply those angles can be done the same way as in performing predefined skills.

III. FLEXIBLE MOVEMENT PLANNING IN HUMANOID SOCCER

The approach that was described in the previous section can be used to develop higher-level skills. Indeed, the flexibility that was obtained can be very useful to dynamically outline body part trajectories. Such ability to plan movements on the basis of particular characteristics of the situation at hand has important applications in humanoid robot soccer.

The kicking motion has been considered the most important motion in robotic soccer [12]. And because it is such a computationally intensive task, its computation is usually performed offline [11], meaning that it consists of an inflexible pre-defined skill. Relevant work regarding this topic includes planning and fast replanning of safe motions [12]. The original approach used in this research consisted in solving a semi-infinite programming problem, using a time-interval discretization. However, their method required CPU times up to 2 hours, compromising its applicability in online mode. An offline application was tested but good results were achieved only under very strict constraints. They have then proposed a re-planning method, which starts from a predefined optimal motion and computes, still offline, a subset of the skill parameters.

Unlike that offline approach, however, we have developed a flexible kicking skill on the basis of the online movement planning described in the previous section. The developed skill was tested in the context of FC Portugal robotic soccer team [13][14][15], confirming the usefulness of the proposed approach in this particular field.

When kicking a ball towards a target, three important parameters can be considered (see Fig. 5):

- $dist_{KB}$: the distance between the kicker and the ball;
- α : the angle between the kicker orientation and the relative direction of the ball;
- β : the angle between the relative direction of the ball and the target direction relative to the ball.

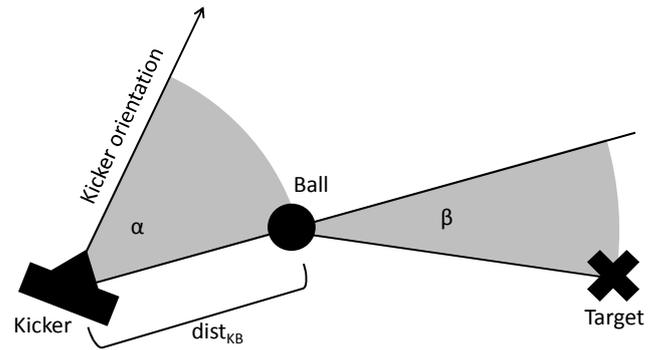


Fig. 5 – Parameters to consider in ball-kicking

In general, humanoid robots are still positioning themselves in line with the ball and the target, so as to be able to kick it properly (see Fig. 6). This corresponds to having $\alpha \approx \beta \approx 0^\circ$. This approach is still the one which teams use in major humanoid robot soccer competitions such as RoboCup.

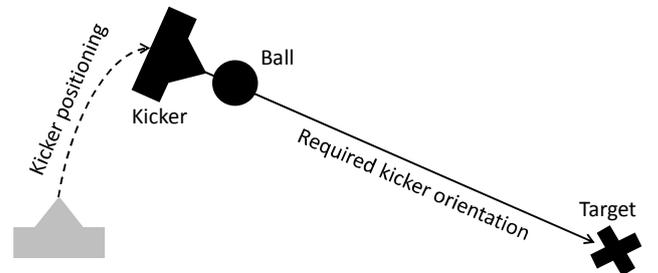


Fig. 6 – In-line positioning and orientation

A method for flexible ball-kicking, i.e. for kicking the ball towards some particular target, was developed and this new skill is composed of the following movements:

1. Transferring the robot weight to its left foot;
2. Slightly raising the robot's right foot;
3. Positioning the right foot near the ball;
4. Kicking the ball;
5. Bringing the right foot back to its original position.

The weight transfer, the right foot raise, and its later return can be achieved with simple predefined skills because they do not depend on the particular circumstances. On the other hand, positioning the foot “behind” the ball, and kicking it “forwards” can have different meanings, depending on the relative positions of the robot, the ball, and the target. One must dynamically determine which direction is “forwards” and “backwards” with respect to the kicking motion and the latter might not even be in line with the foot's initial position (see β in Fig. 5).

