Walking Robot Bio-inspired by Insect's Locomotion for Carbon Dioxide Diagnostic Indexed in the Air

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Abstract: The spiders, in comparison with the majority of others animals, it has the ability to access all 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 with the ability to move in all kind of directions and perform pre-set motions programs such as ascend, descend, obstacles avoiding and gas detections. The paper is presented the dynamic and kinematics model with the purpose of understand how, mathematically the quadruped animal and spiders walk. In this sense we studied the movement of a real spider in order to define a suitable bio-mimetic locomotion model. In additions walking simulations were implemented and the gas detection results are presented.

1 INTRODUCTION

In the recent years, human want to reproduce all kind of movement bioinspired by the nature, given back some successful results. The effort on try to understanding and analyse the locomotion behaviour allowed novel mathematical models. All this models can be used in robotics for certain task instead of risk human lives. This kind of biomimetic replication can be employed in, as example, land mines task, exploration task and even underwater inspection (Zhao, 2017) Another important application of these robots is the incursion in dangerous environments, like contaminated places, or hostile landmarks.

In quick evaluation into the subject at the macro-scale Boston Dynamic's is one research institution or business company that design and produce a huge variety of robots, especially quadruped ones. (Raibert, 2008). The most popular one is Big Dog; it is employing entirely in exploration duties.

Other approaches of walking robots biomimetically inspired at mili-scale are based in the insects like spider locomotion. The spider robot was built around 90's where researches started to innovate the whole world with their robots. (Shoval, 1999) Now, is a big market built hexapod spider robot, which had the ability of climb all kind of surfaces.

Nowadays, the majority of information suggests that the quadruped spider robots are developed by amateurs or fans whom wants to develop a kind of open loop control device. Other approaches are being done by complex close loop control (Lu, 2017) or by using other mechanism for quadruped walking like parallel mechanism (Wang, 2010), soft materials (Garabini, 2017) and so on.

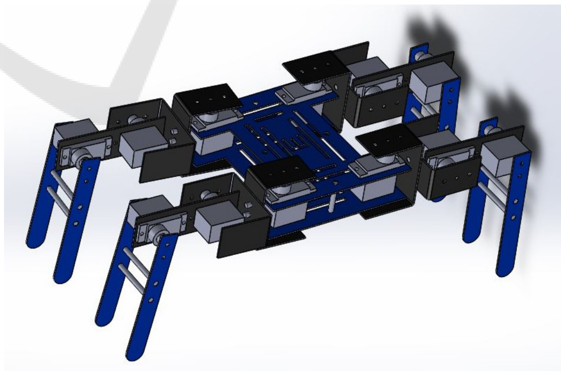

Figure 1: Quadruped robot design.

This paper presents a basic approach of one quadruped robot with its different attributes and characteristics showing in figures 1 and 2. Several historical contributions had been developed by other researches incorporating cameras, sensors, geo-localization and so on. (Semini, 2010) This project is a particular bio inspired robot that carry onboard gas

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sensor to characterize the air in a narrow and/or constrain areas.

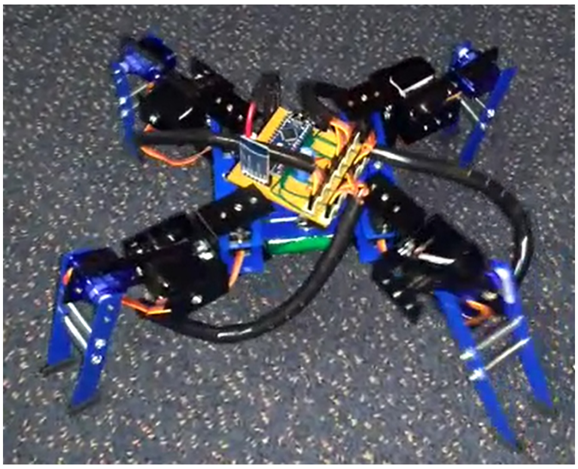

Figure 2: Quadruped robot prototype.

The movement of this robot executed the mathematical control of forward kinematics and evaluates the air environment for gas contamination.

