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Simulating a System of Locomotion Similar to the Architecture of the Frog via Oblique Planes

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ABSTRACT

The aim of this paper is to present an empirical evidence of the mechanical movement of amphibians, taking into account the principles of bionics through graphical representation, to establish a formal and conceptual language of a system of locomotion to explore and analyze the changes generated by the points, lines and planes in space. We use applications CAD-CAE-CAM, to perform, from the cardboard till the rapid prototyping, the simulation of the movement of the front legs of the frog in three movements: when the frog is resting, when the frog is raised 21° and when the frog reaches 42°. In this paper we illustrate the process that took place to generate the parametric modeling of each of the parts of our model.

Keywords: frog, parabolic trajectory, parametric design, locomotion, prototype.

1. INTRODUCTION

Today, researchers at several universities are working on the imitation of the operation of biological organisms inspired in animals through mathematical models, we are working at the laboratory of the university the same subject but through descriptive geometry, i.e. we represent the planes in space, and we focus on locomotion taking into account two important aspects: joints and movements of the oblique planes because:

- In a locomotion system, joints have the function to give mobility and stability to the parts of the structure.
- And in a locomotion system, the oblique planes keep their angular position when moving upward or downward, rightward or leftward and forward or backward.

The goal of this paper is to present the use of oblique planes in the construction and simulation of a system of locomotion similar to the architecture of the frog.

To reach the goal of the research, in this study considers the anatomy and the skeletal structure of the frog (Fig. 2b), resulting in the movement, and also the studies conducted by scientists from Brown University in Rhode Island in USA [1]. The process that was undertaken in this research is the following: it was performed a virtual model in the 3D Autodesk Maya program, to analyze the frog jump; in the Autocad program was traced the orthogonal projection in two and three dimensions to create the model, in the Inventor program were generated the parametric modeling, the assemblies and the simulations, and performed the prototype with the 3D printer.

We know that the mechanics, which is the extension of classical physics, studies the state of rest and motion of bodies and is divided into: kinematics, statics and dynamics. Kinematics studies the motion of bodies without considering the causes that produce movement.

The balance of the bodies is studied by the static, and dynamics studies the movements of the bodies by considering the causes which produce the movement. In the dynamic we find the Newton's Laws also called fundamental laws of motion: the 1st law of inertia, the 2nd law of forces and action and the 3rd law of action and reaction.

The rotational motion of a rigid body is analogous to Newton's second law, which determines how the changes occur in the body movement when it is subjected to the action of a force. Then if we apply a force on the horizontal plane of our model, i.e. on the body of the frog, the oblique planes of the front legs of the frog will also have a rotational motion and change their position in space (Tabs 7, 8, 9 and 10).

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Fig. 1: Frogs species found in the aquarium located in Mazatlan, Sinaloa, Mexico City.

This project start from the premise of creating a system of locomotion similar to the architecture of the frogs, using the elements and resources of descriptive geometry, to identify, develop, describe and generate the morphological and functional behavior of amphibians, using the following methodology [11]:

- Development of the geometric and structural representation of the model.
- Generation of parametric design.
- Description of the movements (locomotion).
- Build the prototype.

In this paper we present the first part of the research on where they can analyze the structure and locomotion of the front legs of the frog design, contributing to the solution of geometric structures which simulates the movements of the amphibians with the handling of the oblique planes without losing sight of the concepts of physics.

This paper is organized as follows: in Section 2 we give a brief explanation of the anatomy of frogs, in Section 3, we explain the geometrical and structural representation of the development of the model. In Section 4 we explain how parametric modeling was generated. Section 5 explains how the parties are assembled and simulating the movements of the frog. Section 6 presents the prototype. Section 7 presents the results and finally Section 8, the conclusions. We want to mention that all the figures presented in this paper are original and created by the authors at the Autonomous Metropolitan University, Cuajimalpa in Mexico City.

2. ANATOMY OF FROGS

Frogs belong to the family of amphibians (Fig. 1), in scientific language, the frogs are known by the name of "anurios", and were the first vertebrates to adapt to a semi-terrestrial life and are distinguished by having a complete transformation during its development, i.e. undergo a metamorphosis. In this metamorphosis, when the tadpoles mature, they develop hind legs for jumping, absorb its tail by apoptosis (controlled cell death) and change their gills to adapt to terrestrial life.

