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Design and Simulation of a Bio-inspired Hexapod Robot Leptynia Attenuata Pantel

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Abstract

Biologically inspired robots represent one of the most significant trends in the development of machines or technological elements. This is because the locomotion or characteristics of certain living beings that allow developing a task or action more efficiently. Among them the hexapods are bio-inspired in some arthropods, of which many of their specimens have a great advantage of mobility in structured and unstructured terrains. In this article, a CAD model of the Leptynia Attenuata Pantel was developed and the simulation of the parameters obtained from Denavit-Hertenberg was carried out in Matlab. That allowed to validate the efficiency of the mechanical model adapted from the anatomical model of the object of study.

Keywords. Bio-inspired robot, Joints of a hexapod robot, Denavit-Hertenberg algorithm.

I. INTRODUCTION

The growing interest in the international field to investigate the robots that use paws for their displacement is motivated both by its inherent complexity, which is an important scientific challenge, and by its potential applications [1]. The locomotion of the robots with paws provides a greater efficiency of maneuverability and displacement in structured and unstructured terrains, according with Rivas "there are very few natural terrains that can not be crossed by animals with paws. The ability to use obstacles as steps is a valuable tool that a locomotion based on wheels and continuous track cannot match" [2], these characteristics are taken from the mobility advantages of some living beings, depending on their anatomy. At present, the design of locomotion systems for walking robots has been derived from the study of biological systems [3]. The adaptation of a biological system is developed with the intention of recreating the most important characteristics that the object of study has in where; The main objective is to find a more efficient way to imitate the animal, using the least amount of motors (gearmotors, servo motors, step motors, etc.) and generate a design as light as possible. To finally create a new design based on the movement of the animal [4].

It is well known that to maintain the position of a structure in three-dimensional space requires three points of support. The Machines with three or more paws continuously in contact with the ground are said to be very balanced if they maintain their projection of the center of gravity within the polygon determined by the paws in the support plane [5]. The insects that have had a greater impact on bio inspiration have been cockroaches and insects stick because of the numerous studies carried out with them [2]. The stick insects are part of the order Phasmatodea which embrace more than 3000 species distributed by most regions of the planet and especially in the tropics [6]. To date, the implementations of the modes of displacement are carried out with 2 different types of architectures: centralized or decentralized. The former manages everything from a single controller and directly specifies the transitions of all paws. In the second six nodes (paws) are connected in a parallel network and walking arises by the interaction between all [2].

In the article by [7] is analyzed the support tripod during the march and the stability range on the horizontal plane, this type of walking is usually the most used by Hexapod insects including Leptynia Attenuata Pantel study element for the construction of a biological robot; to perform this task, the article was divided into sections which allow us to identify characteristics and results that provided the necessary tools to carry out the simulation and design of a bio-inspired robot in the Leptynia Attenuata Pantel. In section II A biological description of the object of study is realized considering structural characteristics of its anatomy; In section III a mechanical adaptation of the obtained characteristics is adapted, and the CAD design of the bio-inspired robot is realized. The locomotion and stability process of a hexapod robot is described in section IV, the Mathematical model of the resulting CAD design is made using the Denavit-Hertenberg parameters, in section V the simulation of the parameters obtained from the kinematic model of the CAD Design is performed.

II. BIOLOGICAL DESCRIPTION OF THE LEPTYNIA ATTENUA PANTEL

Leptynia Attenuata Pantel, commonly known by the name of stick insect, belongs to the insect class of Orden Phasmatodea. Its body is divided into three regions. Head, thorax and abdomen are generally elongated and more or less cylindrical. They are nocturnal and with little mobility. However, they have an extraordinary capacity for camouflage. [6] and [8].

A. Relevant structural characteristics

Head, Prognata (parallel the axis of the body) has a pair of filiform antennas between 3.5mm to 11mm in length. The scape and pedicel articulate the antenna providing mobility, the occiput or nape, is attached to the anterior part of the thorax through a membrane called neck or cervix [6] and [8].

