Walking trajectory control of a biped robot

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Abstract.

A not trivial problem in bipedal robot walking is the instability produced by the violent transition between the different dynamic walk phases. In this work an dynamic algorithm to control a biped robot is proposed. The algorithm is based on cubic polynomial interpolation of the initial conditions for the robot's position, velocity and acceleration. This guarantee a constant velocity an a smooth transition in the control trajectories. The algorithm was successfully probed in the bipedal robot "Dany walker" designed at the Freie Universität Berlin, finally a briefly mechanical description of the robot structure is presented.

1. Introduction.

Biped robots can walk in almost any type of terrain included those that are impossible for robots with wheels. Biped robots compared with other type of robots are better skilled for certain works and have a better degree of mobility especially in environment with obstacles. For this reason, is promising the use of biped robots for human environments and the developing of biped robot's control algorithms.

Many biped robots have been developed in recent years [16], [20], [24], [25] and many researches have put their attention in the development of control algorithms for biped robots [4], [22], [26], [27].

Mc Geer [1] developed a passive biped robot to study dynamic walking. The robot can settle a stable gait without an input control. The gait sequence is generated by the interaction of the gravity and the mechanical system inertias.

Shuuji Kajita [2] designed and developed an almost ideal 2-D model of a biped robot. He used four motors in the robot's body and the legs are configure like parallel links to the mechanism. Kajita supposed for simplicity that the robot's COG (Center of gravity) moves horizontally. With those characteristics he developed a control law for initiation, continuation and termination of the walking process.

Zhen [3] proposed an scheme to enable the robot climb inclined surfaces. By force sensors placed in the robot's feet, the transition of the type terrain can be detected and then the appropriately motors movements to compensate the inclination can be generated. Using other approach, Zhen, uses the inclination (as indirect measure of the COG) of the mechanical structure as correction index in the gait walking.

Shih [5], [6] designed a biped robot of 7 DOF. The robot has a mobile weight structure and variable length feet. The first characteristic allows to control the robot in the lateral plane, while the second enables the robot to adapt the length leg according to the terrain conditions (inclined or horizontal).

Zheng synthesized the algorithm of static walking. Shih [7] proposed the control of the COG in static walking for not structured terrain. Kajita [2] studied the control of the dynamic walking for biped robots based in the energy principle. Jong [11] proposed a biped robot control method based on the control of impedance and the modulation of it.

Pratt proposed the control of a planar robot biped by means of the natural dynamics [9]. This is an algorithm based on the observations of the human gait, which is used as reference for the robot's control. The advantage of this algorithm is that it doesn't require many sensors to allow the robot to walk.

Kajita and Tani [12] used a model of the inverted pendulum to accomplish the walking in rugged terrain. In this work they conducted 2 experiments: the single leg support phase and the change of support leg. As a result, they found that to achieve a smooth exchange of support leg is necessary to maintain a vertical speed as well to maintain for some instants the double support phase.

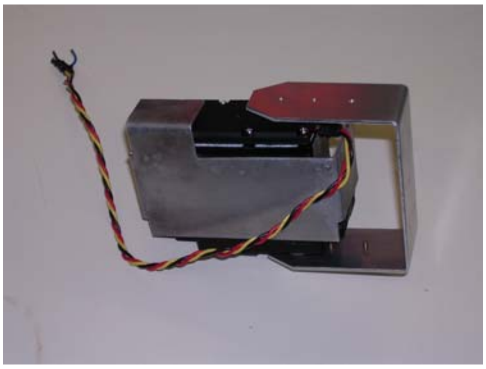
The stable walking of biped robots can be characterized by some criteria. Static walking is characterized by maintaining the COG inside of the support region (the interior perimeter formed by the foot or the feet in contact with the floor). However, the dynamic walking don't need to conserve the COG in the support region, the important criteria is to maintain the ZMP (Zero Moment Point) inside of support region (from now on this criteria will be mentioned as the "ZMP criteria"). The use of this criteria has been broadly used to generate biped control algorithms [13], [14]. Many researches have developed control algorithms controlling the hip trajectories following the ZMP criteria [15], [16].

Cubic interpolation is used for many researchers as a biped robot's gait generation. Shih [5] and Huang [18] have used cubic polynomials to generate the hip and foot trajectory to walk on uneven terrains. The work of Shih discusses only the static walking, while the work of Huang proposes a method for dynamic walking. For our robot is proposed and implemented an algorithm based on cubic polynomials to generate the trajectories. This algorithm produced smoother transitions that others methods used previously.

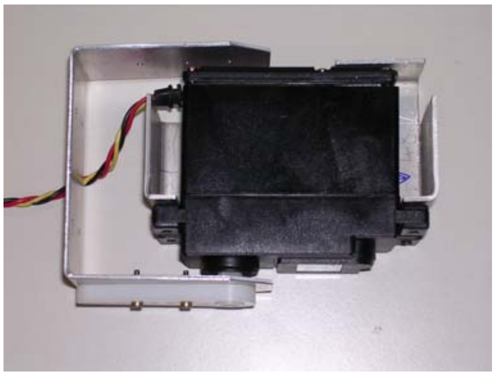
This report briefly describes the mechanical design and proposes a control trajectory algorithm for dynamic walking of a biped robot. This work is organized as follows. In section 2, the mechanical structure is briefly presented. In section 3, the control algorithm is discussed. Finally in section 4, the results of the implementation are presented.