To be able to construct a prototype similar to the architecture of the frogs and create its locomotion system, it must first be understood the anatomy of "anurios" through its form and structure (Fig. 2a). In biology, morphology is a branch of biological sciences dealing with the study of form and structure of organisms and their specific structural features; this includes aspects of the outward appearance (shape, structure, color and patterns) as well as the form and structure of the internal parts like bones and organs.

In the frog skeleton (Fig. 2b), resulting in the movement, we find, first of all, the joints that are what allow to the frog perform the movements. Their forelimbs have three segments: the humerus, radius-ulna (two fused bones), and the third consists of a series of carpal bones, metacarpals and phalanges of five fingers. The hind legs are distributed in number and similarly of the forelimbs: the femur, the tibio-fibular (two fused bones) and the set of tarsal, metatarsals and phalanges of five fingers.

3. GEOMETRIC AND STRUCTURAL REPRESENTATION OF THE DEVELOPMENT OF THE MODEL

Years ago, Luigi Galvani (1737-1798), presented at the Institute of Science, a statement on the muscular movements of the legs of frogs, and in 2001 a team of scientists from Brown University in Rhode Island in the United States, studied in detail the leapfrog to find out how it achieves the frog so high, concluding that the muscles of the frogs are extremely elastic and can achieve the optimum balance of strength and mechanical energy [1].

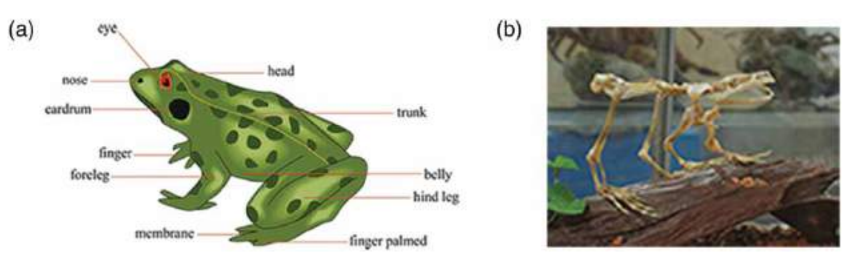

Fig. 2: The frog (a) morphology [5], (b) skeleton.

Taking into account the studies conducted by scientists from Brown University, first we perform, in the program 3D Autodesk Maya, a virtual model of a frog (Fig. 3a) to analyze the trajectory of its jump (Fig. 4).

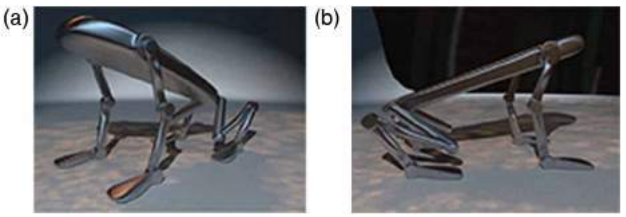

Fig. 3: Virtual model (a) front view, (b) lateral view.

As we know this jump meets the characteristics of the parabolic movement (Fig. 5). In the parabolic movement the speed has a double trajectory, at first moment the body initiates the trajectory with an angle of inclination with respect to the horizontal axis and the body goes up to a maximum height. And in the second moment, speed starts at zero and is increased by the action of gravity until the speed reaches its maximum value before reaching the ground.

Taking into account the frog skeleton, the concepts of parabolic motion and the virtual model, we trace with CAD applications, the orthogonal projection (Fig. 6a), the three-dimensional graphic representation (Fig. 6b), the structure (Fig. 7a) and the render (Fig. 7b) of our design (Fig. 6 and 7).

As shown in Figure 7, the front legs of the frog, which is to be discussed in the first part of the investigation, are formed by three oblique planes of four sides. An oblique plane is defined as a plane that is not at right angles with respect to another plane, which is inclined with respect to the three reference planes of the orthogonal projection and they are not in true form and magnitude.

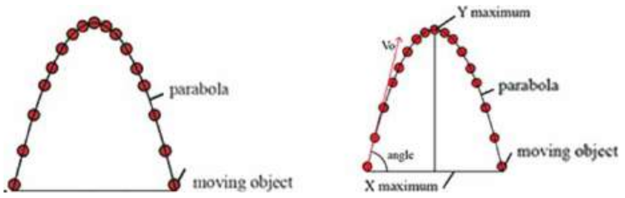

Fig. 5: Parabolic movement.