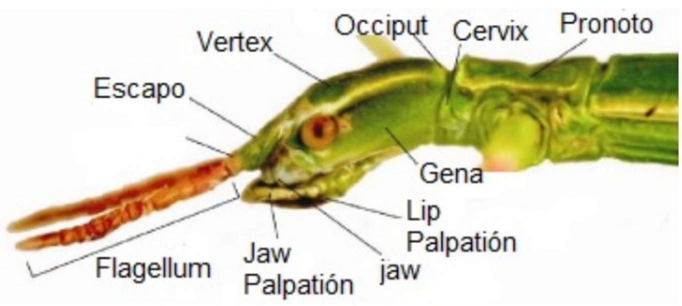

Fig 1. Side view of the head of the female Leptynia Attenuata Pantel

Thorax: It is attached to the head by the laterocervical scleroses that articulate it. This one is formed by three pieces prothorax, mesothorax and metathorax. The prothorax is shorter than the other two regions. From each of these regions, two extremities, which are thin and long, are adapted to move between the branches of the plants, these are divided into five segments: Coxa, trochanter (articulated piece that gives mobility), femur, tibia and tarsus. [6] and [8].

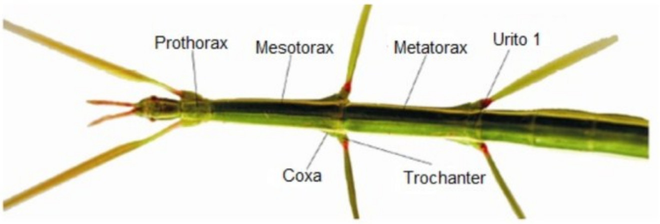

Fig 2. Thorax dorsal view of female of Leptynia Attenuata Pantel.

Abdomen: It is composed by ten segments that receive the name of uritos each one of them is divided in two parts, the first one is fused to the metathorax and the last abdominal segment is smaller than the rest and protects dorsally the anus [6] and [8].

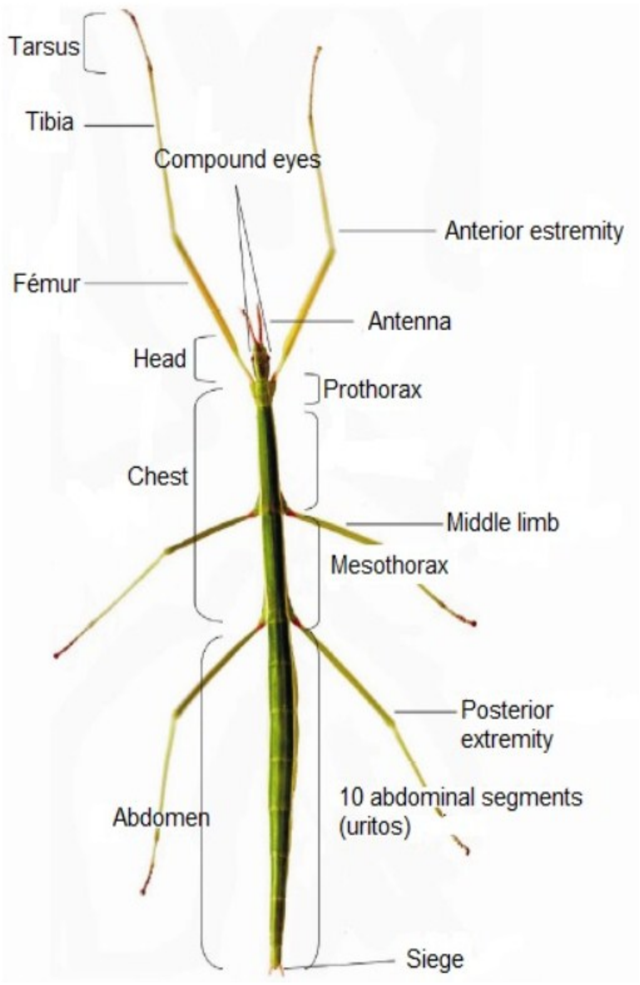

Fig 3. General morphology, dorsal view of female Leptynia Attenuata Pantel.