2. Mechanical structure

The dynamic of a biped robot's are closely related with its mechanical structure. In this section the mechanical structure for the biped robot "Dany Walker" [30] is briefly described.



(a)



(b)

Fig 1. Biped robot links.

"Dany Walker" is a robot composed from 10 low-density aluminium links. Each link (figure 1) consists of a special structure designed to allow an effective torque transmission and low deformation. Each link contains a servomotor J/R Conrad S-8051 BB. The links are connected forming a biped robot of 10 degrees of freedom whose kinematics is shown in figure 2.

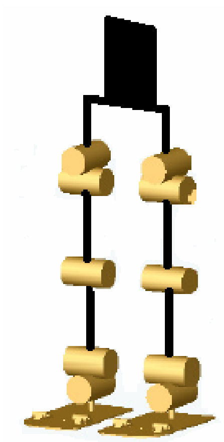


Fig 2. Kinematics arrangement of the "Dany Walker" robot.

The servomotors of the structure are controlled by a PIC microcontroller, able to drive 12 servomotors simultaneously to relatively high speeds.

3. Dynamic trajectory walk algorithm.

The walk of a biped robot can be determined by controlling the hip and foot trajectories. The stability can be achieved by applying the ZMP criteria. Cubic polynomials are used to control the sagittal motion. Only the control for the sagittal motion will be discussed in this paper.

3.1 Polynomial interpolation

The process of building a function *f(x)* such verify that in predetermined values of the independent variable $x_0, x_1, \ldots, x_n$ can takes values like $y_0=f(x_0), y_1=f(x_1),\ldots, y_n=f(x_n)$ is known as interpolation and can be defined as a classic procedure for function approach.

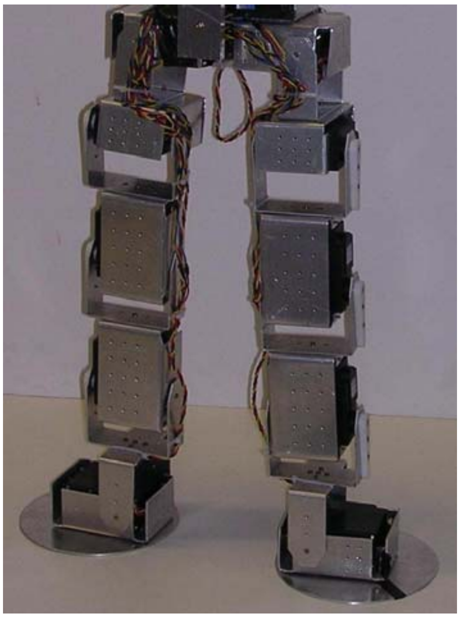


Fig. 3. Final configuration for the "Dany Walker" biped robot.

Very important is to establish the type function such satisfy the interpolation condition $y_i=f(x_i)$ with $i=0,\dots, n$. Then exists an infinity number of functions that satisfy the data conditions to be interpolate.

A polynomial generic function can be generated by n+1 coefficients in respect a fixed base. The n+1 conditions produces a system equations whose resolution generates the searched function.

Considering as a base

$$\Im = \{1, x, x^2 \dots, x^n\} \quad (1)$$

a polynomial can be defined as:

$$P_n(x) = a_0 + a_1 x + a_3 x^2 + \dots + a_n x^n \quad (2)$$

Considering a interpolation support of $x_0 < x_1 < \dots < x_n$ and their corresponding function values $y_0, y_1 \dots, y_n$ the system of equations to generate the interpolation conditions are:

$$\begin{bmatrix} 1 & x_0 & x_0^2 & \dots & x_0^n \\ 1 & x_1 & x_1^2 & \dots & x_1^n \\ \dots & \dots & \dots & \dots & \dots \\ 1 & x_n & x_n^2 & \dots & x_n^n \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \dots \\ a_n \end{bmatrix} = \begin{bmatrix} y_0 \\ y_1 \\ \dots \\ y_n \end{bmatrix} \quad (3)$$

The Matrix of this system acquires a special structure denominated Vandermonde Matrix whose determinant can be calculated easily by:

$$\det(B) = \prod_{i>j} (x_i - x_j) \qquad (4)$$

Because the interpolation nodes $x_0 < x_1 < \ldots < x_n$ are different, is evident that $\det(B) \neq 0$ independently of the interpolation support. Thus, the interpolation problem always have an unique solution.

<u>Example.</u>

Consider the interpolation points (0,2), (1,1), (2,0) ,(3,5).