If an oblique plane is greater than three sides is required triangulation. In geometry, triangulation is used to determine the inclination of the planes with respect to an edge, that is, the oblique plane is divided into triangles, each of the triangles are rotated either downward or upward to form the figure. Triangulation is also used to find the true shape and magnitude of the oblique planes through their lines via two methods: by changing planes or rotation, in this study we used the method of changing planes to find the true shapes and magnitudes of the planes.

We analyze one of the oblique planes of the front legs of the frog (Fig. 8) to better understand our design. In the orthogonal projection of Figure 8, we can observe that the origin is located at the points (0,0,0) and the points of the lines forming the oblique plane are located, from the origin, at the following coordinates (Tab. 1).

Afterwards we performed the mathematical analysis and tracing the parabolic trajectory (Fig. 9) of our model, determined by the distances of the axis “x” and “y” with the angle of 21° and 42°, to find the maximum height, the initial velocity, the maximum distance and the time it would take to make the trajectory the frog.

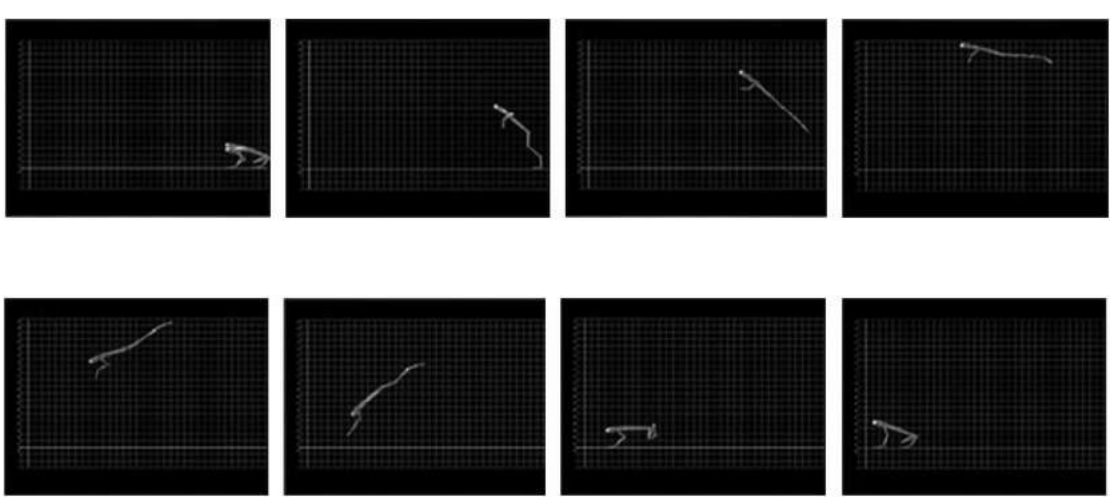

Fig. 4: Trajectory of the frog jump.

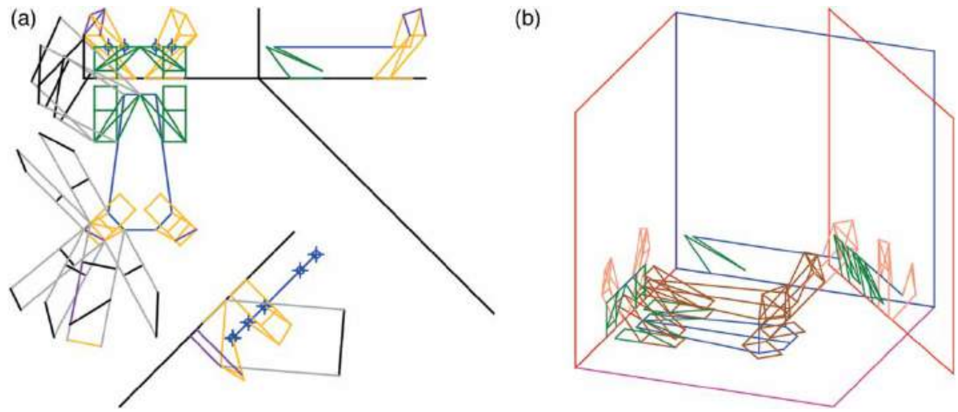

Fig. 6: (a) Orthogonal projection, (b) three-dimensional graphical representation.

