Design and development of a quadruped spider robot

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***Abstract*—The spiders, in comparison with the majority of others animals, it has the ability to access to that kind of environment where others animals or even the humans can't. Those attributes of the spiders are taken into this project in order to design and develop a quadruped spider robot in conditions to move in all kind of directions and perform such movement like ascend or descend. The paper is presented the dynamic and kinematics model with the purpose of understand how, mathematically, a quadruped animal and a spider walk. In this case we studied the movement of a real spider, so we can define a suitable bio-mimetic model for our robot. Similarly, the motion simulation was implemented and the results are shown.**

Index Terms: **Robot´s simulation, Spider motion, Quadruped.**

I. Introduction

In the recent history, the human want to replicate all kind of movement of the animal kind, having really nice results. This effort on doing that, allowed humans to realize that they can use robots for certain task instead of risk human lives. This kind of biomimetic replication can be employed in, for example, land mines task and exploration task. [1] Another important application of these robots is the incursion in dangerous environments, like contaminated places, or hostile landmarks. At first we wanted to implement this robot in exploration task, but due his characteristics, it can be fulfilled in a variety of other task, like the ones we mentioned previously.

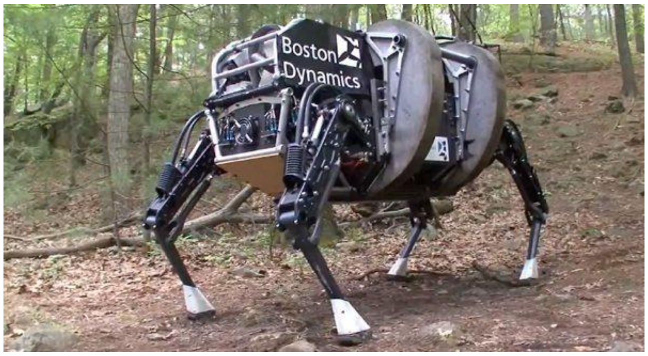

Figure 1: Big Dog [2]

If we deepen in the topic, Boston Dynamic's it's a business that design and produce a huge variety of robots, especially quadruped ones. [2] The most popular quadruped robot of Boston Dynamic's its Big Dog. Figure 1.

Big Dog it's employed entirely in exploration duties. As you can imagine, all the robots produced by Boston Dynamics have a lot of and new technology, a totally different means like, Big Dog wasn't a point of inspiration because this resembles more like a cow or a dog instead of a spider.

The spider robot was built around 90's where researches started to innovate the whole world with their robots. [3] In 2008, this business built a hexapod spider robot, which had the ability of climb all kind of surfaces.

Nowadays, the majority of information found in the internet suggests that the quadruped spider robots are developed by amateurs or fans who want to have that kind of toys. Obviously there are exceptional material and work. Proofs of these are presented in references.

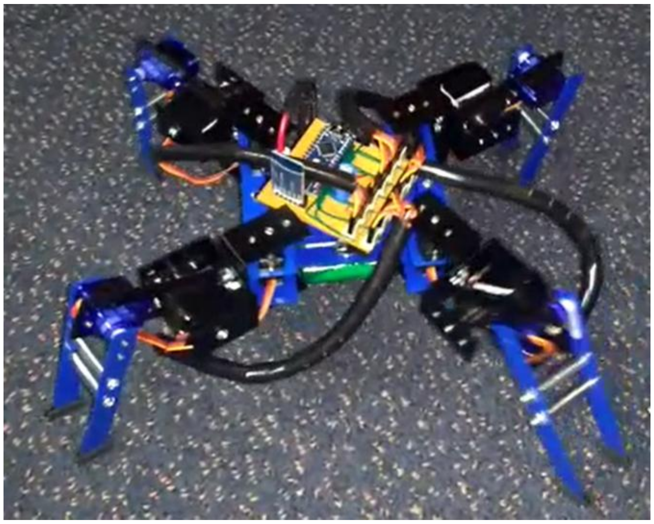

Figure 2: Quadruped Robot

This paper presents a robot based on 4 different quadruped spider robots, all with different attributes and characteristics, See figure 2. at the same way historical contributions, we must mention a particular quadruped spider robot; the machine that we are evaluated represents the biggest inspiration in our project. The particular robot was made by Claudio Semini University of Genoa, Italy, Ph.D. student project. [5].

