A Differential Steering System for Humanoid Robots

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Abstract- Biped locomotion for humanoid robots is a challenging problem that has come into prominence in recent years. As the degrees of freedom of a humanoid robot approaches to that of humans, the need for a better, robust, flexible and simpler maneuverability becomes inevitable for real or realistic environments. This paper presents a new method of controlling the trajectory of a humanoid robot on the basis of differential steering systems. To the best of our knowledge, this is the first time that such a technique has been applied on humanoid robots. It has been empirically shown that a humanoid robot can plan its trajectory by using the same principle applied in differential steering systems, and the change in its orientation can be easily calculated in degrees. Therefore, this method enables the robot to move in a desired curved-shape trajectory, instead of aligning itself with the target prior to walking or performing more complex and time consuming motions like diagonal walk or sidewalk. This method is also beneficial when further trajectory planning constraints such as obstacle avoidance are considered.

Keywords- Humanoid robots, Differential Steering Systems, Biped Walk, Gait

I. INTRODUCTION

Wheeled design has been a proper choice for robot motion due to its relatively easy mechanical implementation and balance since the early days of robotic research. However, wheeled robots are not suitable enough for all terrains. Therefore, the research focus has shifted towards more complex designs such as legged robots, and particularly biped robots. For environments in which the amount of consumed time and energy is considerable in the performance assessment of a robot, the ability to maneuver without decreasing the speed while maintaining the walking motion type is much more efficient.

Several different motion controllers and trajectory planning methods are used for humanoid robots. As an example, [1] introduced a ZMP-based motion controller for a humanoid robot which uses Fuzzy Logic. In the ZMP approach, the main objective is to design robot's motion in such a way that the zero moment point (the point where total inertia force equals to zero), does not exceed a predefined stability region. [2] Uses a Neuro-Fuzzy biped walking model based on ZMP model. Center of Mass (COM) based methods are another popular trajectory controlling method

[3], [4]. All these methods suffer from being design specific based on the underlying humanoid robot structure.

In this research, we focus on a novel trajectory planning method designed especially for a humanoid robot to move along curved-shaped trajectories. We have adapted the motion model from [5] but extended this model for curved-shape trajectories. The proposed curved walking model introduced for a humanoid robot uses the same fundamental principle behind the differential steering system for a wheeled robot. One of the most interesting properties of this method is its independency from the underlying humanoid robot platform. This new method also ensures an energy-efficient trajectory as compared to some other design-specific methods since some joints (i.e., hip's roll joints) are not used in this model to change the orientation.

As an example, in [1] and [2] hip's roll joints are used to change the motion direction of the robot. [1] Uses fuzzy logic for a gait primitive generator in order to construct a curved path and [2] smoothes the desired path based on the curve that guarantees optimum ZMP values within the trajectory. Using these roll joints may help in sharp turns in short distances, but results in more energy consumption in long distances. For an autonomous robot operating in a realistic world, where the robot is not constantly plugged to an energy source and carries a battery instead, following a desired curved path without using all joints is much more efficient. On the other hand, this approach promises a shorter traveling distance without a sudden change in the field of view.

The rest of the paper is organized as follows. The underlying motion fundamentals are presented to clarify the rest of the model. That's why; we introduce our motion model in the first section. Then, an overview of differential steering systems is given to bind these two concepts together to shape a differential steering system for humanoid robots which is presented in the next section. Finally, we present the experimental results and conclude the paper.

II. MOTION MODEL

In this paper, we present a model which is independent from the humanoid robot structure. However, the model is particularly illustrated and experiments are conducted on the simulated Aldebaran humanoid NAO robot. NAO has 22

degrees of freedom of which only 12 have been used in our motion model. The height of the robot is 57 cm and its weight is 4.3 kg [6]. Since the simulated Nao robot (Fig. 1(a)) is a realistic representation of the Nao humanoid robot (Fig. 1(b)), its joint structure (Fig. 1(c)) is the same with the real one.
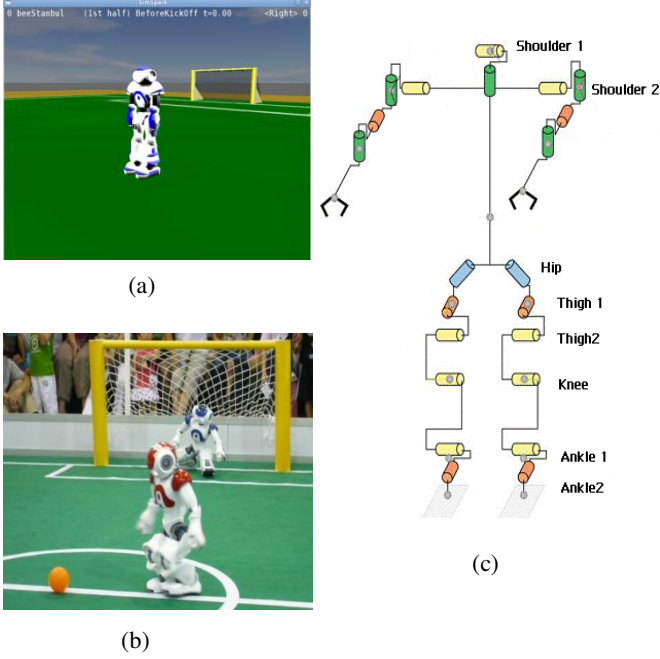