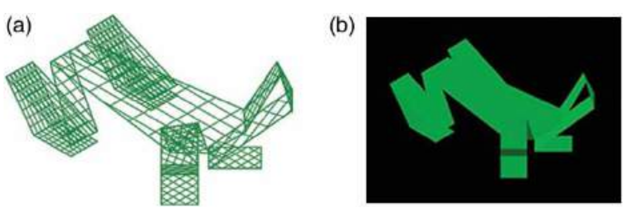

Fig. 7: Model, (a) structure, (b) render.

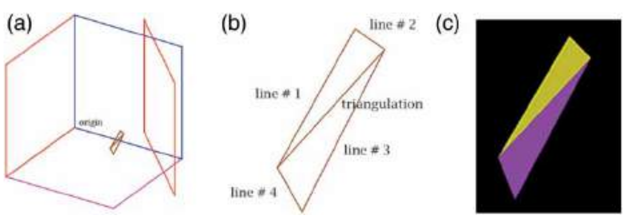

Fig. 8: Oblique plane, (a) orthogonal projection, (b) detail, (c) render.

It is imposible to present all the work done in so few pages, so we present only the parabolic trajectory of the angle of 42° as an example to understand the behavior of our model.

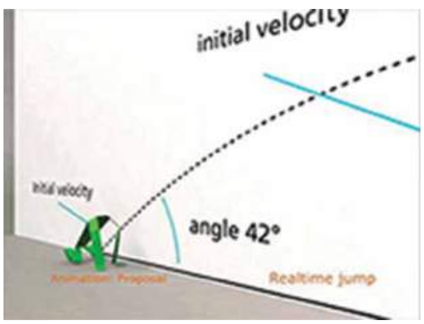

Fig. 9: Parabolic trajectory of our model.

First we define the distances of the axis "x"and "y"(Tab. 2).

To find the maximum height we use the following equation:

$$ymax = \frac{Voy^2}{2g}$$

And the results are in Table 3.

To find the initial velocity we use the following equation: $Voy = \sqrt{Vy^2} + 2g\Delta y$
And the results are in Table 4.

	Line # 1	line # 2	line # 3	line # 4	triangulation
start x	−87.1849	−105.2395	−105.2395	−110	−105.2395
start y	−182.8151	−204.7605	−204.7605	−169.9603	−204.7605
start z	80.3474	87.5147	87.5147	40	87.5147
end x	−110	−87.1849	−130	−130	−110
end y	−169.9603	−182.8151	−191.3832	−191.3832	−169.9603
end z	40	80.3474	40	40	40
delta x	−22.8151	18.3474	−24.7605	−20	−4.7605
delta y	12.8548	21.9455	13.3773	−21.4229	34.8002
delta z	−40.3474	−7.1674	−47.5147	0	−47.5147
length	48.1007	29.3077	55.224	29.3077	59.0878
angle	151	51	152	227	98

Tab. 1: Location of the points of oblique plane.

X	Y
11.11	10.00
22.21	20.00
33.31	30.00
44.42	40.00
55.53	50.00
66.63	60.00
77.74	70.00
88.84	80.00
99.95	90.00

Tab. 2: Distances axis "x" and "y", mm.

X	Y	maximum height
11.11	10.00	5.10
22.21	20.00	20.41
33.31	30.00	45.92
44.42	40.00	81.63
55.53	50.00	127.55
66.63	60.00	183.67
77.74	70.00	250.00
88.84	80.00	326.53
99.95	90.00	413.27

Tab. 3: Maximum height, mm.

X	Y	initial velocity
11.11	10.00	14.14
22.21	20.00	28.28
33.31	30.00	42.43
44.42	40.00	56.57
55.53	50.00	70.71
66.63	60.00	84.85
77.74	70.00	98.99
88.84	80.00	113.14
99.95	90.00	127.28

Tab. 4: Initial velocity, mm/seg.

To find the time it would take to make the trajectory the frog, we use the following equation:

$$tv = 2\frac{Voy}{g}$$

X	Y	total time
11.11	10.00	2.04
22.21	20.00	4.08
33.31	30.00	6.12
44.42	40.00	8.16
55.53	50.00	10.20
66.63	60.00	12.24
77.74	70.00	14.29
88.84	80.00	16.33
99.95	90.00	18.37

Tab. 5: Total time, seg.