In our approach, the first step for determining the foot trajectory to follow during the actual kicking stage is to determine vector \overrightarrow{BT} defined by the ball (B) and the target (T) positions:

$$\overrightarrow{BT} = T - B \quad (1)$$

The starting (I) and stopping (F) foot points for the kicking movement can then be calculated as shown in equations 2 and 3, respectively.

$$I = B - a \frac{\overrightarrow{BT}}{\|\overrightarrow{BT}\|} \quad (2)$$

$$F = B + b \frac{\overrightarrow{BT}}{\|\overrightarrow{BT}\|} \quad (3)$$

in which a and b are coefficients that define how far behind and how far ahead of the current position of the ball the foot will start and stop during the kicking phase, respectively.

After I and F are calculated, inverse kinematics can be applied to determine the joint angles which should be used to reach each of those points. Obviously, a straight line trajectory would be desirable. However, since the robot's kinematics are non-linear, it would be necessary to execute computationally-intensive tasks such as calculating proper joint velocity profiles for yielding straight line trajectories. Such time-consuming strategies were not used because, as mentioned above, we cannot afford the required execution time. On the other hand, if we assign sufficiently short distances to parameters a and b , the type of trajectory will not have much negative influence on the outcome.

Let us focus on movement planning for kicking with the right foot. After observing NAO's joint map (recall Fig. 2), one can select RHip, RThigh1, RThigh2, and RKnee joints for getting the right foot to reach the positions calculated.

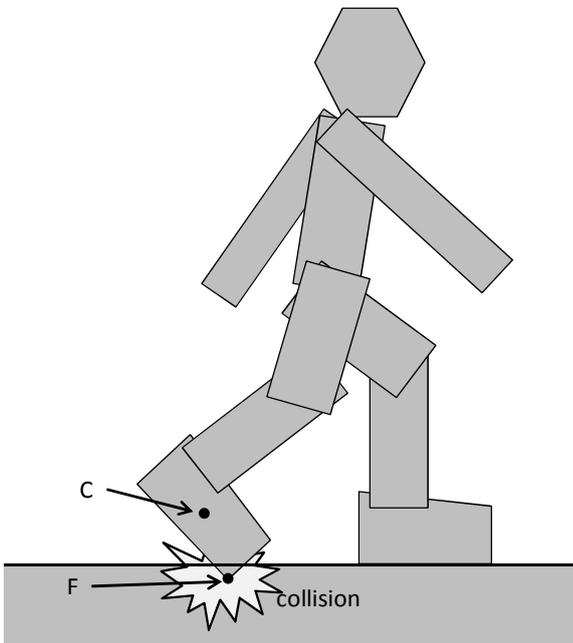


Fig. 7 – Neglecting body part orientation in movement planning

Experience has shown us that, in addition to foot positioning, foot orientation is essential, not only for kick accuracy but also to robot stability. When moving leg joints,

careless foot orientation leads to unexpected positions of foot edges. In case the latter hit the ground, the humanoid loses stability, possibly falling. Thus attention should be paid to keeping feet parallel to the ground. Our solution to this problem comprises some forward kinematics and trigonometry basics to calculate the angles which should be applied to RAnkle1 and RAnkle2 (see Fig. 2). Let us consider a two-dimensional example in which a situation such as the one depicted in Fig. 7 is originally sketched during movement planning.

The position of the foot's center (C) is intentional and it was planned using inverse kinematics. However, the provisory foot orientation would cause the front tip (F) of the foot to hit the ground. Such collisions can be anticipated by calculating the height of the foot tip using forward kinematics and comparing it with that of the foot center. Then, the compensation angle θ that should be applied added to the relevant ankle joint can easily be determined on the basis of the distance from the foot center to its front tip ($|\overrightarrow{CF}|$) and the respective difference in height (Δh):

$$\theta = \sin^{-1} \frac{\Delta h}{|\overrightarrow{CF}|} \quad (4)$$

A method for foot alignment was developed on the basis of this approach and integrated in the kicking skill. With it, the correct compensating angles for RAnkle1 and RAnkle2 joints (see Fig. 2) are applied, avoiding many destabilizing collisions.