(a)

(b)

(c)

Figure 1. The Aldebaran Nao. a) Simulated Nao Robot at Simspark environment, b) Nao Robot at RoboCup Standard Platform League [7], c) Nao Structure [6].

The human walking motion can be modeled by a smoothed rolling polygonal shape and a periodic function accordingly. In this sense, one can use the principle of Partial Fourier Series (PFS) in order to decompose the bipedal walk's periodic function into a set of oscillators [8]. Assigning these oscillators to the joints of a humanoid robot enables one to develop a gait for the robot. According to [5], the main periodic function for the bipedal walk can be formulated as following:

$$f(t) = C + \sum_{i=1}^{N} A_i \sin(i \frac{2\pi}{T} t + \emptyset_i) \qquad (1)$$

Where N is the number of frequencies (degrees of freedom which are used in gait definition), C is the offset, $A_{1...N}$ are amplitudes, T is the period and $\emptyset_{1...N}$ are phases.

Decomposing the main periodic function using PFS gives us the following oscillators for the joints of a humanoid robot:

$$f_{LShoulder1}(t) = C_1 + A_1 \sin\left(\frac{2\pi t}{T} + \emptyset_1\right)$$

$$f_{RShoulder1}(t) = C_1 + A_1 \sin\left(\frac{2\pi t}{T} + \emptyset_1 + \pi\right)$$

$$f_{LThigh1}(t) = C_2 + A_2 \sin\left(\frac{2\pi t}{T} + \emptyset_2\right)$$

$$f_{RThigh1}(t) = C_2 + A_2 \sin\left(\frac{2\pi t}{T} + \emptyset_2\right)$$

$$f_{LThigh2}(t) = C_3 + A_3 \sin\left(\frac{2\pi t}{T} + \emptyset_3\right)$$

$$f_{RThigh2}(t) = C_3 + A_3 \sin\left(\frac{2\pi t}{T} + \emptyset_3 + \pi\right)$$

$$f_{LKnee}(t) = C_4 + A_4 \sin\left(\frac{2\pi t}{T} + \emptyset_4\right) \qquad (2)$$

$$f_{RKnee}(t) = C_4 + A_4 \sin\left(\frac{2\pi t}{T} + \emptyset_4 + \pi\right)$$

$$f_{LAnkle1}(t) = C_5 + A_5 \sin\left(\frac{2\pi t}{T} + \emptyset_5\right)$$

$$f_{RAnkle1}(t) = C_5 + A_5 \sin\left(\frac{2\pi t}{T} + \emptyset_5 + \pi\right)$$

$$f_{LAnkle2}(t) = C_6 + A_6 \sin\left(\frac{2\pi t}{T} + \emptyset_6\right)$$

$$f_{RAnkle2}(t) = C_6 + A_6 \sin\left(\frac{2\pi t}{T} + \emptyset_6\right)$$

This PFS model ensures the right and left feet of the robot alternately perform swing and support roles. Note that, this alternation can be achieved by adding a shift of π for pitch joints of the right foot. The above mentioned oscillators give the desired angle of joints in a specific time. In order to control the robot with these joint angles, we use a simple control method:

$$Speed * (\theta_{Target} - \theta_{Current}) \qquad (3)$$

Sending the outcome to the robot's motion interface causes the joints to move with the desired speed and value. The robot can move with a maximum speed of nearly 50 cm/sec by using this motion model. The produced gait is plotted graphically in Fig. 2.
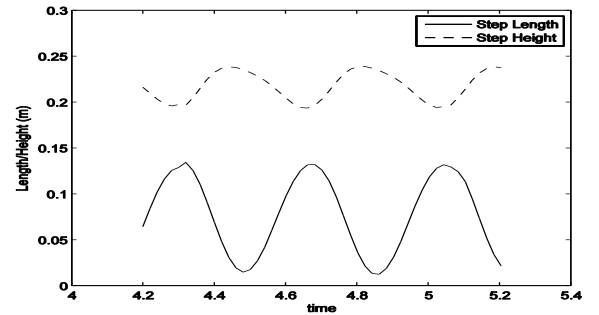

Figure 2. The analysis of the step length and height values for forward walking at 50cm/s speed. The step height is 5 cm in average and the step length is 12 cm in average.

