On the maximum walking speed of NAO humanoid robots

3 authors:

Julián Cristiano
Universitat Rovira i Virgili
28 PUBLICATIONS **97** CITATIONS

Domenec Puig
Universitat Rovira i Virgili
298 PUBLICATIONS **4,089** CITATIONS

Miguel Angel García
Universidad Autónoma de Madrid
14 PUBLICATIONS **112** CITATIONS

On the maximum walking speed of NAO humanoid robots

Julian Cristiano
Dept. of Computer Science and Mathematics
Univ. Rovira i Virgili
Avinguda dels Paisos Catalans, 26
43007 Tarragona
julian11495@yahoo.com

Domenec Puig
Dept. of Computer Science and Mathematics
Univ. Rovira i Virgili
Avinguda dels Paisos Catalans, 26
43007 Tarragona
domenec.puig@urv.cat

Miguel Angel Garcia
Dept. of Electronic and Communications Technology
Autonomous University of Madrid
Francisco Tomas y Valiente 11
28049 Madrid
miguelangel.garcia@uam.es

Abstract

This paper reviews previous motion control systems proposed over the last years in order to maximize the walking speed of the NAO humanoid robot. These proposals manage to exploit the physical resources of the humanoid with the aim of increasing its maximum walking speed in straight line. A comparative table with relevant results supported by demonstrable evidence is presented. Finally, some rules to standardize the measurement of the NAO's maximum speed are proposed in order to be able to compare the most relevant solutions of the state-of-the-art on equal terms.

1. Introduction

The motion of living organisms by means of legs, specially the locomotion of bipeds, has always been a problem of interest to scientists. However, the study of legged locomotion systems and, particularly, anthropomorphic mechanisms involves complex dynamic systems from the mechanical, structural and control points of view. However, in spite of the research efforts, biped locomotion has not yet been solved in a satisfactory way.

Currently, the interest in humanoid robots is increasing due to the variety of applications that are expected to come, for example: people entertainment, execution of dangerous tasks, people rescue, helping people with disabilities, cleaning, etc. Humanoid robots are complex electromechanical autonomous systems that have the appearance of a human being. Each humanoid has around 22 degrees of freedom (DoF) to control the complete body structure (arms, feet, head and trunk). Its weight is mainly located at its upper body and it only has two possible contact surfaces on its feet soles.

Many humanoid robotic platforms have been developed for research purposes, such as: ASIMO [1], NAO [2], QRIO [3], etc. In addition, powerful simulators of mobile robots, including legged robots, have been developed, which allow researchers to test their algorithms before transferring them to the real robots, for instance [4]. During the last years, research on humanoid locomotion has been growing, trying to solve the gait generation and stability control problems, looking for a robust motion control system.

Integrating humanoid robots in our society is a complex task. This is precisely the final goal of the RoboCup, an international initiative that fosters research in robotics and artificial intelligence by means of robot competitions. Since 2008, the RoboCup Standard Platform League (SPL), a humanoid robot soccer league, uses the NAO robot.

NAO is a biped robot manufactured by Albebaran Robotics as a research platform. It has 21 DoF (RoboCup edition) for controlling the robot body, as well as different types of sensors (2 cameras, sonars, 3-axis accelerometer, a 2-axis gyrometer, hall effect sensors, force sensors, etc.). This robot can be programmed in different languages (C, C++, URBI, Python, .Net). In the soccer matches of the RoboCup SPL, those teams that manage to make faster movements have an extra advantage over their opponents. Therefore, it is worthwhile to study the different motion models proposed over the last years for maximizing the walking speed of NAO humanoid robots.

Currently, research on biped locomotion is focused on developing models that generate stable, faster and energy efficient movements, with the goal of imitating the motion control of human beings.

This paper presents a review of the fastest motion control systems developed up to date for the

NAO humanoid robot. More in detail, the main contributions of this paper are described below:

- A survey of techniques previously proposed in the literature in order to generate and control the maximum walking speed in straight line of the NAO humanoid robot.
- A comparative analysis of the theoretical principles of the aforementioned techniques, which is summarized in Table 1.
- The proposal of a new method for measuring the speed of a given straight line locomotion pattern by means of three standard measures. This method has been applied in order to measure the performance of the two fastest locomotion patterns of the NAO previously proposed in the literature that were supported by demonstrable evidence. This procedure makes it possible to compare the performance of locomotion patterns proposed by different research teams in equality of terms.