The nodes support are $S=\{1,2,3\}$ that corresponds to $n=3$, then, the searched polynomial have to be of third degree or smaller.

$$P_3(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \qquad (5)$$

The equations system represented as:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 2 & 4 & 8 \\ 1 & 3 & 9 & 27 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 2 \\ 1 \\ 0 \\ 5 \end{bmatrix} \qquad (6)$$

Solving the equation system, we obtain $a_0=2$, $a_1=1$, $a_2=-3$ and $a_3=1$, and the polynomial is represented as:

$$P_3(x) = 2 + x - 3x^2 + x^3 \qquad (7)$$

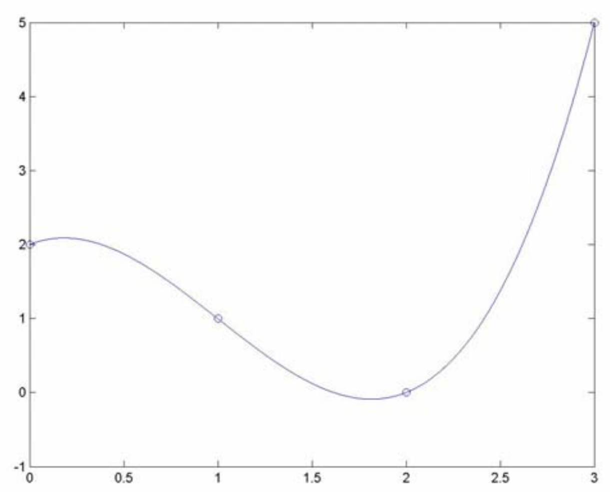


Fig 4. Polynomial interpolation.

3.2 Developing the algorithm.

The control algorithm have three parts:

1. For each step, the desired velocity (v_{xhe},v_{zhe}) and the step length *Ls* are previously specified.
2. The desired angle is previously specified (figure 4).
3. The hip and foot trajectories are generated by different walking periods, then is chosen the trajectory that guarantees the ZMP criteria.

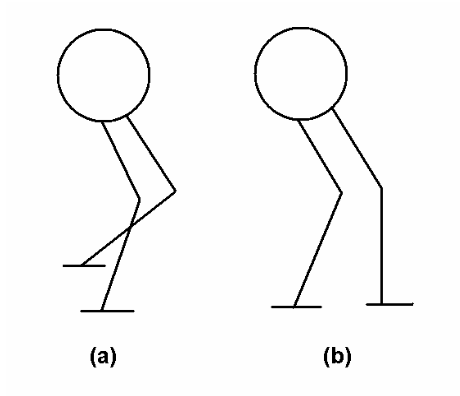


Fig. 5 Walking phases, (a) single support and (b) double support.

A walking cycle can be divided into single support phase and double support phase. As shown in the figure 5. In the single support phase, One foot support the robot's weight while the other foot is moving on the air from backward to forward, at the same time the hip moves along a trajectory *Th* as shown in figure 6.

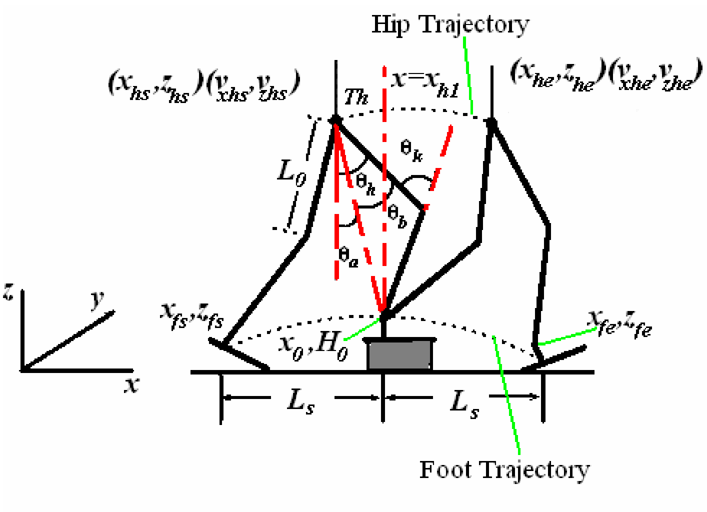


Fig. 6 Hip and foot trajectory.

The simple support phase begins when the foot in movement leaves the floor and lift on the air and finishes when returns to the floor. The double support phase begin when the foot in movement (at single support phase) touch the floor and ends when the foot at the floor (at single support phase) leaves the floor. To achieve dynamic walking, the change between simple supports phase and double supports phase should be smooth. Usually in the beginning of the double supports phase, the foot impact against the floor when it returns from the air is very strong and obviously affects the walking balance. A solution for this problem is the use of feedback-force control.