IV. SIMULATIONS AND RESULTS

Experiments were carried out in a 3D simulated environment (simspark and rcssserver), testing the applicability of the presented flexible movement planning methods in humanoid robot soccer. In this environment, the radius of the ball is 0.04 m. A robust right-foot kick movement was developed as described by the examples given in the previous sections. Coefficients for determining I and F points (see equations 2 and 3, respectively) were set as follows:

$$\begin{cases} a = 0.16 \text{ m} \\ b = 0.00 \text{ m} \end{cases} \quad (5)$$

Assigning parameter b to 0 means that the trajectory of the foot during the kicking phase finishes when the centre of the foot reaches the centre of the ball at the time of planning. Obviously, the foot hits the ball as soon as its edge reaches the surface of the ball.

In order to test the flexibility of this skill, simulations were done using random parameters α , β , and dist_{KB} (see Fig. 5), although satisfying the following restrictions:

$$\begin{cases} 0.15 \text{ m} \leq \text{dist}_{KB} \leq 0.25 \text{ m} \\ -45^\circ \leq \alpha + \beta \leq 45^\circ \end{cases} \quad (6)$$

The first restriction guarantees that the distance between the robot and the ball is reasonable for kicking. The second restriction is related to NAO's feet shape. Although the flexibility of the developed skill allows for kicking in any direction in the xy -plane, the foot's projection on the latter is

not a circle. In fact, the side edges of NAO's foot are completely straight, which compromises diagonal kicking. Only near the foot tips is the edge rounded and we thus estimate that kicking within a -45° to $+45^\circ$ angle range would prove reasonably accurate. However, the simulator models NAO's foot as a parallelepiped and not with a rounded shape. Therefore, we will consider the results as a lower bound for the potential of the approach proposed.

An extra parameter which controls the kick stage speed was used. The time to be spent in moving the foot from I to F (Δt) was assigned to three different values: 170, 200, and 230 ms, thus defining three different foot speeds. This variation was meant to confirm whether this parameter would reflect a compromise between kick accuracy and kick range. It seems reasonable to expect that faster kicks have worse accuracy and better range than slower ones.

Ten kicks have been carried out for each assignment of Δt and, for each individual kick, random parameters α , β , and dist_{KB} were randomly chosen (though satisfying equation 6). After each kick, two measurements were performed:

- $|\text{dev}|$: the modulus of the direction deviation. i.e. the angle defined by the planned and resulting directions;
- dist_B : the distance between the pre-kick and post-kick ball positions, i.e. the kick range.

Table 1 presents the average and standard deviation of the measured results for each assignment of Δt .

TABLE I
RESULTS OF THE SIMULATIONS

Δt (ms)	$\mu(\text{dev})$ ($^\circ$)	$\sigma(\text{dev})$ ($^\circ$)	$\mu(\text{dist}_B)$ (m)	$\sigma(\text{dist}_B)$ (m)
170	17.026	13,666	0.581	0,560
200	14.707	26,414	1.029	0,377
230	11.287	13,144	1.168	0,505

It is interesting to observe that for higher Δt , although the average deviation angle was lower (as expected), the average kick range was higher. We strongly believe that this can be the result of how collisions are modelled by the simulator, and that tests with actual NAOs (set as future work) will not reveal this unpredicted tendency.

Results reveal high standard deviation for both kick properties measured. This might have been caused by the combination of two factors: NAO's foot being modelled as a parallelepiped rather than its real rounded shape; and the fact that the directions of the kicking motions varied.

Simulations were carried out with fixed coefficients a and b , which are used for determining I and F points (see equations 2 and 3, respectively). As future work, we plan to study the influence of these parameters on the results. Additionally, we want to introduce a dynamically adjustable interval size for scanning the assignable angle space of the joints during the search process. When the scanning is leading to better results, the interval can be widened so as to save precious time. Future work will also include determining the value of the various parameters for yielding the compromise which can be considered the best.