X	Y	maximum distance
11.11	10.00	22.67
22.21	20.00	90.65
33.31	30.00	203.94
44.42	40.00	362.61
55.53	50.00	566.63
66.63	60.00	815.88
77.74	70.00	1110.57
88.84	80.00	1450.45
99.95	90.00	1835.82

Tab. 6: Maximum distance, mm.

And the results are in Table 5.

And to find the maximum distance we use the following equation: $Xmax = Vox * tv$

And the results are in Table 6.

Finally we trace the parabolic trajectory of the distance $V = 99.95\hat{\imath} + 90.00\hat{j}$, as an example to understand the behavior of the frog (Fig. 10).

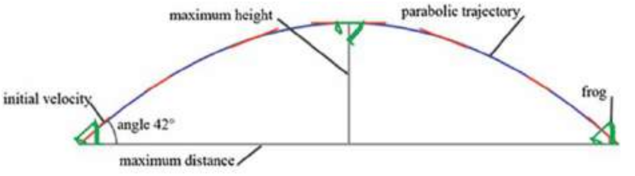

Fig. 10: Parabolic trajectory of our model.

After completing the parabolic trajectory of the frog and with the location of all planes of our model and the points of the lines containing them, we constructed the structure in three dimensions (Fig. 11) using CAD applications and rapid prototyping (Fig. 12). As we can see prisms and cylinders are used in the structure because they allow us to form the joints so that the frog can move.

4. GENERATION OF PARAMETRIC MODELING

The parametric modeling is defined as the method of modeling three-dimensional objects from their dimensional and geometric relations. In this research, we used the 2012 Inventor program to generate the parametric modeling of each of the parties of our model (Fig. from 16 to 19), the assemblies (Fig. from 20 to 23), and the simulations (Fig. 24).

Before generating parametric modeling of each of the parties of our model, we build three models in cardboard (Fig. 13) to locate the points and lines containing the oblique planes and also to observe the movements of each of the oblique planes of the front legs of the frog before the frog jump start, i.e. when the frog is resting, when the frog is raised 21° and when the frog reaches 42°.

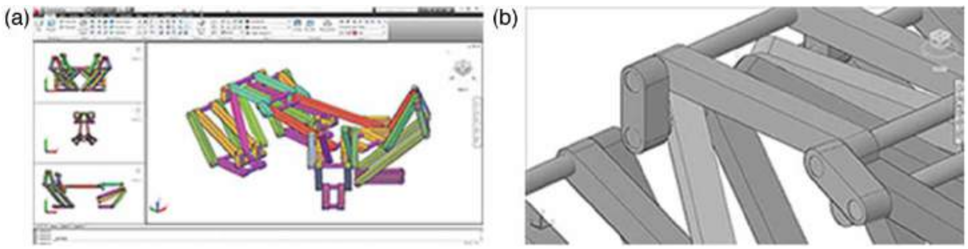

Fig. 11: Structure, (a) modeling, (b) detail of the articulations.

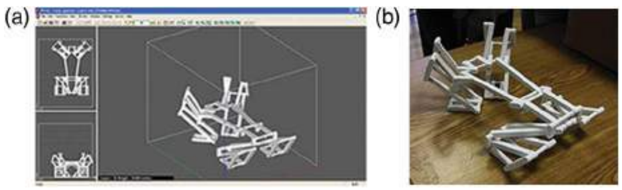

Fig. 12: Prototype, (a) STL file, (b) top view.

Considering the triangulations of oblique planes, we continue with the two-dimensional tracing of each of the parties (Fig. 14).

For parties rotate freely and they act as hinges fifteen cylinders are placed as components of the mechanism for guiding the movement of rotation. Therefore, all the parties were redesigned (Fig. 15a) to place the cylinders taking into account the tolerances.

In the laboratory of the university, we perform several tests of tolerance considering the 3D printer material, and the result of the geometric tolerance obtained was 1.6 mm per side (Fig. 15b).

Finished the tolerance analysis, we begin to generate the parametrically modeling of each of the parties of our model including the cylinders (Fig. from 16 to 19).

5. ASSEMBLING AND SIMULATION OF MOVEMENTS OF THE FROG

The assembly word is derived from the French verb "assembler"and is defined as the union of two pieces forming part of a structure. To make the assembling of our model, in the 2012 Inventor program, was used the restriction, insert. Since with this restriction it determined the relative position of the geometry of the parties, respect to the axes of the cylinders (Fig from 20 to 23).