The ZMP is a point on the ground where the sum of all momentums are zero. Using this principle, the ZMP can be computed as follows:

$$x_{ZMP} = \frac{\sum_i m_i(\ddot{z}+g)x_i - \sum_i m_i \ddot{x} z_i - \sum_i I_{iy} \ddot{\theta}_{iy}}{\sum_i m_i(\ddot{z}+g)} \tag{8}$$

$$y_{ZMP} = \frac{\sum_i m_i(\ddot{z}+g)y_i - \sum_i m_i \ddot{x} z_i - \sum_i I_{ix} \ddot{\theta}_{ix}}{\sum_i m_i(\ddot{z}+g)} \tag{9}$$

where ***(x_{ZMP}, y_{ZMP},0)*** are the ZMP coordinates, ***(x_i,y_i,z_i)*** is the mass center of the link *i* in the coordinate system, *m* is the mass of the link *i*, *g* is the gravitational acceleration. I_{ix} and I_{iy} are the inertia moment components, θ_{iy} and θ_{ix} are the angular velocity around the axes *x* and *y* (taked as a point from the mass center of the link *I*) . The robot's masses distribution is shows in figure 7.

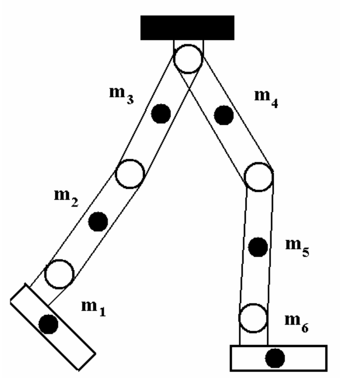


Fig. 7. Distributions of the robot's masses.

In the sagittal plane, the ZMP is directly calculated dividing the ankle torque by the force reaction at the ground:

$$x_{ZMP} = \frac{\tau_x}{\sum_i m_i(\ddot{z}_i+g)} \tag{10}$$

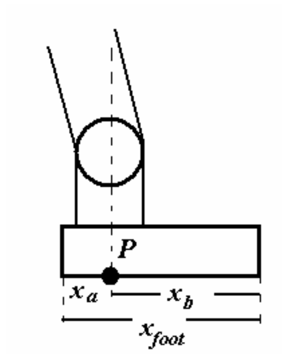


Fig. 8. Stable area of the ZMP in the axis x.

To maintain the balance in dynamic walking the ZMP point must be in the foot convex area, in contact with the floor as shown 8. The ZMP can be defined as:

$$x_{ZMP} \in \{S | S \in R, S \in (-x_a, x_b)\} \quad (11)$$

the negative sign of x_a means that point P is at the origin.

Suppose that the robot has a mass point in the hip and the support knee is in a constant position, for these conditions the inverted pendulum model can be used to model the dynamics movements of the robot's structure. The figure 9 shows the robot's model to determine the ankle torque.

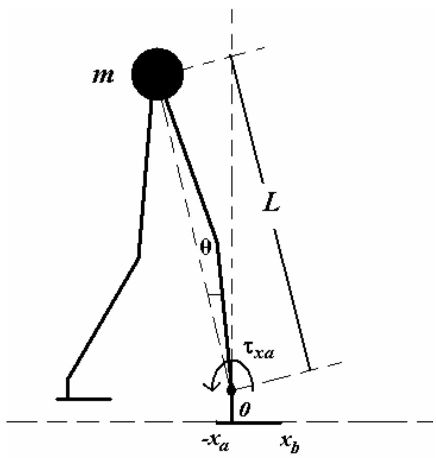


Fig 9. Biped robot's model obtained from the inverted pendulum model.

L is the leg longitude, $\tau_{xa}(\theta)$ and $\tau_{xb}(\theta)$ are the maximum and minimum possible torques for the ankle in the sagittal plane. Then this relationship can be described as:

$$\tau_{xa}(\theta) = m(g + (\frac{\tau_{xa}(\theta)}{Lm} - g\sin(\theta))\sin(\theta) - \frac{v^2}{L}\cos(\theta))x_a \quad (12)$$

where v is the hip velocity and $\frac{v^2}{L}$ is the centripetal acceleration.

The centripetal acceleration is smaller than other components so it can be eliminated from equation 12, then the ankle torque can be redefined as:

$$\tau_{xa} = \frac{mgx_a(1-\sin^2(\theta))}{1-\frac{\sin(\theta)}{L}x_a} \tag{13}$$

$$\tau_{xb} = \frac{mgx_b(1-\sin^2(\theta))}{1-\frac{\sin(\theta)}{L}x_b} \tag{14}$$

3.2.1 Hip Trajectory for single support phase

As was shown in figure 6, the hip trajectory can be generated by cubic polynomials algorithms, if the initial and final state are known from single phase. The initial state in figure 6, define [x_{hs},z_{hs}] and [x_{he},z_{he}] for the final state. The initial velocity [v_{xhs},v_{zhs}] (produced when the robot leaves the initial position) is also specified in the trajectory model. The same case is for the final velocity [v_{xhe},v_{zhe}] (when the robot arrives to his final position).