III. DIFFERENTIAL STEERING SYSTEMS

This paper presents a differential steering system for humanoid robots, and it is based on the kinematic model for differential drive robots. For convenience, the common

notation for differential steering systems is repeated here. A differential steering robot is mounted on two wheels with a single axle. Each wheel is controlled and powered independently and this provides both drive and differential functions. When both wheels turn in the same direction and speed, the robot follows a straight line. When the wheel speeds are different in the same direction, the robot tracks a curved path towards the slower wheel. Equal speed for both wheels but in opposite directions makes the robot pivot [9].

Robots driven by a differential steering system, obey the respected simple kinematic model which provides the robot with the trajectory path and the desired wheel speeds for a specific trajectory.

The following equations can be used to find the displacement of the wheels [9]:

$$D_L = r\ \theta \qquad\qquad\qquad (4)$$

$$D_R = (r + b)\ \theta \qquad\qquad\qquad (5)$$

$$D_M = \left(r + \frac{b}{2}\right)\theta \qquad\qquad\qquad (6)$$

where r is the turn radius, b is the axle length and θ is the angle of the turn in radians. D_L and D_R are the distances traveled by left and right wheels respectively and D_M is the speed at the center point on the main axle.

The following equations are used to update the pose of a differential drive robot during its trajectory. Note that, since the robot is assumed to travel at a fixed and constant speed, acceleration/deceleration effects are ignored in these equations.

$$x(t) = x_0 + \frac{b(V_R + V_L)}{(V_R - V_L)}\left[\sin\left((V_R - V_L)\frac{t}{b}\right) - \sin(\theta_0)\right] \qquad (7)$$

$$y(t) = y_0 - \frac{b(V_R + V_L)}{(V_R - V_L)}\left[\cos\left((V_R - V_L)\frac{t}{b}\right) - \cos(\theta_0)\right] \qquad (8)$$

$$\dot{\theta} = (V_R - V_L)/b \qquad\qquad\qquad (9)$$

where V_L and V_R are the linear velocities of the left and right wheels respectively, $[x_0, y_0, \theta_0]$ represents the initial pose of the robot. Based on this background, in the next section, we show that the same principle can be successfully applied to a humanoid robot for the construction of a curved trajectory with a given turn amount.

IV.   THE DIFFERENTIAL STEERING SYSTEM FOR HUMANOID ROBOTS

We propose a method to control the trajectory of a humanoid robot on the basis of differential steering systems. Before the design of this new model, a thorough analysis of the robot's foot trajectory was made. When the trajectories of the joints are analyzed for the walking model of the

humanoid robot, it is easy to see that each foot performs a semi-circular locomotion around the axle of the hip of the robot. This is as expected, since the motion model ensures that every joint moves according to a sinusoid shifted by an offset, particular to that joint. The trajectory of each joint and that of its counterpart in the neighboring leg are complementary of each other. On the other hand, each pitch joint for the right leg follows the same trajectory of that of the left leg but with a phase shift of π. As a conclusion, the half circle drawn by the sinusoid of each joint in the left leg (the swinging foot), is completed by the half circle drawn by the sinusoid of the same foot joint in the right leg (the left leg is the support leg) and vice versa. This behavior is illustrated in Fig 3 for knee joints (both for left and right legs):
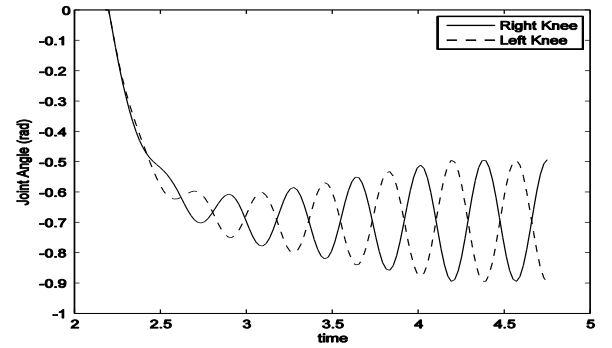

Figure 3. Joint trajectories for knee joints.