B. Description of the paws of the Leptynia Attenuata Pantel

Once the morphological study of the Leptynia Attenuata Pantel has been carried out, it is necessary to detail more precisely the limitations of movement that it has since one of the main characteristics that can be mentioned is that they are not often moved often because the capacity that it has of movement is actually limited compared to other insects [9].

The joints and junction are the sections of the paws where the displacements of the links that make up the paw are generated, which in the mechanical adaptation of the robot represents the degrees of freedom to be assigned. structural composition of the hind paw of a stick insect, in section (A) of the image the union of the trochanter and the coxa are observed, which have very few restrictions or restrictions of movement and where a rotational movement can be carried out in the red arrow represents the femur. This can be moved from section (1) to section (2) or vice versa and from section (3) to section (4) or vice versa. movement has a high limiting range; in section (B) is the connection between the femur and the tibia section having various restrictions of movement since the mentioned element can only be moved from the section (5) to the section (6) or vice versa.

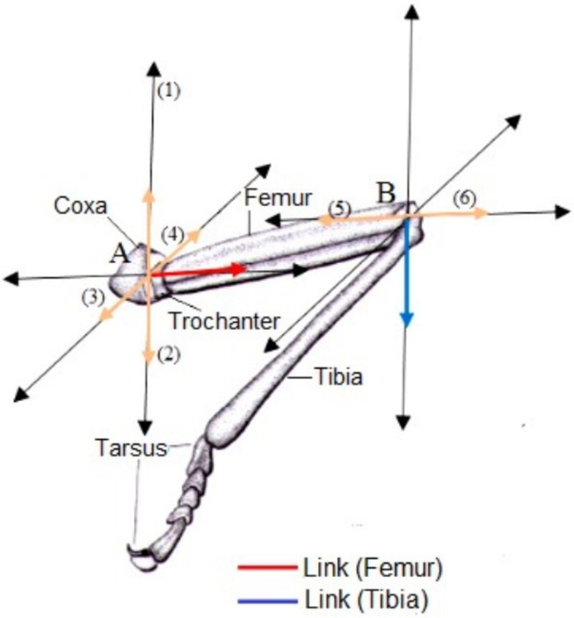

Fig 4. Back paw of a stick insect (male of Anisomorpha monstrosity) where the respective movements are presented to the links corresponding to the femur and the tibia

C. Ability to recover from loss of supports links

In most phasmids, the trochanter and the femur are welded together. Its junction zone is a break point whereby the animal can detach itself from the entire paw in case of danger. This autonomy occurs without the animal suffering great damage, since the trochanter has a special membrane that prevents the loss of hemolymph, some of the nymphs can regenerate the lost limbs. After the next moult [8].

III. DEVELOPMENT AND ADAPTATION OF THE LEPTYNIA ATTENUATA PANTEL TO A ROBOTIC MODEL

The efficient simulation of a robotic model starts from the correct adaptation of the anatomical characteristics of the study model. In this case, it is only to pretend to replicate in detail the anatomical structure of the paws of the Leptynia Attenuata Pantel without taking greater care in the structural and articulation characteristics of the head and abdomen.

A. Robot CAD design bioinspired on the Leptynia Attenuata Pantel

In the complete CAD design of the robot, not all of the qualities described in section II.A, were implemented, this is because they are not of great relevance for the study that was performed, these traits were replaced by a simpler design but conservative of the esthetics of the stick insect in this case Leptynia Attenuata Pantel; the qualities that were maintained are with respect to the proportion, shape and location of the structural elements that make up the paws.