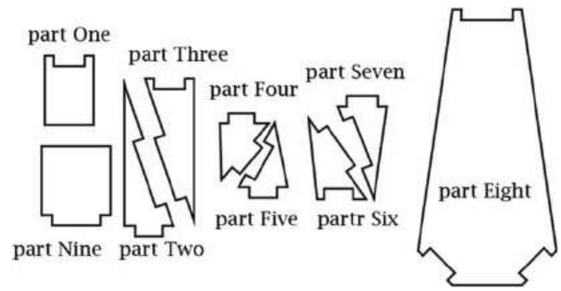

Fig. 14: Tracing of the parties.

Afterwards were performed in the 2012 Inventor program the simulations (Fig. 24) and the geometric planes (Fig. 25) of the three positions: when the frog is resting, when the frog is raised 21° and when the frog reaches 42°.

Newton's second law says: "When a force acts on an object, the object accelerates in the direction of the force. If the mass of an object is held constant, increasing force will increase acceleration.", then to simulate the mechanism of our model, a force is applied in the horizontal plane (Fig. 26), so that when the plane is rotating in the direction of clockwise reaches the angle of inclination of 42° and the oblique planes keep their angular position, and when the plane is rotating in the direction of the counterclockwise, all the planes returns to its original position, the results we can see in Table 7.

6. PRINTING THE PROTOTYPE

Once finished with the model analysis, the last step that was performed was to print the prototype Fig. 27a and b generated with CAM applications, where we can see how the mechanism works.

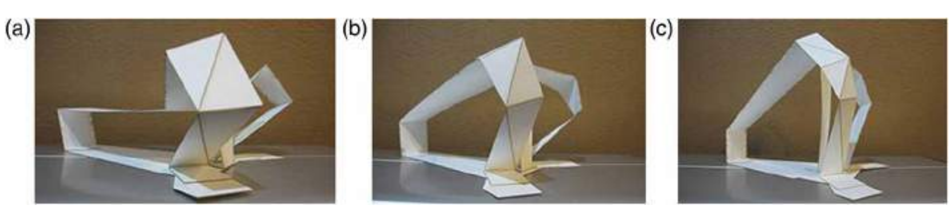

Fig. 13: Models in cardboard, the frog is (a) at rest, (b) raised 21° (c) reach 42°.

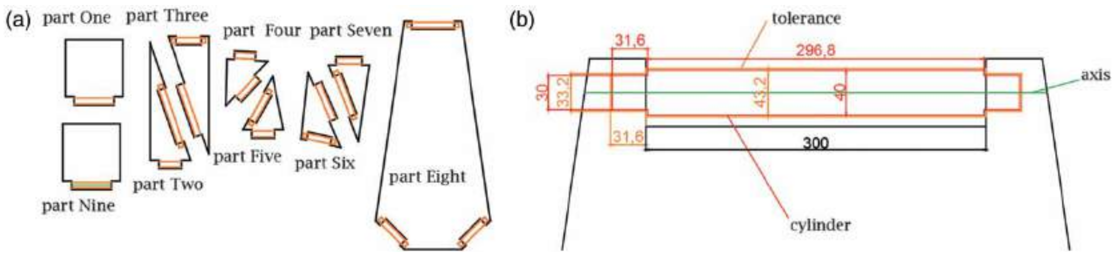

Fig. 15: Tolerance, (a) parties, (b) detail.

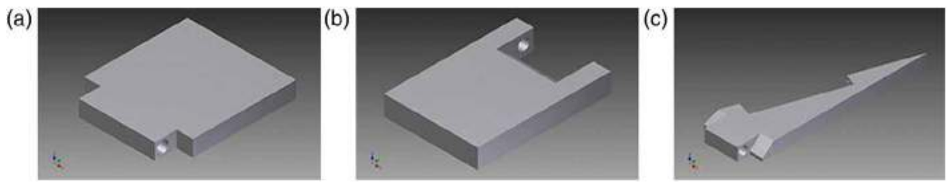

Fig. 16: Parametrically modeling, parties (a) nine, (b) one, (c) two.