As can be seen in this figure, the motion starts with a start-up phase in which the speed is increased constantly during the time until it reaches its maximum. This is done, for all the joints, to prevent robot's instability due to initial acceleration. During the walk motion, when the speed reaches its maximum at approximately 50 cm/sec, it is kept constant.

To ensure a curved path by a humanoid robot, the corresponding joints of the robot's legs should be moved with a different angle in the same direction. Since the amount of movement of a leg in a certain amount of time will be different, the foot speed which can be interpreted as wheel speed will be different.

The following general equation describes the value of a joint angle for a curved trajectory of a humanoid robot:

$$f_{xL}(t) = \left(C_x + A_x \sin\left(n\frac{2\pi}{T}t + \emptyset_x\right)\right)(1 + CA) \qquad (10)$$

$$f_{xR}(t) = \left(C_x + A_x \sin\left(n\frac{2\pi}{T}t + \emptyset_x + \pi\right)\right)(1 - CA) \qquad (11)$$

Where *CA* is the curve amount in radians and is applied to left and right joints symmetrically to create different joint angle values for the left and right legs in the same direction. Note that, symmetry is crucial for mathematical simplification of the model, which is illustrated through

equations 12 -14 in this section. Different joint angles cause the left leg to make a larger step than the right leg when the *CA* is positive and vice versa. Adding the time parameter to the problem results in different step speeds for left and right legs. Fig. 4 shows the effect of applying the curve amount value of 0.058 to a normal step when the robot travels at its maximum speed:
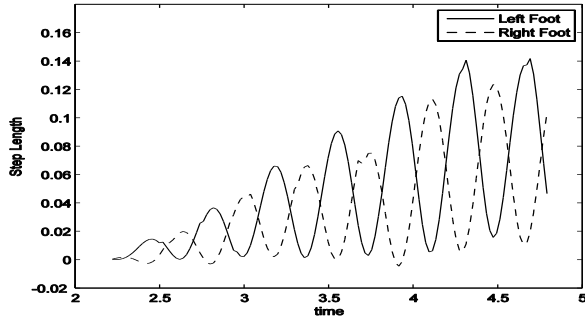

Figure 4. The effect of applying the Curve Amount variable, on the foot trajectory.

The important question here is whether the proposed model obeys the mathematical fundamentals of differential steering systems when applied to a humanoid robot. A convincing answer can be given by rewriting Eqautions (7) - (9) in terms of the *CA* variable.

Taking the proportional control model in (3) into consideration, we can rewrite (10) and (11) for all joints as following:

$$V_L = (1 + CA) * \frac{J'_l - J_l}{t} \quad , V_R = (1 - CA) * \frac{J'_r - J_r}{t} \qquad (12)$$

J'_l is a specific joint's calculated angle value for the left leg and J_l is that joint's current angle value. J_r and J'_r can be interpreted in the same way for the right leg.

It is clear that without applying the *CA* variable, the speed of the left and right legs are equal and the default joint angular speeds are calculated via the following equations:

$$V_{Default} = V_R = V_L = \frac{J'_l - J_l}{t}$$

So we can again rewrite the equations for V_L and V_R, as following:

$$V_L = (1 + CA) * V_{Default} \quad , V_R = (1 - CA) * V_{Default}$$

Replacing V_L and V_R in (9) and doing the mathematical simplifications, which are now possible due to the fact that *CA* has been applied for left and right leg symmetrically, we have the following equation:

$$CA = -\frac{b \ \dot{\theta}}{2 \ V_{Default}} \qquad (13)$$

Where *b*, is the distance between the legs of the robot. This equation is in fact the relationship between the *CA* variable and robot's orientation change. Using the same method we can rewrite (7) and (8) like the following:

$$x(t) = x_0 - \frac{b}{CA}\left[\sin\left(\frac{-2.CA.V_{Default}.t}{b}\right) - \sin(\theta_0)\right] \qquad (14)$$

$$y(t) = y_0 + \frac{b}{CA}\left[\cos\left(\frac{-2.CA.V_{Default}.t}{b}\right) - \cos(\theta_0)\right] \qquad (15)$$

By using equations (13)-(15) we can calculate the new position of a humanoid robot based on the differential steering odometry.

V. EXPERIMENTAL REULTS

In this paper, we have used the realistic Simspark simulation environment as our test platform. Simspark is the official simulator for RoboCup competitions and uses ODE (Open Dynamics Engine) for physics simulation [6].