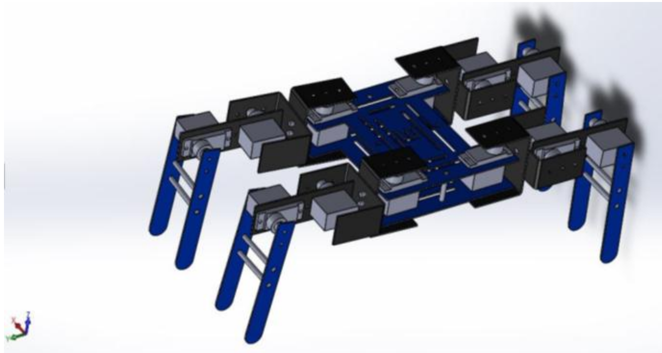

Figure 3: Quadruped robot design

The movement of this robots served to us as inspiration for our motion process, which we want to replicate in a biomimetic way. Other approaches are being done by using other mechanism for quadruped walking like parallel mechanism [6], soft materials [7] and so on. Nevertheless, we get a bunch of ideas from other institutes and individual to make our project. Figure 3.

II. The Quadrupeds

In order to accomplish this robot, we initially observed the behavior of the quadrupeds in the animal kind, this means, in their natural environment. We stablished how they move, the algorithm behind this process. But we found a problem in this section. The majority of the quadrupeds move in a mammalian form, like a dog or a horse, for example. This represented a problem because we wanted it to move in an arachnid way. Besides this, the spider has 8 limbs, so we couldn´t use them as a direct source of inspiration, at least in the beginning.

To solve this problem, we used a mixture of sources of inspiration; we had the quadrupedal animals (their movement and behavior) and by the other hand we had the anatomy of the spider. So in this orders of ideas, the anatomy or physic shape of the spider, and the movement of the quadruped animals in an arachnid way was used.

III. Motion Analysis

Initially, it's important to know that the spider has 7 parts by leg (figure 4). These parts are: coxa, trochanter, femur, patella, tibia, metatarsus and tarsus. This spatial arrangement it's illustrated in the figure 4. From the original anatomy of the spider, we suppress some components which we didn't need. The reason of this it's because we wanted to simplify the whole system. Having said this, instead of using the Patella part, we linked the femur and the tibia by a direct joint. The metatarsus and the tibia were united as a single link or part. Similarly, we dismiss the tarsus. All of these dismissals were executed in the robot, but for the kinematics we took account the entirely system for a realistic approach and because we wanted to know what exactly we were suppressing.

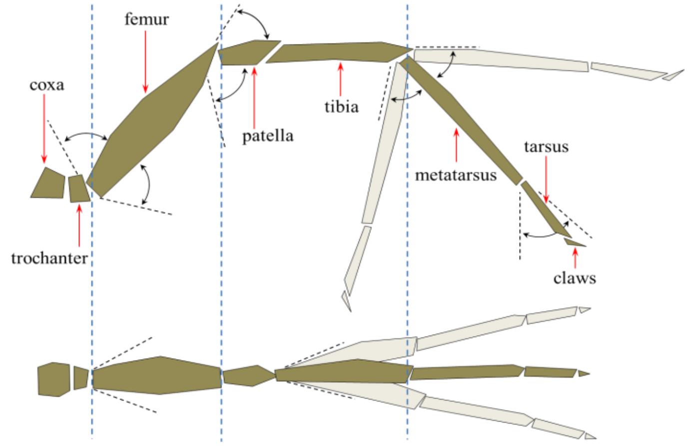

Figure 4: Spider's leg

One important aspect is the amplitude that has every part of the spider leg. This means, for example, that the coxa has amplitude of 35 degrees while tibia has a mobility of 70 degrees. Also, every of the seven components of the limb, has a different axis of movement; for example, the trochanter has a movement in X-Y axis, meanwhile the femur in X-Z axis. This kind of association and motion, it's explained graphically in the figure 5.

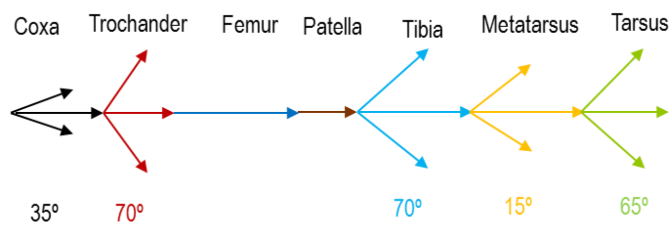

Figure 5: Range of movement of the spider

So, in this point it's convenient to establish the different joints and links which constitute the system limb of the spider.