2 THE QUADRUPEDS

In order to achieve this project initially observes the behaviour of the quadruped locomotion in the animal kind in their natural environment. The motions and algorithms are well established, like how they move, avoid obstacles and synchronise its motion behind. As a result, the majority of the quadrupeds move in a mammalian form, like a dog or a horse, as example. This represented to follow its complex locomotion or used a mixture of sources of inspiration to meet the quadruped animal movement and behaviour. On the other hand, the mili-scale inspired the anatomy for spiders. As a result, the anatomy, movements and physic shape of insects are not yet well stables in the robotics field.

3 MOTION ANALYSIS

Initially, it's important to know that the spider has 7 parts by leg (figure 3). 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, this project suppresses some leg's part and component´s joints. Based in simplification some spider´s leg part the robot is reduced as follow: 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, however, for kinematic analysis and simulation we took the entirely system for a realistic approach resulting to know which parts can be considering redundant.

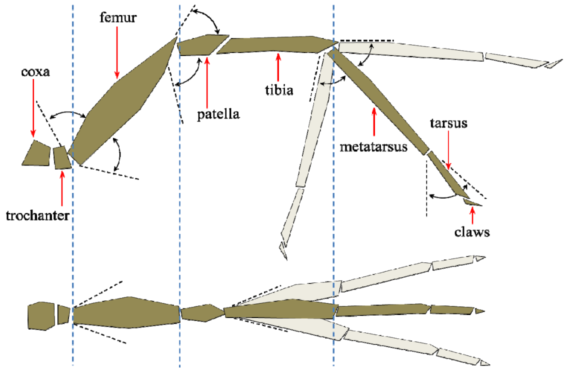

Figure 3: Spider's leg parts.

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 4.

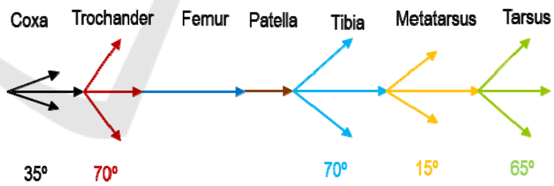

Figure 4: Range of movement of the spider.

In order to establish the different joints and links which constitute the system limb of the spider, it is defined as follow:

- Body-Coxa joint: joint with three degrees of freedom (DOFs) ball-and-socket joint.
- Coxa-Trochanter joint: either 3-DOFs ball-and-socket or a 2-DOFs saddle joint.
- Trochanter-Femur joint: this modeled as a universal joint with 2-DOFs.
- Femur-Patella joint: Commonly this joint can be modeled as a hinge joint 1-DOF.

- 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.

4 MATHEMATICAL ANALYSIS

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.

Table 1: Limited ranges of angular rotation.

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

4.1 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.

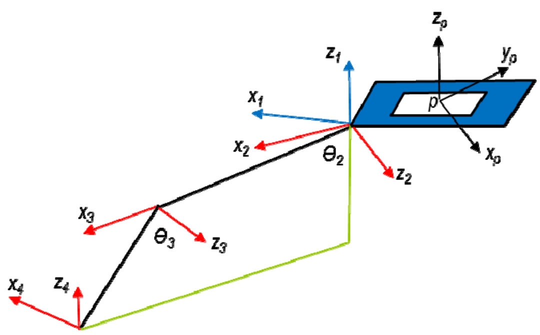

Figure 5: Coordinate frames of the robot.

Taking into account the figure 5 and knowing *OAi* vectors, which are the end points of contact legs, we can establish the next expression:

$$rBi=rAi+rMi/Ai+rBi/Mi \quad (1)$$

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 6 it can be detail these parameters.

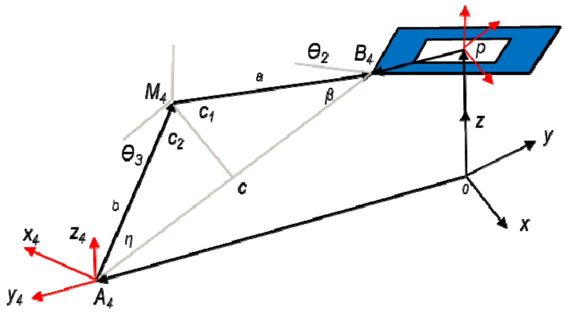

Figure 6: Parameters of the system.