Our experiments show that the *CA* value is bounded by a maximum at 0.15 for a stable curve walking at a constant speed of 50 cm/sec. The validity of the approach has proven empirically and the boundary values have been determined on the simulated Nao robot. The determined values are successfully used by the beeStanbul team for the Robocup 3D simulation league competitions at Singapore, 2010 [10]. A sample illustration of the simulated Nao robot path is given in Fig. 5. In this figure, the robot tracks a cyclic path by setting the CA value as 0.058. The related video can be found at [11].
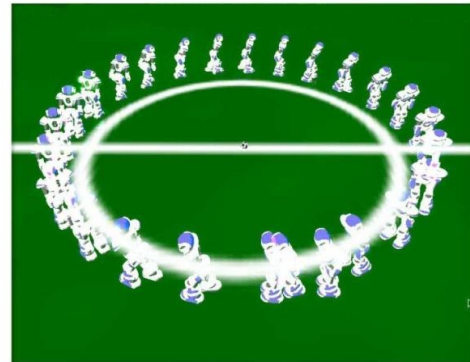

Figure 5. The robot completes a full turn using differential steering system

We have also investigated the relationship between the *CA* value and the speed of the robot. It has been observed through simulations that the threshold of *CA* is closely related to the speed of walking. In our experiments, we have used 0.0775 (maximum speed) as our speed coefficient in Eq. (2), and decreased this coefficient linearly with respect to CA. As the speed decreases, the maximum boundary for CA increases. As the empirical analysis illustrates, the

differential steering system is successfully simulated by using the proposed model for a humanoid robot.

The graphs in Fig. 6 show the effect of increasing the Curve Amount variable on the stability of the robot, both for forward walking and backward walking (the speed is set to a constant value of 0.0775):
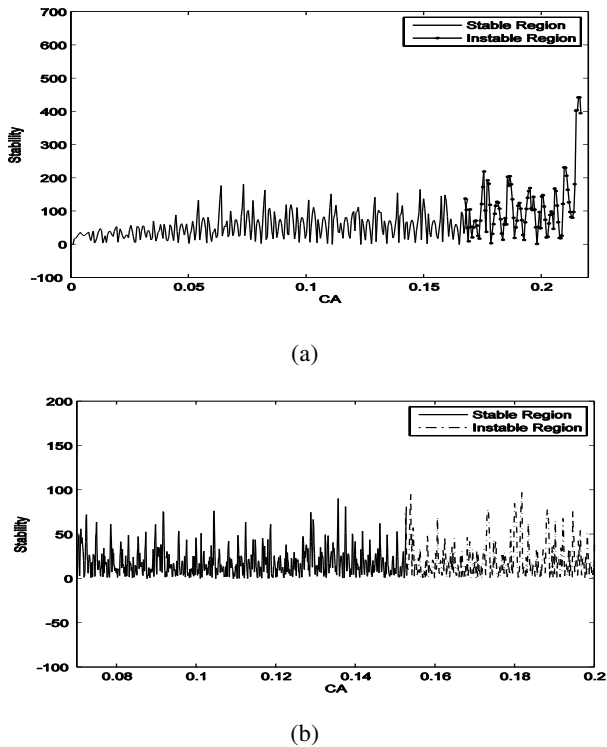

(a)

(b)

Figure 6. The effect of increasing CA on stability (a) forward walking (b) backward walking

For both forward and backward walking cases, the increase in Curve Amount value leads to a very slight increase in instability, which is normal due to the nature of motion. After a certain threshold (nearly 0.15 for forward and 0.17 for backward walking) the robot starts to make a large pendulum to the sides and forth, and then falls. Before reaching that threshold, the instability is fairly small. The difference between the *CA's* maximum threshold for forward and backward walking comes from the fact that in both motion types the trunk of the robot is inclined forward. In backward walking, the direction of motion vector (and hence the created force vector) is in the opposite direction of inclination and this makes backward walking more stable.The stability of the robot is measured by aggregating the gyro values in *x, y, z* directions. The gyro is mounted at the torso of the robot.

VI.   CONCLUSION AND FUTURE WORK

In this work, we have shown both theoretically and empirically that the fundamentals of differential steering robots can be applied to biped robots of which the odometry can be calculated by the mathematical rules of differential steering systems. The empirical analysis of the proposed model is given for the simulated Nao robot in Simspark environment. Although the analysis is given for a specific robot type, the model presented here can be extended to any humanoid robot type. As the experimental results illustrate, the curve walking behavior for a humaonid robot can be successfully obtained by using our extended TFS model involving new parameters for curve walking. The future work includes utilizing the benefits of wheeled robot dynamics for humanoid robots on rough terrains, stairs, slopes and etc.

VII.   REFERENCES

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