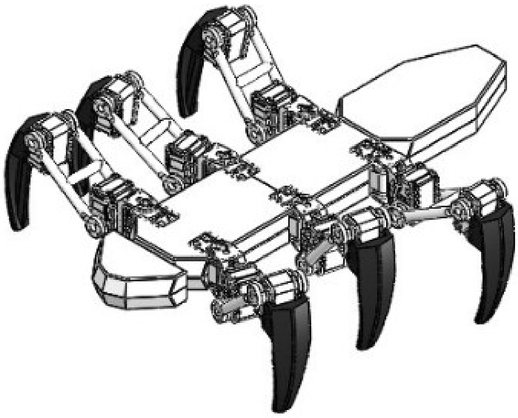

Fig 5. Shows the similarity of the mechanical design obtained from the anatomical adaptation of the Leptynia Attenuata Pantel where the proportion and location of the previously mentioned segments is maintained.

B. Design of the paw of the hexapod robot

The CAD model performed has the most important characteristics of the paws described in section II. C, where the displacements performed by the joints are optimized and implemented as degrees of freedom that are acquired through servomotors. for the ability to move the links that are part of the assembly, which correspond to the segments of the femur and the tibia, figure 6 and 7.

Fig 6. CAD design of the paw of the hexapod robot.

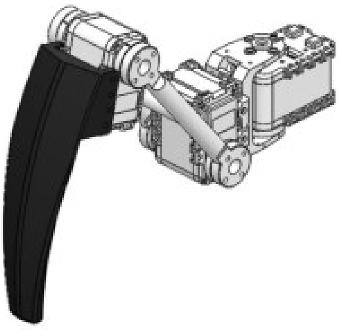

Fig 7. CAD design of the paw of the hexapod robot without tarsus.

The mechanical structure of the paw has three degrees of freedom of rotational type, achieving with this a design that makes it possible to adapt the robot to the irregularities that present different types of terrain [10].

The servomotors (1) and (2) represent the degrees of freedom proposed in section A of Figure 4 with the difference that the servo motor (2) has fewer limitations than its biological analog whose movement is more restricted and less observable, the servo motor (3) is equivalent to the joint between the femur and the tibia proposed in section B of figure 4 whose function is more limited than the displacement provided by the servo motor.

IV. LOCOMOTION OF THE HEXAPOD ROBOTS

The analysis of the motion of a hexapod robot is one of the most important characteristics to evaluate, this is because the mechanical distribution of the robot, gives it maneuverability and exceptional performance on irregular terrain this is one of the main characteristics for which these types of robot are used; The studies that are most used are kinematic analyzes, displacement algorithms, and motion correction algorithms.

During the locomotion of the hexapod robot, problems have been found in the control, it must first to determine what type of locomotion is going to be used, this always taking to considering the type of terrain in which the robot is going to move, the most common way to get a robot to move is by using fixed locomotion, this is based on established movements that are going to be repetitive where the parameters of locomotion are regular and determined previously, with orders already established [11].

A. Stability on the hexapod robots

In order to achieve stability, the hexapods have three supports that support it and at the same time have three others who are in charge of the movement to give it a new position [12].

The CAD design of the hexapod robot uses 3 servomotors for each of the paws, that is to say that the complete design is formed by 18 servomotors which are divided in six assemblies corresponding to the paws of the robot; the locomotion described for an stick insect is usually given by the tripod trip which consists of displacements in which three of the paws are used as supports and three of the paws for meaningful movements see more information about tripod displacement in the article "Tripod gaits for fault tolerance of hexapod walking machines with a locked joint failure by Jung-ming Yang" [7].

B. Polygon support for hexapod robots

The hexapod Robots when they move usually use three or more support extremities these extremities form a polygon that indicates if the robot is stable or not with respect to the support surface depending on the location of the center of gravity of the robot, The robot is statically stable if the projection of the center of mass lies within the support polygon, is at the stability limit if the projection of the center of mass is on one side of the support polygon and will be statically unstable if the projection of the center of mass is located outside the support polygon [5].