- Body-Coxa joint: Some authors view this joint as a three degrees of freedom (DOFs) ball-and-socket joint.
- Coxa-Trochanter joint: Some individuals view this joint as, either a 3-DOFs ball-and-socket or a 2-DOFs saddle joint.
- Trochanter-Femur joint: this joint can be modeled as a universal joint with 2-DOFs.
- Femur-Patella joint: Commonly this joint can be modeled as a hinge joint.
- Patella-Tibia joint: There are two options to model this joint; first as a hinge joint or a universal joint with very limited joint on Y-Z axis.
- Tibia-Metatarsus: it is also possible to assume this joint as a hinge joint, or a universal joint but with some constraints.
- Metatarsus-Tarsus joint: this joint can be modeled as a universal joint.

In this case, the claws are the end-effector of the system. This means that this part of the limb is whom interacts with the outside.

IV. Mathematical development

As we mentioned previously, there are some constraints that we applied in the anatomic development. We applied these modifications in the mathematical development and we decided to involve all the possible variables, based on the following table to produces the most faithful model and prototype.

Parts	Movements	Plane
Coxa	75	Transversal
Femur	140	Sagittal
Tibia	40	Sagittal

A. Direct Kinematics

In order to study the direct kinematics of the robot at first by using the joint variables of contact limbs, position and orientation of the platform based on fixed frame are determined.

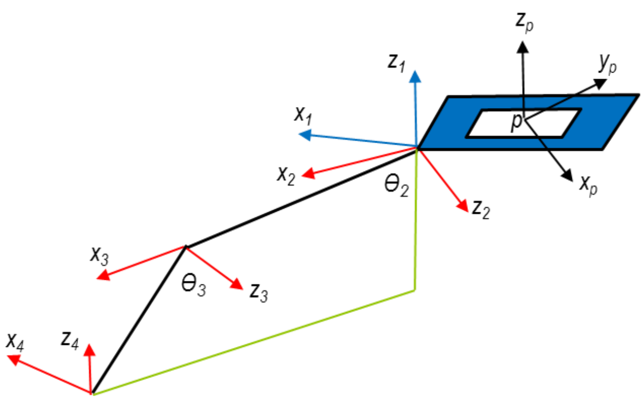

Figure 6: Coordinate frames of the robot

Taking into account the figure 6 and knowing *OAi* vectors, which are the end points of contact legs, we can establish the next expression:

$$rBi = rAi + \frac{rMi}{Ai} + \frac{rBi}{Mi} \quad (1)$$

In this expression, rBi and rAi represent the position vector of Bi. In the same way, we needed to determinate all the parameters of the system in a graphically mean. In the figure 7 it ca be detail these parameters.

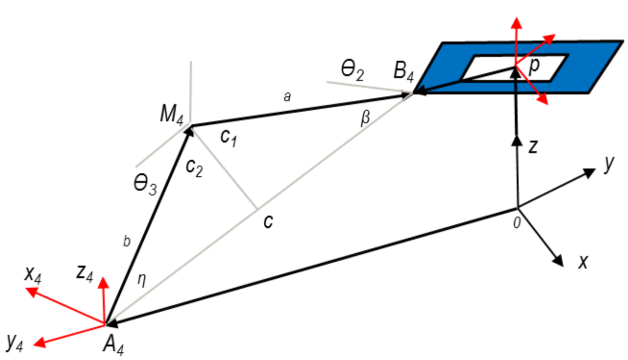

Figure 7: Parameters of the system.

One highly important aspect in our robot was the motion and the sequence that a quadruped robot must follow in order to walk correctly. This item is the quadruped walk, which it's illustrated in the figure 8.