Future work can include overcoming the diagonal kicking limitation due to NAO's feet shape. It would be interesting to study whether NAO's hip joints can be used to adjust the kicking-foot's orientation in the z axis, so as to orthogonally hit the ball with the straight edge on the foot's side. Alternatively, we can study different ways to hit the ball with any edge which can be oriented orthogonally to the kicking motion. We believe that such solution would greatly improve the accuracy in general and allow kicking in any direction of the xy-plane.

Thrust generation can also be subject to optimization. In this context, it would be interesting to test how simultaneous joint motion can enhance range by means of speeding up the kick.

V. CONCLUSIONS

In general, achieving optimal solutions for planning humanoid skills requires too much time, compromising its use online. Thus, many of the skills used by simulated and real humanoid robots are predefined to a very high extent. This fact comes along with certain limitations which can be overcome if flexible movement planning is employed. In robotics, passing from predefined skills to flexible ones can correspond to passing from forward kinematics to inverse kinematics.

We have proposed a technique to perform inverse kinematics taking a set of joints, a body part, and a target position as parameters and returning the best set of angles to be applied. The approach is based on a multi-stage search which uses forward kinematics to rehearse robot postures, leading to relatively good solutions, although not optimal in the general case. In order to enhance performance, the search was broken down to different resolution levels; using bigger angle intervals for a coarse search over the entire angle range, and then tightening both the angle range and the angle intervals for more refined searches over the angle area which gave the best results.

In the end, the approach guarantees that it reaches a reasonable solution within a reasonable amount of time, thus rendering it applicable online. As a consequence, the specificity of the different scenarios which the robot might find itself in can be taken into consideration and such adaptability is a characteristic of major importance in robotics.

Reusing the proposed inverse kinematics technique to calculate a sequence of intermediate postures can be used to plan trajectories for complex flexible humanoid movements. A method for flexible ball-kicking composed of 5 movements was developed as an application in the field of humanoid robot soccer. A secondary technique was implemented for collision avoidance, using extra joints for keeping the robot's feet parallel to the ground at every stage of the planned movement. Strategies for yielding straight line trajectories are generally time-consuming and they were not used, as we aim for applications based on online planning.

Experiments with the developed techniques were carried out with a virtual NAO model in a 3D simulated environment. The starting foot position for the kicking phase was set to 16

cm behind the ball, whereas the stopping position was the initial position of the ball. Independent experiments were performed for different kicking phase durations: 170, 200, and 230 ms. In order to test the flexibility of the developed skill, experiments were done using random values for α , β , and dist_{KB} but with some range restrictions.

The results of the experiments revealed that the average direction deviation was lower for slower kicks. However, against what seemed reasonable to expect, the average distance of the slower kicks was also better (higher) than that of quicker kicks.

Relevant work regarding this topic includes planning and fast replanning of safe motions. The original strategy consisted of solving a semi-infinite programming problem, using a time-interval discretization. However, the CPU time that their method requires compromises its applicability in online mode. They have then proposed a replanning method which still did not provide for the flexibility we aimed for.

As future work, we plan to do the following:

- study the influence of coefficients which are used for determining the initial and final points of the kicking phase;
- introduce a dynamically adjustable interval size for scanning the assignable angle space of joints, during the search process, so as to save precious time;
- determine the values to assign to the various parameters for yielding the best compromise;
- overcome the diagonal kicking limitation due to NAO's feet shape, adjusting its hip joint to hit the ball with an edge orthogonal to the kicking motion;
- optimize thrust generation by means of simultaneous joint motion.

ACKNOWLEDGMENTS

This work was partially supported by the Portuguese National Foundation for Science and Technology FCT-PTDC/EIA/70695/2006 Project - "ACORD: Adaptive Coordination of Robot Teams".