To our knowledge, a study like this has not been published before from the point of view of the NAO humanoid robot in a real environment, which makes it valuable for researchers working with this robot and robots alike in real environments, such as in the RoboCup.

The rest of the paper is organized as follows. Section 2 presents the most common approaches for tackling the biped locomotion problem. Section 3 summarizes those locomotion models previously proposed for the NAO humanoid that manage to achieve maximum walking speeds. Section 4 discusses the results yielded by those models in which demonstrable evidence is available. Section 5 proposes several rules for standardizing the measurement of maximum walking speeds. Finally, conclusions and future work are given in section 6.

2. Biped locomotion

Currently, one of the most active research areas in humanoid robotics is locomotion generation and stability control. The main solution to generate and guarantee the stable movement of a biped robot on flat terrain is based on the Zero Moment Point (ZMP) [5]. The ZMP is the point on the ground in which the sum of the moments of all active forces equals zero. If the ZMP is within the convex hull (support polygon) of all contact points between the feet and the ground, the robot's gait is dynamically stable. This is a well-established methodology that controls the robot's stability using full models [6] or simplified dynamic models [7][8] of the humanoid. Its main inconvenience is that it requires precise models of the robot and the environment.

Currently, most humanoid robots are controlled using simplified dynamical models that reduce the complexity of the associated motion control, something suitable for real-time applications. The most accepted simplified model is the inverted pendulum, as it models the robot's motion by means of a smooth motion of the robot's center of masses (CoM). Moreover, it allows an easy control of the robot in structured environments, such as in the soccer matches of the RoboCup SPL, in which the floor is flat.

In order to develop stable gaits with an inverted pendulum model, it is necessary to obtain suitable CoM trajectories from ZMP reference trajectories. Afterwards, the trajectories of the robot's links are calculated according to the required CoM trajectory, computing a stable movement of the robot's body in order to achieve the desired ZMP trajectory.

Other solutions to the problem of biped locomotion are based on the use of biologically inspired models [9][10], which try to mimic the neural control of motion in animals and human beings. The advantage of these techniques is that they do not require precise descriptions of the robot or the environment. The current problem of these approaches is that they lack a design methodology to develop robust control systems for locomotion of biped robots.

3. Review of recent related work

In soccer competitions, speed is one of the most important skills as it allows players to take advantage over their opponents, for instance, in the fast approach to the goal and the ball. The NAO robot has a library supplied by the manufacturer that was not designed to maximize the robot's speed. In fact, according to its documentation, it only reaches a maximum speed of 9.52 cm/s in straight line.

Therefore, most teams that participate in the RoboCup SPL have developed their own models to generate and stabilize the motion of NAO robots.

		NAO HTWK	rUNSWift	B-human	NAO devils
Motion generation methodology	Inverted pendulum model		X	X	
	ZMP controller				X
	Evolutionary algorithms	X			
Feedback strategy	Swinging the robot according to the current state, sensory feedback and preview action based on future demand				X
	Update of the pendulum state from the torso pose			X	
	Force sensors and accelerometer measures		X		X
	Control of the shoulder's pitch joint angles with the current error of torso angles	X			

Table 1. Summary of the fastest motion control systems currently proposed for NAO robots.

For instance, the world speed record in 2009 was obtained by the NAO Team HTWK (Leipzig University of Applied Sciences), which reached a maximum speed of 32 cm/s [11]. They use motion patterns trained using a specialized evolutionary algorithm. In addition, they stabilize the straight line walk by controlling the shoulder's pitch joint angles with a modified PD controller. The input to the controller consists of the current torso angles and a pre-recorded base-line of an optimal situation [12].

In turn, the second place in the RoboCup 2010 was for the rUNSWift team (University of New South Wales), which achieved a maximum speed of 22 cm/s. They applied a closed-loop control system based on the inverted pendulum model with stabilisation feedback supplied via the feet sensors and accelerometer measurements for the coronal and sagittal planes [13].