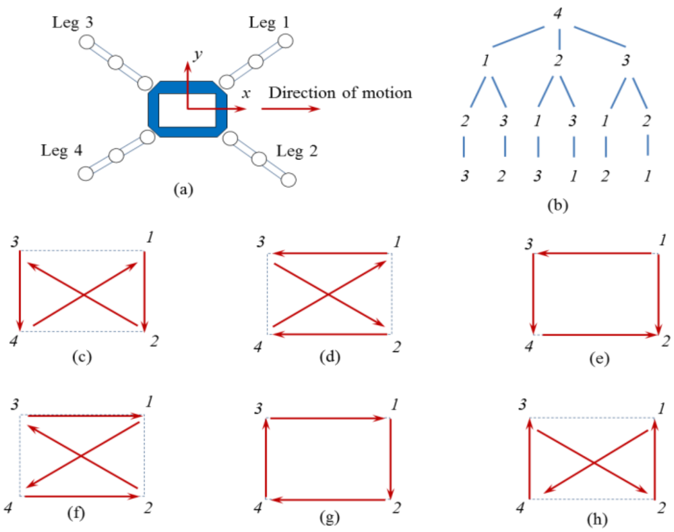

Figure 8: Quadruped walk

Suppose that the leg 1, 2 and 3 are standing on the ground. According to relation (1) the location of points Bi versus fixed coordinate are determined and as direction of x axis of P-coordinate system is direct to $B3B1$ vector can determine the direction of x-axis unit vector:

$$Ex = \frac{B3B1}{[\![B3B1]\!]} \quad (2)$$

In the same way, we can determinate the vector B3B2

$$Em = \frac{B3B2}{[\![B3B2]\!]} \quad (3)$$

By having this information, we can determinate the direction of unit vector, normal to the platform plane. To do this, we first needed to implement the cross product of the two previous vectors:

$$Ez = EmxEx \quad (4)$$

In the same way, having the vectors Ex and Ez, it's possible to determinate the Ey by the same method:

$$Ey = Ex\ x\ Ez \quad (5)$$

These three vectors are necessary because we can establish the matrix of the platform versus fixed coordinates with the next expression:

$${}^{P}_{B}R = [Ex\ Ey\ Ez] \quad (6)$$

In order to specify the origin of coordinate system, we can use the equation of the circle in this way:

$$(Xb1 - Xp)^2 + (Yb1 - Yp)^2 + (Zb1 - Zp)^2 = r^2 \quad (7)$$

$$(Xb2 - Xp)^2 + (Yb2 - Yp)^2 + (Zb2 - Zp)^2 = r^2 \quad (8)$$

$$(Xb3 - Xp)^2 + (Yb3 - Yp)^2 + (Zb3 - Zp)^2 = r^2 \quad (9)$$

If we solve the equations system previously established, we can determinate the position of the body in the coordinate system.

B. Platform velocity

In order to determinate the velocity of the robot's platform its necessary to determine the velocity and angular velocity of robot platform by using the position and velocity of joint variables. In order to specify the direct kinematics of platform velocity can use (10):

$$\overrightarrow{OA_\iota} + \overrightarrow{A_\iota M_\iota} + \overrightarrow{M_\iota B_\iota} + \overrightarrow{B_\iota P} = \overrightarrow{OP} \quad (10)$$

In the previous expression, OAi represents a vector was drawn from fix coordinate origin to point "A" from leg No. i. It's possible to determinate the relation between velocity of joint variables and platform velocity by differentiating from (10). The result is (11):

$$\vec{Vp} = \overset{B\to Tib}{\omega_i} \times \vec{A_i M_i} + \overset{B\to Fem}{\omega_i} \times \vec{M_i B_i} + \overset{B\to P}{\omega} \times \vec{B_i P} \quad (11)$$

In (11), the first and third element of the equality represents the absolute angular velocity of femur and tibia of limb No. i respectively. If we take into account the symmetry of our robot, (11) can be used for the other three contact legs. By using the fifth element of (11), it's possible establishes Vp. Based on figure 7:

$$\overset{1\to Tib}{\omega_i} = \dot{\theta}_1 {}^i\vec{K}_1 + \dot{\zeta}\, {}^i\vec{K}_2 \quad (12)$$

$$\overset{1\to Fem}{\omega_i} = \dot{\theta}_1 {}^i\vec{K}_1 + \dot{\zeta}\, {}^i\vec{K}_3 \quad (13)$$

Regarding to the figure 7:

$$\zeta = \frac{\pi}{2} - \theta_2 - \theta_3 \rightarrow \dot{\zeta} = (\dot{\theta_2} + \dot{\theta}_3) \quad (14)$$

$$\gamma = \frac{\pi}{2} - \theta_2 \rightarrow \dot{\gamma} = -\dot{\theta}_2 \quad (15)$$