V. MATHEMATICAL ROBOT MODELING

The mathematical model of the robot is based on the kinematic analysis, since the research element has displacements at low speeds, the method of analysis established was direct kinematics since the position and orientation of the robot end with respect to a system of coordinates of reference, In order to perform the kinematic analysis of the paws of a hexapod robot, only one subassembly corresponding to a single paw should be considered. This is because although all the paws that were implemented in the hexapod robot are independent, they perform the same movement already which have the same degrees of freedom and to obtain the equations of a paw will obtain the kinematic equations of the rest of the paws of the robot [13].

A. Direct kinematics of the robot paw using the Denavit-Hertenberg method

The Denavit-Hertenberg parameters were used to calculate the direct kinematics equation. However, these parameters are frequently obtained in the work carried out for the locomotion analysis of the hexapods. In this section we present the comparison of two models of kinematic analysis using the Denavit-Hertenberg algorithm of an insect paw, the articles on which the comparison are based are "Biologically Inspired Self-Reconfigurable Hexapod with Adaptive Locomotion" presented by [14], and "Navigation Control System of Walking Hexapod Robot" presented by [15].

The direct kinematics of the robot paw considered in this section is performed without taking the segment of the coxa as a link.

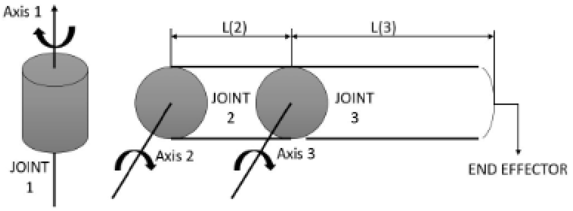

Fig 8. Kinematic forward configuration for one paw.

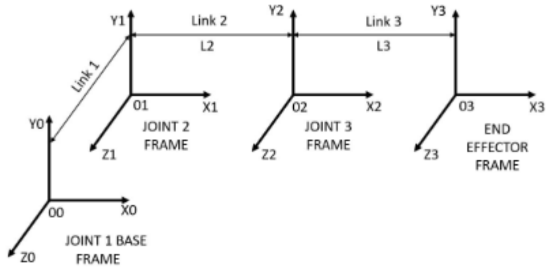

Fig 9. Frame assignment for robot paw.

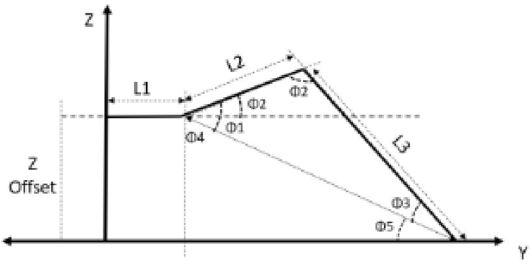

Fig 10. Two-dimensional representation of the paw of an insect where L1= representation of the coxa in the two-dimensional model, L2 = femoral link, L3= tibial link.

Table 1. Link Parameters

Link	α1	a1	Cos α1	Sin α1	di	Variable
1	90	0	0	1	0	ϴ1
2	0	L1	1	0	0	ϴ2
3	0	L2	1	0	0	ϴ3

$$H = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} \tag{1}$$

Where R = Rotational Matrix, d = Translation Matrix, O = Representative matrix, 1 = Scalar matrix.

The general form of the link transformation matrix i for i-1 implements the parameters of Denavit-Hertenberg is represented by means of the matrix.

$$Ai = \begin{bmatrix} cos\,\Theta i & -\sin\Theta i\, cos\,\alpha i & \sin\Theta i \sin\alpha i & ai\cos\Theta i \\ \sin\Theta i & cos\,\Theta i\, cos\,\alpha i & -\cos\Theta i\sin\alpha i & ai\sin\Theta i \\ 0 & \sin ai & \cos ai & di \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Using the binding parameters obtained in Table 1, the matrices for the D-H convention are obtained, these matrices can be reduced to matrices for joints as indicated in equations (3), (4) and (5). The transformation matrices for each joint can be defined using equation (2).