The initial and final state positions for the cubic trajectory for z (the $z_h(t)$ direction) can be expressed as:

$$z_h(t) = \begin{cases} z_{hs} & if \quad t = kT \\ z_{he} & if \quad t = kT + T_s \end{cases} \tag{15}$$

where T is the period for the robot's step and T_s the period in single support phase.

$$\dot{z}_h(t) = \begin{cases} v_{zhs} & if \quad t = kT \\ v_{zhe} & if \quad t = kT + T_s \end{cases} \tag{16}$$

The cubic polynomial can be generalized by the following expression:

$$z_h(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{17}$$

obtaining:

$$z_h(t) = z_{hs} + v_{zhs}(t-kT) + \frac{3(z_{he}-z_{hs}) - 2v_{zhs}T_s - v_{zhe}T_s}{T_s^2}(t-kT)^2 \tag{18}$$

$$+\frac{2(z_{hs}-z_{he}) + (v_{zhs}+v_{zhe})T_s}{T_s^3}(t-kT)^3 \qquad kT < t \le kT + T_s$$

$x_h(t)$ is divided in two parts: from $x_h(KT)$ to $x_h(kT+T_1)$ and from $x_h(kT+T_1)$ to $x_h(kT+T_p)$. The configuration for $x_h(t)$ is:

$$\begin{cases} x_h(t) = x_{hs} & t = kT \\ x_h(t) = x_{h1} & t = kT + T_1 \\ x_h(t) = x_{he} & t = kT + T_p \\ \dot{x}_h(t) = v_{xhs} & t = kT \\ \dot{x}_h(t^-) = \dot{x}_h(t^+) & t = kT + T_1 \\ \dot{x}_h(t) = v_{xhe} & t = kT + T_p \\ \ddot{x}_h(t) = a_0 & t = kT \end{cases} \tag{19}$$

where a_o should be previously specified to satisfy the initial condition of acceleration. The trajectory cubic polynomial can be obtained as follows:

$$x_h(t) = \begin{cases} x_{hs} + v_{xhs}(t-kT) + \frac{1}{2}a_0(t-kT)^2 \\ + \frac{(x_{h1} - x_{hs} - v_{xhs}T_1 - \frac{1}{2}a_0 T_1^2)(t-kT)^3}{T_1^3} & kT < t \leq kT + T_1 \\ x_{h1} + v_{xh1}(t - kT - T_1) \\ + \frac{(3(x_{he} - x_{h1}) - 2v_{xh1}(T_p - T_1))(t - kT - T_1)^2}{(T_p - T_1)^2} \\ + \frac{(2(x_{h1} - x_{he}) + (v_{xh1} + v_{x2})(T_p - T_1))(t - kT - T_1)^3}{(T_p - T_1)^3} & kT + T_1 < t \leq kT + T_p \end{cases} \tag{20}$$

3.2.2 Swing and foot trajectory at single support phase

The cubic interpolation is used to generate the foot trajectory in single support phase. The initial and final foot position that represents the satisfied states and velocities are:

$$x_f(t) = \begin{cases} x_f(t) = x_{fs} & t = kT \\ x_f(t) = x_{fe} & t = kT + T_s \\ \dot{x}_f(t) = 0 & t = kT \\ \dot{x}_f(t) = 0 & t = kT + T_s \end{cases} \tag{21}$$

$$z_f(t) = \begin{cases} z_f(t) = z_{fs} & t = kT \\ z_f(t) = z_{fe} & t = kT + T_s \\ \dot{z}_f(t) = 0 & t = kT \\ \dot{z}_f(t) = 0 & t = kT + T_s \end{cases} \tag{22}$$

Considering that we know the initial and final states in x and z directions, a smooth trajectory can be generated by the cubic polynomial interpolation. Defined in this case as follows:

for $x_f(t)$

$$x_f(t) = x_{fs} + 3(x_{fe} - x_{fs})\frac{(t-kT)^2}{T_s^2} - 2(x_{fe} - x_{fs})\frac{(t-kT)^3}{T_s^3} \quad kT < t \le kT + T_s \tag{23}$$

for $z_f(t)$

$$\begin{cases} z_{fs} + 3(z_{fm} - z_{fs})\frac{(t-kT)^2}{T_m^2} - 2(z_{fm} - z_{fs})\frac{(t-kT)^3}{T_m^2} & kT < t \le kT + T_m \\ z_{fm} + 3(z_{fe} - z_{fm})\frac{(t-kT-T_m)^2}{(T_s - T_m)^2} - 2(z_{fe} - z_{fm})\frac{(t-kT-T_m)^3}{(T_s - T_m)^3} & kT + T_m < t \le kT + T_s \end{cases} \tag{24}$$

The hip and knee position to produce the leg's movement can be calculated using the inverse kinematics of the robot's structure.

3.3 Determination of the algorithm parameters

The determination of the parameters T_p,v_{xhs},T_1,T_m and z_{fm} is not trivial because the modification of one of them supposes a change in the trajectory and conditions of smoothness in the velocity and accelerations. One of the main characteristics of this approach is that the velocity at the end of single support phase is zero or near to zero, therefore a smooth contact with the floor surface is guaranteed.