REFERENCES

- [1] Hiroaki Kitano, Minoru Asada, Yasuo Kuniyoshi, Itsuki Noda, Eiichi Osawa, and Hitoshi Matsubara. *RoboCup: A challenge problem for AI and robotics*. In Hiroaki Kitano, editor, *RoboCup*, volume 1395 of Lecture Notes in Computer Science, pages 1–19. Springer, 1997.
- [2] Oliver Obst, Markus Rollmann. *Spark - a generic simulator for physical multi-agent simulations*. In Gabriela Lindemann, Jörg Denzinger, Ingo J. Timm, and Rainer Unland, editors, *MATES*, volume 3187 of Lecture Notes in Computer Science, pages 243–257. Springer, 2004.
- [3] RoboCup Community. *RoboCup Soccer Server 3D Users Manual*, 2008.
- [4] David Gouaillier, Vincent Hugel, Pierre Blazevic, Chris Kilner, Jerome Monceaux, Pascal Lafourcade, Brice Marnier, Julien Serre, Bruno Maisonnier. *The NAO humanoid: a combination of performance and affordability*. CoRR, abs/0807.3223, 2008.
- [5] RoboCup 2010 Singapore Website. [Available online]. <http://www.robocup2010.org/>. [consulted on February 2010].
- [6] Nima Shafii, Omid Mohamad Nezami, Siavash Aslani, Saeed Shiry Ghidary. *Evolution of Biped Walking Using Truncated Fourier Series (TFS) and Particle Swarm Optimization (PSO)*. *RoboCup Symposium 2009*, pp. 344-354, June 30-July 3, Austria.
- [7] Hugo Picado, Marcos Gestal, Nuno Lau, Luís Paulo Reis, Ana M. Tomé. *Automatic Generation of Biped Walk Behavior Using Genetic Algorithms*. In Proceedings of the IWANN 2009: 10th International Work-Conference on Artificial Neural Networks, Salamanca, Spain, pp. 805 – 812, Jun. 2009.
- [8] Y. Fujimoto, A. Kawamura. *Simulation of an autonomous biped walking robot including environmental force interaction*. *Robotics & Automation Magazine*, IEEE , vol.5, no.2, pp.33-42, Jun. 1998.
- [9] M. Vucobratovic, B. Borovac, D. Surdilovic. *Zero Moment Point – Proper Interpretation and New Applications*. In Proceedings of IEEE-RAS International Conference on Humanoid Robots, pp. 237-244, 2001.
- [10] S. Anderson, C. Atkeson, J. Hodgins. *Coordinating Feet in Bipedal Balance*. In Proceedings of the 2006 IEEE-RAS International Conference on Humanoid Robots, pp. 624-628, 4-6 Dec. 2006.
- [11] S. Carpin, E. Pagello. *The challenge of motion planning for human robots playing soccer*. In Proceedings of the Workshop on Humanoid Soccer Robots, 2006 IEEE-RAS International Conference on Humanoid Robots, pp. 71–77, Dec. 2006.
- [12] S. Lengagne, P. Fraisse, N. Ramdani. *Planning and fast re-planning of safe motions for humanoid robots: Application to a kicking motion*. *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on* , pp.441-446, 10-15 Oct. 2009.
- [13] Luís Paulo Reis, Nuno Lau. *FC Portugal Team Description: RoboCup 2000 Simulation League Champion*. In Peter Stone, Tucker Balch and Gerhard Kraetzschmar, editors, *RoboCup-2000: Robot Soccer World Cup IV*, Springer LNAI, vol. 2019, pp.29-40, Berlin, 2001.
- [14] Luís Paulo Reis, Nuno Lau, Eugénio Oliveira. *Situation Based Strategic Positioning for Coordinating a Team of Homogeneous Agents*. In Markus Hannebauer, Jan Wendler and Enrico Pagello Editors, *Balancing Reactivity and Social Deliberation in Multi-Agent System – From RoboCup to Real-World Applications*, Springer LNAI, vol. 2103, pp. 175-197, Berlin, 2001.
- [15] Nuno Lau, Luís Paulo Reis. *FC Portugal - High-level Coordination Methodologies in Soccer Robotics*. *Robotic Soccer*, Book edited by Pedro Lima, Itech Education and Publishing, Vienna, Austria, pp. 167-192, Dec. 2007, ISBN 978-3-902613-21-9.