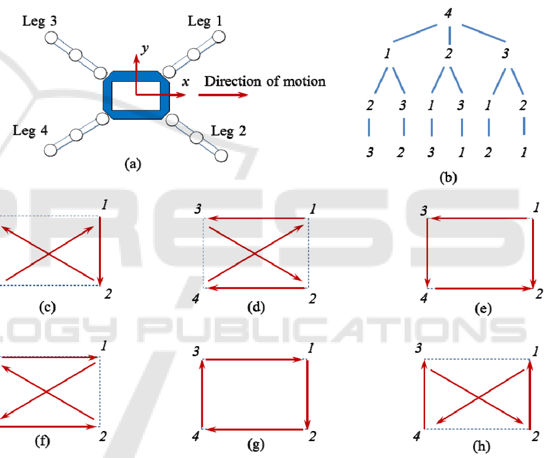

Figure 7: Quadruped walk locomotion.

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:

$$Ex=[\![B3*B1]\!]/[\![B3*B1]\!] \quad (2)$$

In the same way, we can determinate the vector B3B2 as follow:

$$Em=[\![B3*B2]\!]/[\![B3*B2]\!] \quad (3)$$

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:

$$z = Em * Ex \quad (4)$$

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

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

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.

4.2 Platform Velocity

In order to determinate the velocity of the robot's platform its necessary to determinate 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):

$$\overrightarrow{OA_i} + \overrightarrow{A_iM_i} + \overrightarrow{M_iB_i} + \overrightarrow{B_iP} = \overrightarrow{OP} \quad (10)$$

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):

$$\vec{Vp} = \overset{B\to Tib}{\omega_i} \times \vec{A_iM_i} + \overset{B\to Fem}{\omega_i} \times \vec{M_iB_i} + \overset{B\to P}{\omega} \times \vec{B_iP} \quad (11)$$

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 6:

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

Regarding to the figure 6:

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

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 6 as follow:

$$\overrightarrow{\iota_{K_3}} = \overrightarrow{\iota_{K_2}} \quad (14)$$

$$\overrightarrow{\iota_{K_2}} = -\sin(\theta_1)\overrightarrow{\iota_{I_1}} + \cos(\theta_1)\overrightarrow{\iota_{J_1}} \quad (15)$$

$$\overrightarrow{\iota_{J_4}} = -\overrightarrow{\iota_{K_3}} \quad (16)$$

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

$$\overset{1\to Tib}{\omega_i} = \dot{\theta}_1\, {}^{i}\vec{K}_1 - (\dot{\theta}_2 + \dot{\theta}_3)(-S(\theta_1)\, {}^{i}\vec{i}_1 + C(\theta_1)\, {}^{i}\vec{j}_1) \quad (17)$$

$$\overset{1\to Fem}{\omega_i} = \dot{\theta}_1\, {}^{i}\vec{K}_1 - \dot{\theta}_2 (-S(\theta_1)\, {}^{i}\vec{i}_1 + C(\theta_1)\, {}^{i}\vec{j}_1) \quad (18)$$

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:

$$\overset{B\to Fem}{\omega_i} = {}^{P}_{B}R\ {}^{1}_{P}R_i\ \overset{1\to Fem}{\omega_i} \quad (19)$$

$$\overset{B\to Fem}{\omega_i} = {}^{1}_{B}R_i\ \overset{1\to Fem}{\omega_i} \quad (20)$$

$$\overset{B\to Tib}{\omega_i} = {}^{1}_{B}R_i\ \overset{1\to Tib}{\omega_i} \quad (21)$$

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:

$$R = \begin{bmatrix} \cos\left[(i-1)\frac{\Pi}{3} + \frac{\Pi}{6}\right] & -\sin\left[(i-1)\frac{\Pi}{3} + \frac{\Pi}{6}\right] & 0 \\ \sin\left[(i-1)\frac{\Pi}{3} + \frac{\Pi}{6}\right] & \cos\left[(i-1)\frac{\Pi}{3} + \frac{\Pi}{6}\right] & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (22)$$

In (24) is the number of limbs.