The winner of the RoboCup 2010 was the B-human team (Bremen University), which achieved a maximum forward speed of 28 cm/s. Their model uses a closed-loop with two alternating inverted pendulums to generate the trajectories for each foot. Stabilization is based on an estimated pose of the torso, which updates the parameters and the state of the pendulum model to react to external disturbances appropriately [14][15].

The current world speed record for the NAO robot is 44.47 cm/s [16]. It was set in the RoboCup 2010 by the NAO Devils Team (Dortmund University). They use a controller that transforms the reference ZMP to a trajectory of the robot's CoM [17]. The feedback strategy is based on an observer-based controller, [18], which adds a constant error to the ZMP measurement for a fixed period of time according to: the current state, sensory feedback and preview action based on future demand. The objective is to compensate for both errors in the model and perturbations while the robot is walking by adjusting the CoM trajectory, swinging the robot to the opposite direction when it undergoes an unexpected inclination with respect to the ground or a constant force pushing it [19]. In addition, they have also explored motion on sloped terrains [17].

4. Summary of relevant results supported by demonstrable evidence

The results obtained by the research groups described in the previous section in terms of maximum walking speed of the NAO robot are summarized in Table 2. These solutions have mainly been tested in the RoboCup SPL during the last two years.

The two fastest solutions will only be discussed hereafter, since they provide videos that constitute demonstrable evidence about the maximum speed they claim to reach [11][16]. Those videos also allow further analysis as discussed in section 5.

The walking gait developed by the NAO Devils Team [16] reduces the lateral and coronal acceleration of the torso, which yields an easily controllable gait. Another important feature of this

Country	Team	Publication date	Maximum speed [cm/s]	Methodology
Germany	NAO Devils	June 30, 2010	44.47	ZMP Controller
Germany	NAO HTWK	October 12, 2009	32	Evolutive algorithm
Germany	B-human	December 7, 2010	28	Inverted pendulum
Australia	rUNSWift	October 30, 2010	22	Inverted pendulum

Table 2. Summary of published relevant results

gait is the low location of the CoM, which guarantees a single stability control through an arms' motion designed to keep balance while the robot is walking quickly.

In the walking gait developed by NAO Team HTWK [11], however, the location of the CoM is high. This complicates the stability control if the robot undergoes an internal mismatch or an external disturbance. The main advantage is that it guarantees a natural motion more similar to that of human beings. They compensate the feet motion by means of the torso movement.

The teams described above use different approaches to calculate the average speed reached by the humanoid. In the case of the NAO Devils, the velocity is calculated along 2.9 meters after

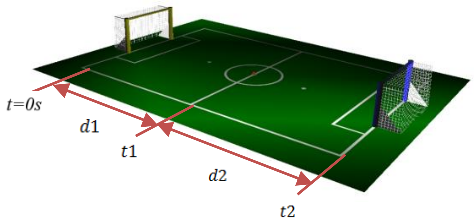

Figure 1. Time and distance measures, where $t1$ is the time employed by the robot for walking from a static initial position until it reaches a distance $d1$, and $t2$ is the time needed by the robot for crossing the soccer field from the start line to the finish line. These measures of time take into account the acceleration time.

5. Standardizing the measurement of maximum speeds

The RoboCup is an international meeting point for research groups in robotics. Therefore, this competition is suitable for comparing the advances in motion control systems, in particular, those that aim at maximizing the walking speed of NAO robots.

accelerating the robot to maximum speed for 3 meters. On the other hand, the NAO Team HTWK measures the maximum average speed along 6 meters, starting their movement from a static pose. In this case, the velocity measure takes into account the acceleration time.

In summary, the walking patterns proposed so far manage to exploit the physical resources of the NAO humanoid robot, which is necessary to develop a walking model that maximizes the robot's speed. Moreover, the results obtained by the RoboCup teams support the development of gaits for humanoid robots based on either simplified dynamic models or evolutionary algorithms in order to generate faster and stable motion patterns running in real time.

As discussed in the previous section, different teams make different assumptions in order to measure walking speeds. Therefore, it is necessary to standardize the way of measuring walking speeds in order to be able to compare different solutions on equal terms.