$$A_0^1 = \begin{bmatrix} cos\,\Theta 1 & 0 & \sin\Theta 1 & 0 \\ \sin\Theta 1 & 0 & -\cos\Theta 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$A_2^1 = \begin{bmatrix} cos\,\Theta 2 & -\sin\Theta 2 & 0 & L2\cos\Theta 2 \\ \sin\Theta 2 & cos\,\Theta 2 & 0 & L2\sin\Theta 2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$A_3^2 = \begin{bmatrix} cos\,\Theta 3 & -\sin\Theta 3 & 0 & L3\cos\Theta 3 \\ \sin\Theta 3 & cos\,\Theta 3 & 0 & L3\sin\Theta 3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

The product of the individual transformed matrices can be given using the equation:

$$T_3^0 = A_1^0 \times A_2^1 \times A_3^2 \tag{6}$$

The parametric equations are derived using equation (6) getting:

$$x = L2cos\Theta 1\cos(\Theta 2 + \Theta 3) + \mathrm{L3cos\Theta 1cos\Theta 2} \tag{7}$$

$$y = L2sin\Theta 1\cos(\Theta 2 + \Theta 3) + \mathrm{L3sin\Theta 1cos\Theta 2} \tag{8}$$

$$z = L2\sin(\Theta 2 + \Theta 3) + \mathrm{L3sin\Theta 2} \tag{9}$$

C. Denavit-Hertenberg algorithm taking the coxa as a paw link

The direct kinematics of the robot paw taken into consideration in this section is performed by taking the coxa segment as a link.

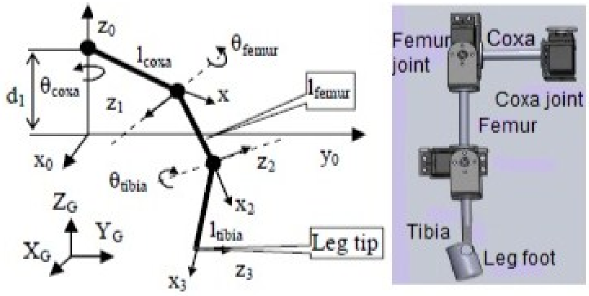

Fig 11. CAD design of the robor paw (righ) and the kinematic model with the attached coordinate fram (left) [15]

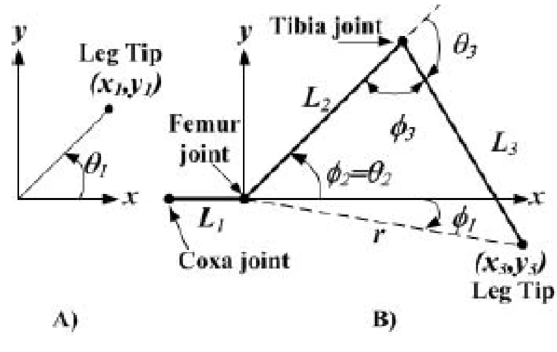

Fig 12. Two-dimensional representation of the paw of an insect [15]

General form of the link transformation matrix i for i-1 implements the Denavit-Hertenberg parameters.

$$T_i^{i-1} = \begin{bmatrix} cos\ \theta i & -\sin\theta i\ cos\ \alpha i & \sin\theta i \sin\alpha i & Li\cos\theta i \\ \sin\theta i & cos\ \theta i\ cos\ \alpha i & -\cos\theta i \sin\alpha i & Li\sin\theta i \\ 0 & \sin\alpha i & \cos\alpha i & di \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

The transformation matrix is calculated from the following series of transformations.