4.3 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:

$$OAi = OP + PBi + BiMi + MiAi \tag{23}$$

$$PBi = {}^P_B R \; PBi \tag{24}$$

$$BiMi = {}^P_B R \; {}^1_P R \; BiMi \tag{25}$$

$$MiAi = {}^P_B R \; {}^1_P R \; MiAi \tag{26}$$

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

$$PBi = \begin{bmatrix} r\cos(\frac{\Pi}{6} + (i-1)\frac{\Pi}{6}) \\ r\sin(\frac{\Pi}{6} + (i-1)\frac{\Pi}{6}) \\ 0 \end{bmatrix} \tag{27}$$

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:

$$\vec{V}_{Ai} = \vec{Vp} + \overset{B\rightarrow P}{\omega} \times \vec{B_i P} + \overset{B\rightarrow Fem}{\omega_i} \times \vec{B_i M_i} + \overset{B\rightarrow Tib}{\omega_i} \times \vec{M_i A_i} \tag{28}$$

Using the information from (11):

$$\overset{B\rightarrow Fem}{\omega_i} = \dot{\theta}_1 \, {}^i\vec{K}_1 + \dot{\theta}_2 \, {}^i\vec{K}_2 + \overset{B\rightarrow P}{\omega} \tag{29}$$

$$\overset{B\rightarrow Tib}{\omega} = \dot{\theta}_3 \, {}^i\vec{K}_3 + \dot{\theta}_1 \, {}^i\vec{K}_1 + \dot{\theta}_2 \, {}^i\vec{K}_2 + \overset{B\rightarrow P}{\omega} \tag{30}$$

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

5 SIMULATION AND CONTROL

Figure 8 is showing the conceptual map of robot control based in arduino controller and Bluetooth communication system sending and receiving routine commands from mobile device.

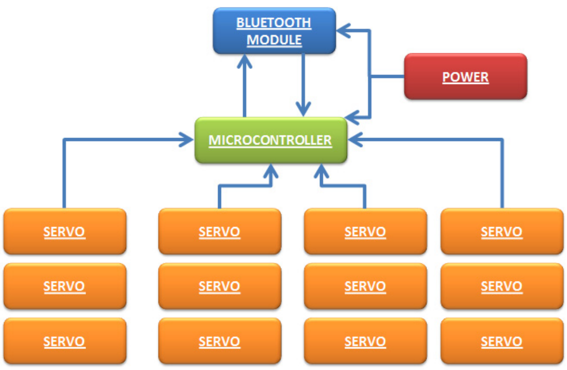

Figure 8: schematic control design of quadruped robot.

Figure 9 is showing the representation of 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.

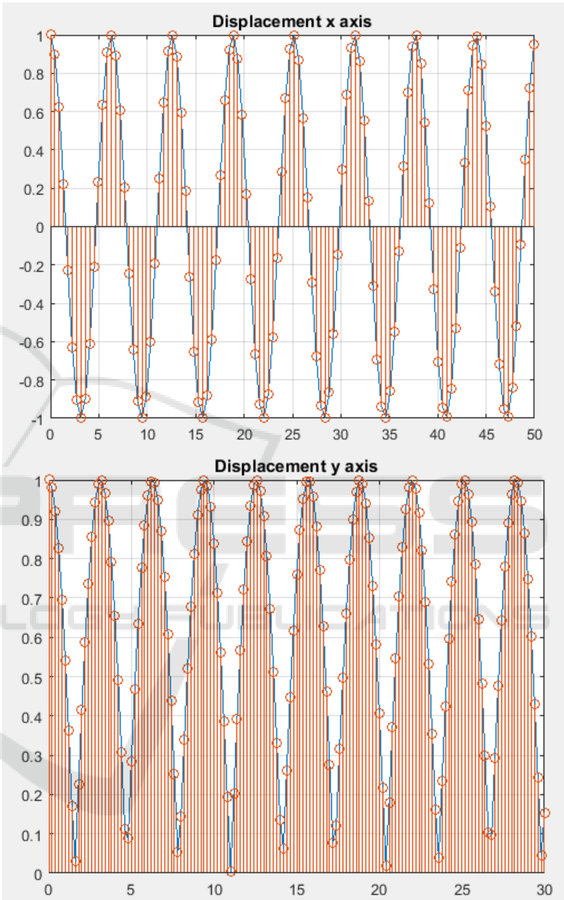

Figure 9: Oscillation motion of each leg in x and y axis.