In this section, three average speeds are proposed as standard measures by taking advantage of the well-defined soccer field lines of the standard RoboCups's football pitch.

The parameters necessary to obtain the proposed average speeds are shown in Fig. 1. The two time measures, $t1$ and $t2$ are taken approximately along three meters, since according to the RoboCup SPL rules [20], the soccer field size satisfies that $d1 = d2 = 3m$. These distances can be measured before the competition. The following average speeds are calculated:

$$V1 = \frac{d1}{t1} \quad (1)$$

$$V2 = \frac{d2}{t2 - t1} \quad (2)$$

$$V = \frac{d1 + d2}{t2} \quad (3)$$

These three measures should be maximized and be the most similar possible, since that guarantees a small acceleration time and a constant speed along the six meters. This feature is very important for reaching the maximum walking speed in a short period of time, since most robots' workspaces have a limited size and the robots cannot be previously accelerated over a long distance, such as in the case of the RoboCup SPL soccer matches.

In order to validate a given walking pattern, some restrictions are proposed:

a) The initial pose should be any one that starts without dynamical effects, in a similar way to human athletic competitions.
b) The initial robot position should be behind the start line, including the vertical projection on the horizontal plane of the head, legs, arms and trunk (see Fig. 2).
c) The final deviation with respect to the horizontal straight line should be bounded. For example, 50 cm could be a good deviation margin, which should be reduced as new gaits describe better trajectories in straight line.

The aforementioned three speed measures have been calculated for the two fastest gaits described in section 4. The results are shown in Table 3. These values were obtained from the videos published by both teams [11][16]. Although the real measures can have a small variation, the goal is showing a numeric comparison between the two current fastest NAO's gaits.

As shown in Table 3, the NAO Devils team reaches a maximum average speed in the second half field. But over the six meters, the NAO Team HTWK reaches the maximum average speed. This is due to the fact that the acceleration time of the NAO Team HTWK is lower.

Figure 2. Example of a valid initial pose.

The three aforementioned restrictions that validate a walking pattern were not taken into account in this study. Therefore, they should be adopted in the future in order to compare the different proposals fairly. Thus, if the walking pattern deviates more than the previously defined minimum deviation distance or if the initial pose is not valid, that pattern should not be considered to qualify for a maximum speed test. In order to satisfy the minimum required deviation, it is necessary to calibrate the walking pattern in advance in case of open-loop motions. In turn, in the case of closed-loop motions, it is necessary that the models incorporate faster feedback strategies to correct the walking direction online, for instance, through real time image processing, aiming to describe a straight line.

6. Conclusions

The two comparable fastest teams in the RoboCup SPL use different methodologies for generating walking patterns in real time. The first one uses the well-known ZMP methodology, which calculates a CoM trajectory with the goal of describing the necessary dynamic movement, while the second team uses dynamic movements previously generated with an evolutionary algorithm.

According to the analysis of the proposed speed measures for the fastest teams, it can be affirmed that the fastest walking pattern for a straight line trajectory of approximately three meters is the one proposed by the NAO Devils team, without taking into account acceleration time.

	$V1$ [cm/s]	$V2$ [cm/s]	V [cm/s]
NAO Devils 2010	23.73	44.47	31
NAO HTWK 2009	32	31	32

Table 3. Average speeds for the two fastest teams.

Furthermore, it can be stated that the NAO Team HYWK has a better acceleration time, but the stability control of the movement is more complicated due to the inherent instability associated with the CoM's height.

The best walking pattern for six meters is the one performed by the NAO Team HYWK, as it has a small acceleration time, which guarantees a constant speed along the path. This faster acceleration allows them to use their motion in real soccer competitions, without the need for a previous acceleration distance.

When the robot describes fast walking patterns, it is necessary that the feedback system reacts in a short period of time, trying to prevent the robot from falling down. According to the analysis of the two fastest patterns, the feedback control will be easier if the accelerations of the sagittal and coronal planes are reduced, avoiding the stability control by means of the torso movement, and balancing the movement with the arms motion.

When the robot walks quickly, it is complicated to obtain understandable measures for some walking patterns. Therefore, it is necessary to develop walking patterns that allow an adequate measurement of the different sensorial signals (force sensors, accelerometer, gyrometer, etc) in order to obtain an easily interpretable feedback signal that allows a fast reaction.