To determine these parameters a Matlab interface was programmed, it allows to modify all the important parameters (represented at the equations 18, 20, 23, 24) in automatic form. Thus we can easily vary the parameters and verify the consistency of the trajectories. The figure 7 show the program interface.

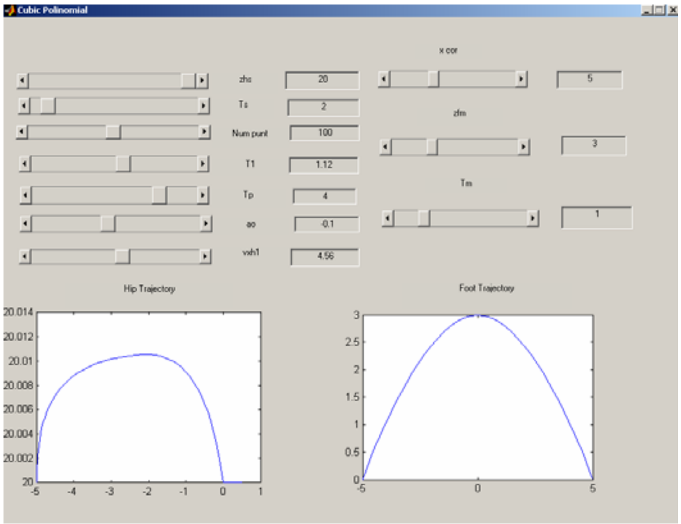


Fig 7. Matlab program to calculate the algorithm parameters.

3.4 Control position of the links

The inverse kinematics from the robot's structure is used to find the angular reference (motor’s positions). The trajectories for the hip and the foot at single support phase are calculated using equations 18, 20, 23, 24.

This control problem can be divided in two parts, the first one is represented by the leg having contact with the floor and the second part is represented by the leg rising in the air moving from backward to forward.

In the first case the hip motor don’t changes its position, at the same time, the necessaries movements to perform the foot trajectory are made only by the knee and ankle motors as shown in figure 11 .

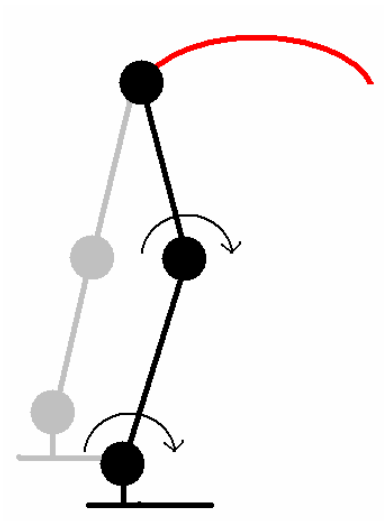


Fig. 11. Motors movement preformed by the leg in contact with the floor.

In the second case the ankle motor don't changes its position, at the same time, the necessaries movements to perform the foot trajectory are made only by the knee and hip motors as shows figure 12.

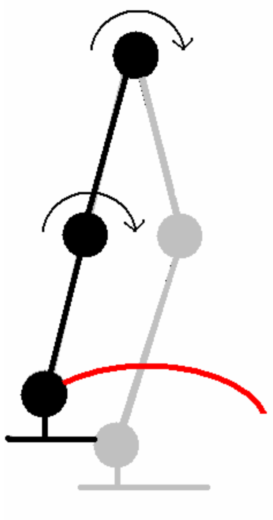


Fig. 12. Motors movement performed by the leg rising in the air.

4. Implementation results.

Configuring the parameters for the trajectory walk algorithm proposed the following values were obtained:

Parameter	Value
x_{hs}	-5
x_{he}	0
z_{he}	20
z_{hs}	20
x_{h1}	-2.5
v_{xhs}	0.1
v_{xhe}	0.18
v_{zhs}	0.01
v_{zhe}	-0.03
T_s	2
T_1	1.14
T_p	4
a_0	-0.02
v_{xh1}	4.56
z_{fm}	3
T_m	1

The following links positions are obtained by resolving the robot's inverse kinematics:

a) *For the leg in contact with the floor:*

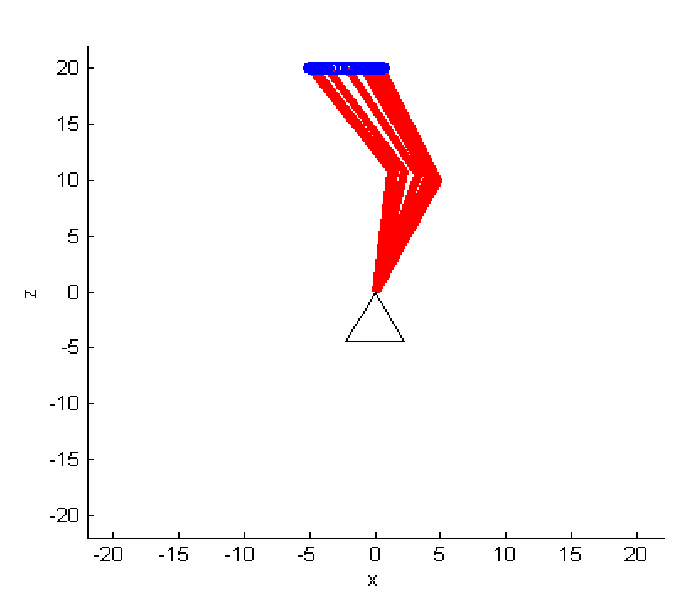


Fig. 13. Motor's position for the ankle and knee.
(obtained resolving the inverse kinematics of the "Dany Walker" robot.)