6 GAS SENSOR EVALUATION

Regarding to the reading of the carbon dioxide index, an embedded circuit capable of monitoring various types of gases was implemented. Thanks to the micro-controller implemented to achieve the movement of the spider, it was easy to incorporate the sensor in question. The challenge was to recreate the characteristic curve of this device through a function based in the response with different types of gases, figure 10.

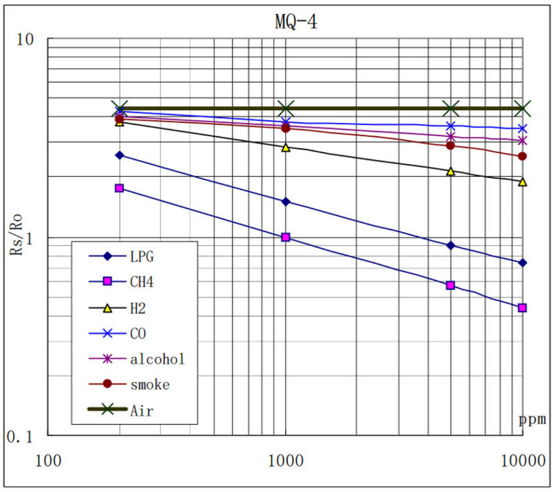

Figure 10: Gas sensor curve (MQ-4).

Initially, the characteristic curve of the sensor was expected to have a directly proportional relationship between the voltage at the output of the sensor, and the carbon dioxide concentration, as shown below.

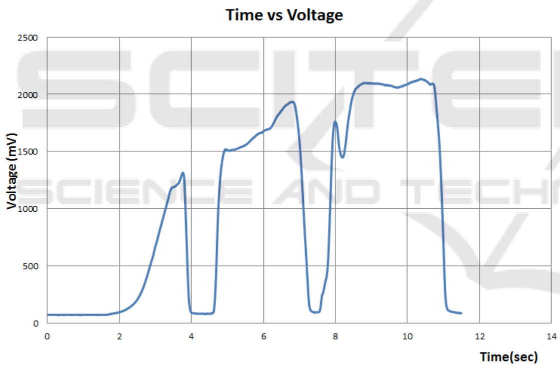

Figure 11: Response profile MQ4, time vs voltage.

The figure 11 shows the output voltage of the sensor depending of the gas concentration reading by the sensor. In this order of ideas, a gas source was arranged next to the sensor; as the gas concentration increased, so did the voltage. Then it will show a graph that link the voltage at the output of the sensor, with the carbon dioxide concentration.

Figure 12 is showing the characterization of the sensor was achieved through a linear regression model, obtaining fairly accurate results. An extremely important aspect to mention is the fact that currently this issue is still being evaluated and treated, with the purpose of implementing the sensor that best shapes itself, and conditioning the signals of it with the purpose of achieving the best results.

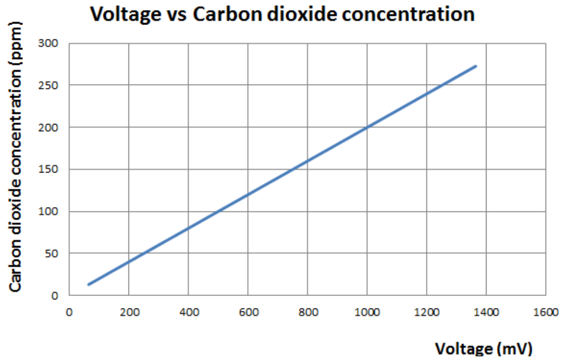

Figure 12: Voltage vs Carbon dioxide concentration.

7 CONCLUSIONS

The project had achieved step by step the design, development and control of a quadruped walking robot. The mathematical model helped out the modelling of the motion´s behaviour of the robot.

The robot has achieved 12 DOF in total, 3 DOF for each leg, controlled by an Arduino Nano via remote mobile device. The movement has been analysed with biomimetic inspirations take from spider.

The gas sensor MQ4 was an excellent first approach to the sensing technology because it allowed characterizing the behaviour of the gas. Additionally, these results will serve as a foundation in future research.

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