Translation (di) along the zi-1 axis

Rotation (θi) around the zi-1 axis

Translation (li) along the xi-1 axis

Rotation (αi) around the zi-1 axis

The product of the individual transformed matrices can be given using the equation:

$$T_{base}^{coxa} = T_{femur}^{coxa} \times T_{tibia}^{femur} \times T_{base}^{tibia} \quad (11)$$

The product of the three matrices determines the geometric model of the paw. Each of these matrices is defined as.

$$T_{fémur}^{coxa} = \begin{bmatrix} cos\ \theta 1 & 0 & \sin\theta 1 & L1\ cos\theta 1 \\ \sin\theta 1 & 0 & -\cos\theta 1 & L1\ sin\theta 1 \\ 0 & 1 & 0 & d1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

$$T_{tibia}^{fémur} = \begin{bmatrix} cos\ \theta 2 & -\sin\theta 2 & 0 & L2\cos\theta 2 \\ \sin\theta 2 & cos\ \theta 2 & 0 & L2\sin\theta 2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (13)$$

$$T_{base}^{tibia} = \begin{bmatrix} cos\ \theta 3 & -\sin \text{⍰}3 & 0 & L3\cos \text{⍰}3 \\ \sin \text{⍰}3 & cos\ \theta 3 & 0 & L3\sin \text{⍰}3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

The parametric equations are derived using equation (8).

$$x = cos\theta 1(\mathrm{L1} + L3\cos(\theta 2 + \theta 3) + \mathrm{L2cos}\theta 2) \quad (15)$$

$$y = sin\theta 1(l1 + L3\cos(\theta 2 + \theta 3) + \mathrm{L2cos}\theta 2) \quad (16)$$

$$z = d1 + L3\sin(\theta 2 + \theta 3) + \mathrm{L2cos}\theta 2 \quad (17)$$

The most remarkable difference found in the realization of the kinematic study for the paws of an insect is whether or not to appreciate the coxa as a link.

In a first review we can identify that the matrix of transformation of bond and for i-1 implementing the parameters of Denavit-Hertenberg are coincident in their values i.e., there is no difference between the two analyzes performed equation (2) and (3). However, this does not happen with the first transformation matrix and the values are similar until the last column where the first three values are replaced from *0* to $(L1\ cos\theta 1)$, $(L1\ sin\theta 1)$ *y* $(L1\ sin\theta 1)$, equation (3) and equation (10) correspondingly; the second and third transformation matrix are equivalent equations (4) and (5) and equation (13) and (14), in the two cases however, the parametric equations differ totally in the studies performed see equation (7), (8), (9), (15), (16) and (17).

VI. RESULTS OF SIMULATION OF THE PARAMETERS OBTAINED FROM THE DENAVIT-HARTENBERG METHOD

The realization of the simulation of the virtual prototype allows to verify the feasibility and precision of the design of mechanisms and the investigation of the theory, in addition provides a reference and guide for the subsequent design and investigation. This process allows to improve the efficiency in the work, to shorten the design cycle, to reduce the cost of production and to identify more intuitive mechanical defects, besides presenting the most reasonable design scheme [16].

The simulation of the design was done using the Simulink tool, which allows to take all the assembly files made in SolidWorks and create an XML document that Matlab can examine, this document has all the information that allows to recreate the piece made, these pieces is in a system of block diagrams that describe the assembly in detail.

Once Matlab recognizes the assembly, inputs are added to the systems, physical conditions and movement restrictions with which the assembled assembly counts.