In expression (12) and (13), the first factor in both of them, indicates the unit vector direct to z-axis of first coordinate frame of limb No. i. The relation between the unit vectors of different coordinate frames of each leg is determined in function of the figure 7 as follow:

$$\overrightarrow{\iota_{K_3}} = \overrightarrow{\iota_{K_2}} \quad (16)$$

$$\overrightarrow{\iota_{K_2}} = -\sin(\theta_1)\overrightarrow{\iota_{I_1}} + \cos(\theta_1)\overrightarrow{\iota_{J_1}} \quad (17)$$

$$\overrightarrow{\iota_{J_4}} = -\overrightarrow{\iota_{K_3}} \quad (18)$$

Using the expressions from (12) to (18), we can determine the values of ωi as follows:

$$\overset{1\to Tib}{\omega_i} = \dot{\theta}_1 {}^i\vec{K}_1 - (\dot{\theta}_2 + \dot{\theta}_3)(-S(\theta_1){}^i\vec{\iota}_1 + C(\theta_1){}^i\vec{j}_1) \quad (19)$$

$$\overset{1\to Fem}{\omega_i} = \dot{\theta}_1 {}^i\vec{K}_1 - \dot{\theta}_2(-S(\theta_1){}^i\vec{\iota}_1 + C(\theta_1){}^i\vec{j}_1) \quad (20)$$

In (19) and (20) the S's and the C's, means cosines and sines. In this case, for mathematical simplicity, que can express all the previous equations as rotational matrices as follows:

$$\overset{B\to Fem}{\omega_i} = {}^P_B R\, {}^1_P R_i \overset{1\to Fem}{\omega_i} \quad (21)$$

$$\overset{B\to Fem}{\omega_i} = {}^1_B R_i \overset{1\to Fem}{\omega_i} \quad (22)$$

$$\overset{B\to Tib}{\omega_i} = {}^1_B R_i \overset{1\to Tib}{\omega_i} \quad (23)$$

As we mentioned previously, 'R' represents the rotational matrix of platform relative to fix coordinate frame. In this order R1p is rotation matrix of first coordinate frame of limb No.i relative to P-coordinate frame system. This last rotational matrix is defined as follow:

$$R = \begin{bmatrix} \cos\left[(i-1)\frac{\Pi}{3}+\frac{\Pi}{6}\right] & -\sin\left[(i-1)\frac{\Pi}{3}+\frac{\Pi}{6}\right] & 0 \\ \sin\left[(i-1)\frac{\Pi}{3}+\frac{\Pi}{6}\right] & \cos\left[(i-1)\frac{\Pi}{3}+\frac{\Pi}{6}\right] & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (24)$$

In (24) is the number of limbs.

C. Direct kinematics of non-contact leg

Direct kinematics of position for a non-contact limb it's similar to the direct kinematics for a serial robot. As shown in Fig. 7 can write:

$$OAi = OP + PBi + BiMi + MiAi \quad (25)$$

$$PBi = {}^P_B R\ PBi \quad (26)$$

$$BiMi = {}^P_B R\ {}^1_P R\ BiMi \quad (27)$$

$$MiAi = {}^{P}_{B}R\ {}^{1}_{P}R\ MiAi \tag{28}$$

Based on the previous expressions PBi can be establishing as follows:

$$PBi = \begin{bmatrix} r\cos(\frac{\Pi}{6} + (i-1)\frac{\Pi}{6}) \\ r\sin(\frac{\Pi}{6} + (i-1)\frac{\Pi}{6}) \\ 0 \end{bmatrix} \tag{29}$$

As we did with the contact legs, we wanted to determinate the velocity of the non-contact limbs, so the procedure is similar. We first need to differentiate (25) as follows:

$$\vec{V}_{Ai} = \vec{Vp} + \overset{B\to P}{\vec{\omega}} \times \vec{B_iP} + \overset{B\to Fem}{\vec{\omega_i}} \times \vec{B_iM_i} + \overset{B\to Tib}{\vec{\omega_i}} \times \vec{M_iA_i} \tag{30}$$

Using the information from (11):

$$\overset{B\to Fem}{\omega_i} = \dot{\theta}_1 {}^i\vec{K}_1 + \dot{\theta}_2 {}^i\vec{K}_2 + \overset{B\to P}{\omega} \tag{31}$$

$$\overset{B\to Tib}{\omega} = \dot{\theta}_3 {}^i\vec{K}_3 + \dot{\theta}_1 {}^i\vec{K}_1 + \dot{\theta}_2 {}^i\vec{K}_2 + \overset{B\to P}{\omega} \tag{32}$$

With (30) to (32) we can determinate the velocity of end point of noncontact legs; as a result, these values can be specified.