Humanoid robots have limited computational capabilities. Therefore, the motion control systems must be able to generate a motion pattern online at the same time that control the robot's stability. Furthermore, the robots must perform other types of computations, such as image processing, localization, etc.

One interesting aspect for further research would be the comparison of the different gaits from alternative points of view other than speed, such as the robot's power consumption or the robot's stability margin, which are also relevant from a practical viewpoint.

Future work will consist of the development of a motion control system for the NAO robot that is competitive with the ones described in the state-of-the-art in terms of both walking speed and the other alternative criteria mentioned above.

7. Acknowledgment

Julián Cristiano is supported by a scholarship from the Fundación Carolina.

References

[1] Y. Sakagami et al, "The intelligent ASIMO: system overview and integration", IEEE International Conference on Intelligent Robots and Systems, vol. 3, pp. 2478 – 2483, 2002.

[2] D. Gouaillier et al, "Mechatronic design of NAO humanoid", IEEE International Conference on Robotics & Automation, pp. 769-774, 2009.

[3] T. Ishida, "Development of a small biped entertainment robot QRIO", Proceedings of the International Symposium on Micro-Nanomechatronics and Human Science, pp. 23-28, 2004.

[4] O. Michel, "Webots: Professional Mobile Robot Simulation", International Journal of Advanced Robotic Systems, vol. 1, no. 1, pp. 39–42, 2004.

[5] M. Vukobratović and B. Borovac, "Zero-moment point - thirty five years of its life", International Journal of Humanoid Robots, vol. 1, no. 1, pp. 157–173, 2004.

[6] J. Park and Y. Youm, "General ZMP Preview Control for Bipedal Walking", International Conference on Robotics & Automation, pp. 2682-2687 , 2007.

[7] S. Kajita et al, "Biped walking pattern generation by using preview control of zero-moment point", International Conference on Robotics & Automation, vol. 2, pp. 1620-1626, 2003.

[8] T. Sugihara et al, "Real-time humanoid motion generation through ZMP manipulation based on inverted pendulum control", International Conference on Robotics & Automation, vol. 2, pp. 1404-1409, 2002.

[9] G. A. Bekey, Autonomous robots: from biological inspiration to implementation and control, MIT Press, 2005.

[10] A. Jan Ijspeert, "Central pattern generators for locomotion control in animals and robots: A review", Neural networks, vol. 21, no. 4, pp. 642-653, 2008.

[11] Nao-Team HTWK gait, available online in: http://www.youtube.com/watch?v=rsFCe6yKVOI&feature=player_embedded

[12] K. Jahn et al, Nao-Team HTWK, Team Research Report 2009. Available online in: http://naoteam.imn.htwk-leipzig.de/documents/techReportHTWK.pdf

[13] A. Ratter et al, rUNSWift Team Report 2010 Robocup SPL. Available online in: http://www.cse.unsw.edu.au/~robocup/2010site/reports/report2010.pdf

[14] C. Graf and T. Röfer, "A Closed-loop 3D-LIPM Gait for the RoboCup Standard Platform League Humanoid", Proceedings of the Fourth Workshop on Humanoid Soccer Robots, 2010.

[15] T. Röfer et al, B-Human Team Report and Code Release 2010. Available online in: http://www.b-human.de/en/publications/

[16] Nao Devils gait, available online in: http://www.youtube.com/watch?v=3aOuQ1_e--k

[17] S. Czarnetzki et al, "Applying Dynamic Walking Control for Biped Robots", RoboCup 2009: Robot Soccer World Cup XIII, Lecture Notes in Computer Science, vol. 5949, pp. 69-80, 2010.

[18] S. Czarnetzki, S. Kerner and O. Urbann, "Observer-based dynamic walking control for biped robots", Robotics and Autonomous Systems, vol. 57, no. 8, pp. 839–845, 2009.

[19] S. Czarnetzki et al, Nao Devils Team Report 2010. Available online in: http://www.nao-devils.de/

[20] RoboCup Standard Platform League (Nao) Rule Book, 2010. Available online in: http://www.tzi.de/spl/pub/Website/Downloads/Rules2010.pdf