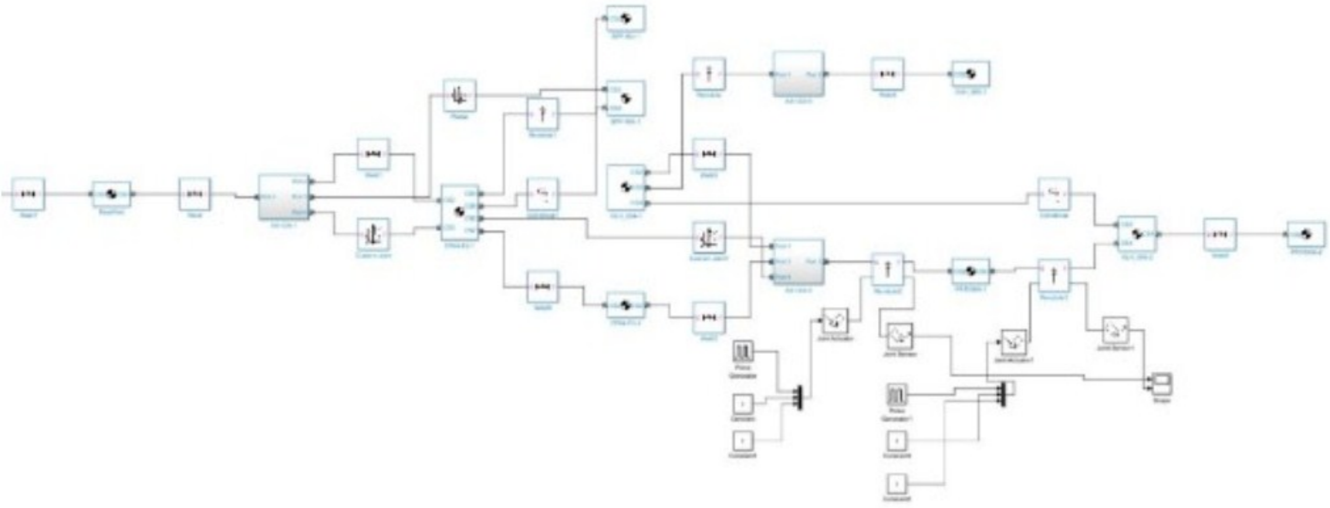

Fig 13. Representation by block diagram of the Leptynia paw assembly

Fig 14. Matlab paw assembly by Simmechanics

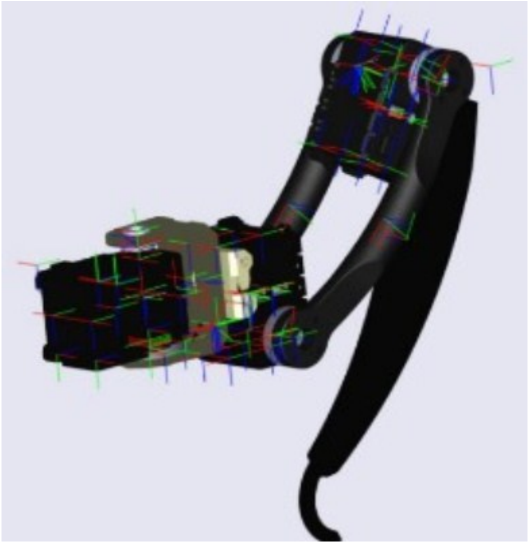

Fig 15. Displacement of the tibial link

The simulations made allow to identify the stability of the displacement of each of the links corresponding to the actuators that generate the movement.

In this article the simulation only focuses on the generation of movement of the assembly and the stability analysis of the corresponding joint, so that no more attention is paid to the control or stress characteristics to which the pieces are subjected.

VII. RESULTS

For the design process different techniques or elements are used to get a final phisical prototype, there are different techniques for choosing both the material and the mechanical characterization when it comes to the construction of the pieces. the choice of each of the elements that are part of the hexapod robot is performed taking into consideration that they will meet minimum requirements of construction and operation. although in this work the design and simulation of the robot was performed. the choice of materials and electronic components is made taking into considering that the costs of the same are not very high for its future realization and are the most appropriate when it is implemented.

As a result, there is a CAD design of the single-joint hexapod robot, both its physical parts, and the complete robot assembly.

VIII. CONCLUSIONS

The stability of a hexapod robot can be determined from the support polygon, where depending on the location of the center of mass corresponding to the polygon defined by the support points of the robot, you will know in which state of equilibrium the robot is.

By means of the Denavit-Hertenberg algorithm, it was possible to determine the mathematical model of the paw of the bio-inspired robot in the Leptynia Attenuata Pantel, where it was identified that the robot model has more outstanding characteristics than those mentioned in the anatomical description of the object of study, this is because the body of the phasmid has limitations and restrictions that are not taken in the design of the robot.

The simulations performed in Matlab give us information corresponding to the stability of the movements of the robot system.

Acknowledgments

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