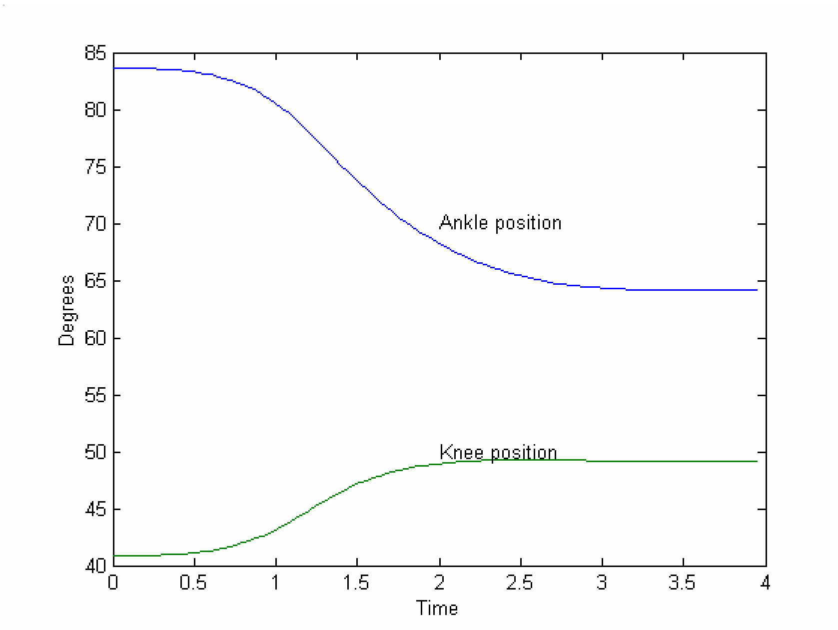


Fig 11. Motor's positions for the ankle and knee.

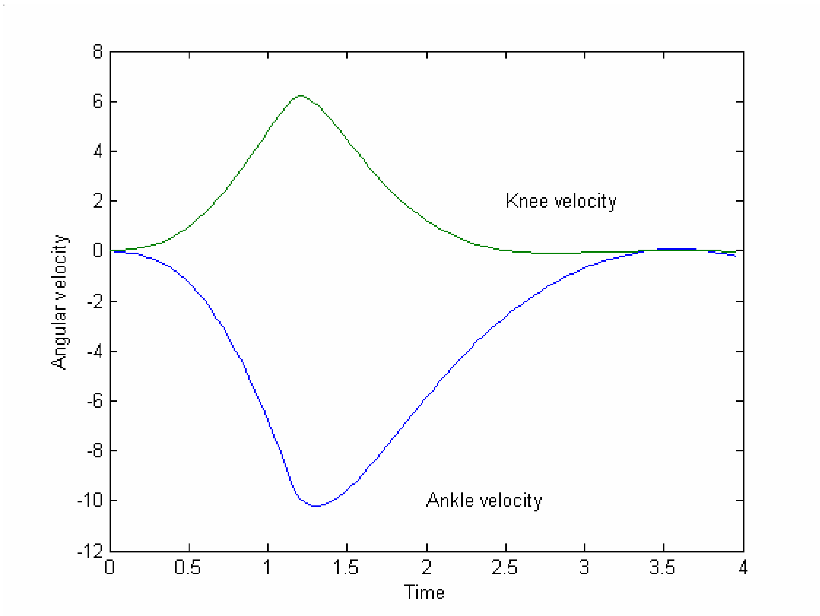


Fig 12. Velocity for the ankle and knee motors.