V. SOFTWARE AND SIMULATION

Figure 9 is showing the conceptual map of robot control based in arduino controller and Bluetooth communication system sending and receiving routine commands from mobile device.

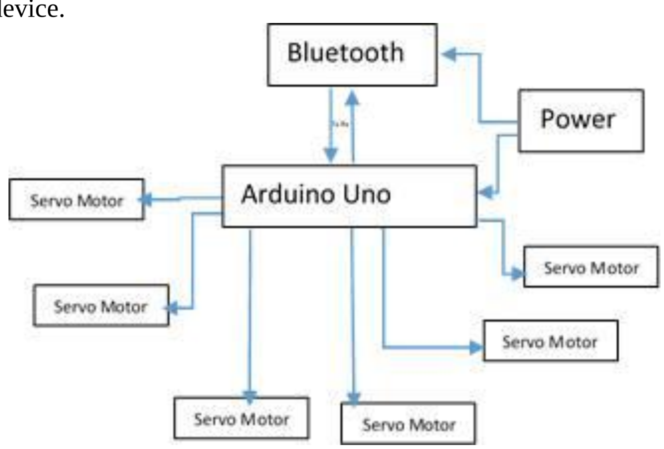

Figure 9: schematic control design of quadruped robot

the figures 10 and 11 are representing the forward movements of each axis of the robot using Matlab ©. We use Arduino as a controller for the full platform control and communication. For motion, 12 servo-actuators were set, 3 for each leg with torque of 2.2Kg-cm. these servo-motors are attached directly as a joint of each link-leg. The supply voltage and current for the robot was a battery package of 4.8 V and 3000 mA with around power of 7.5 W approx.

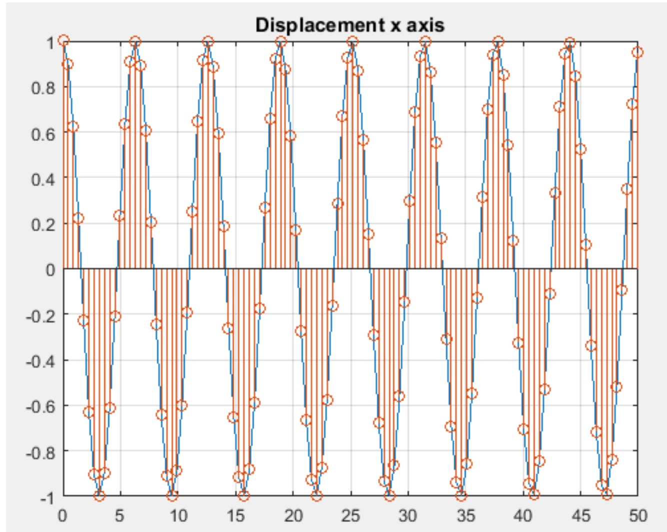

Figure 9: Displacement x axis

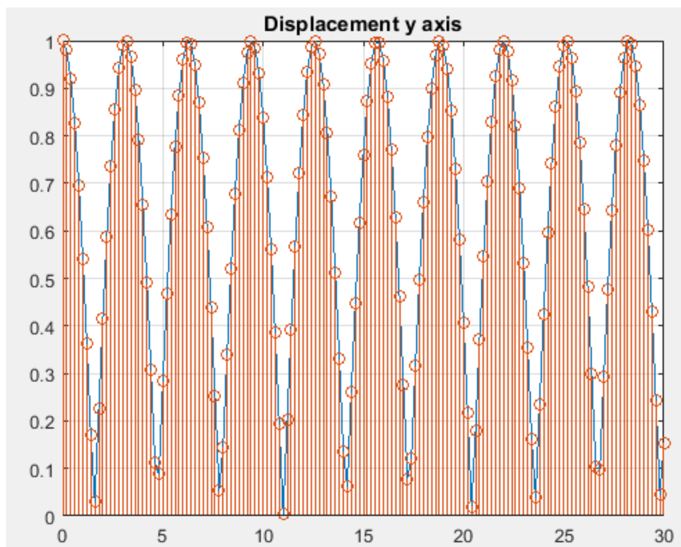

Figure 10: Displacement y axis

CONCLUSIONS

The project had achieved step by step the design, development and control of a quadruped walking robot. The mathematical model helped out the modeling of the motion´s behavior of the robot. The robot has 12 DOF in total, 3 DOF for each one, controlled by an Arduino Nano via remote mobile device. The movement has been analyzed with biomimetic inspirations take from spider.

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