b) *For the leg rising from backward to forward:*

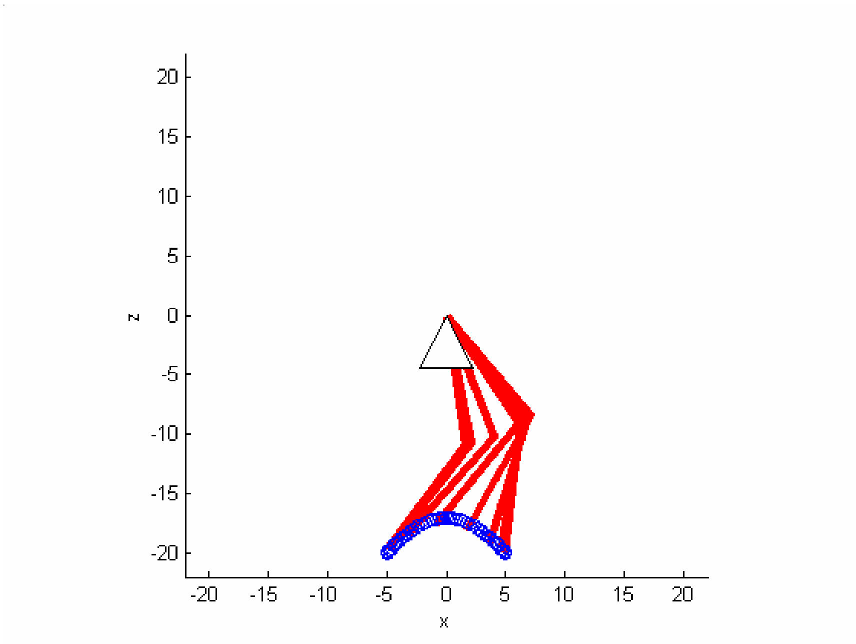


Fig. 16. Motor's position for the hip and knee.
(obtained resolving the inverse kinematics of the "Dany Walker" robot.)

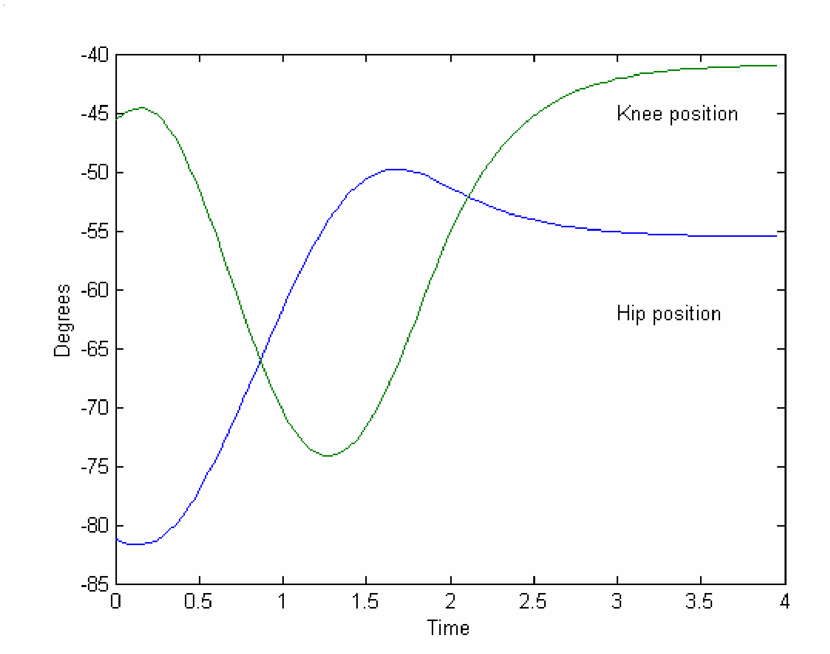


Fig 17. Motor's positions for the hip and knee.

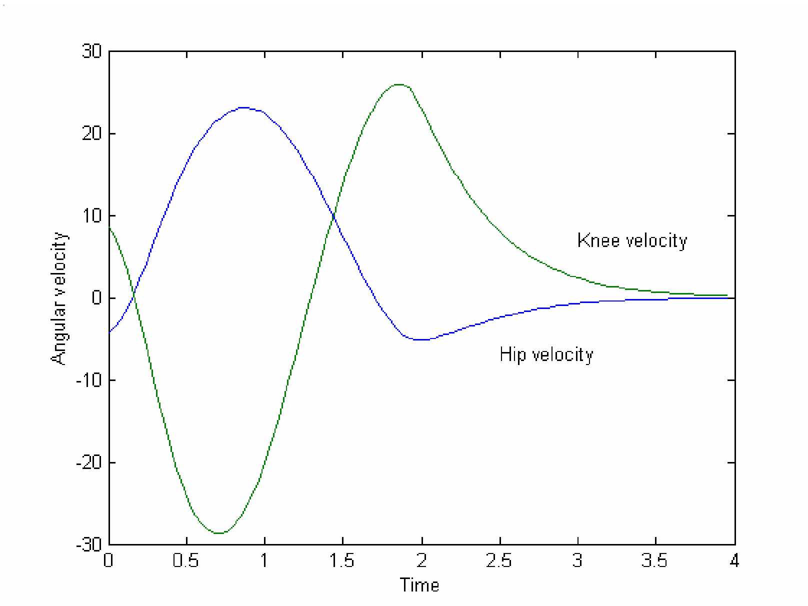


Fig 18. Velocity for the hip and knee motors.

From the previous graphs is possible to observe the smooth transition between the single support phase and the double support phase. (because the velocities reached at the end of this cycle are zero or very near to zero). This characteristic of the algorithm allows the robot to gain stability even in violent impact as those produced by the link's velocity during single support phase. The algorithm was programmed in Visual C++ and proved in the "Dany Walker" biped robot running in a Pentium PC at 900MHz.

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