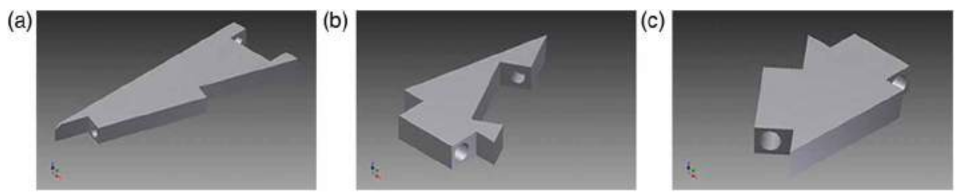

Fig. 17: Parametrically modeling, parties (a) three, (b) four, (c) five.

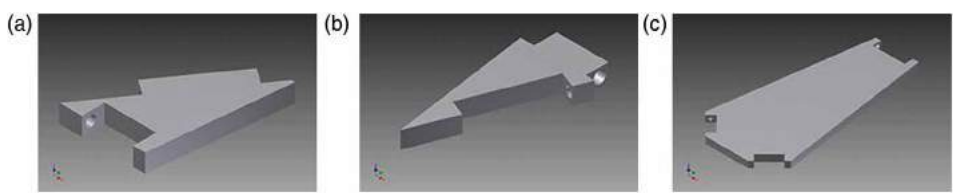

Fig. 18: Parametrically modeling, parties (a) six, (b) seven, (c) eight.

Fig. 19: Parametrically modeling, cylinder (all the cylinders are equal but have different measurement).

The file is saved with STL (Fig. 27a) format to open it in the program ZPrint. The program ZPrint comes with the 3D printer, who reads the virtual designs to analyze them and place them in the work area of the machine to materialize.

7. RESULTS

There are many figures that mimic the movements of animals; we can mention the robot developed at the University of Tokyo [6] that is able to jump like a frog more than 50 cm in height, the design of the robot has no forelegs. We can mention the mechanical animals made by Amit Drori [10], the structures of these animals are prisms that rotate upwards and downwards. And we can also mention the figures made by Theo Jansen [14], these animals are able to walk with the wind, their structures are based on vertical and inclined planes or by tubes and their movements are lineal.

The difference between the locomotion of the examples mentioned and the design model presented

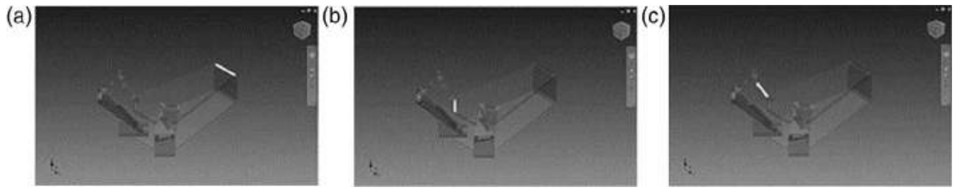

Fig. 20: Assembly, (a, b, c) cylinders one, two and three, parties nine, eight, seven and six.

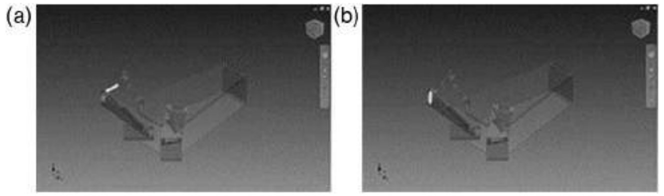

Fig. 21: Assembly, (a, b, c) cylinders four, five and six, parties six, five, four and three.

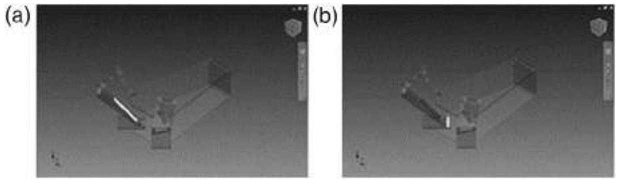

Fig. 22: Assembly, (a, b, c) cylinders seven and eight, parties three, two and one.

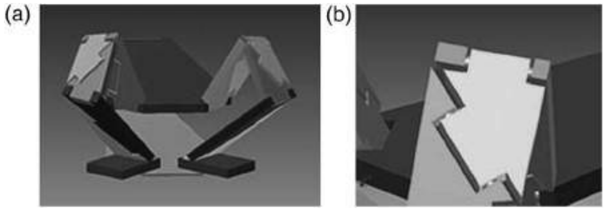

Fig. 23: Render of parametric design, (a) front view, (b) hinge detail.

in this paper is the use of oblique planes and the location of the joints, which are not parallel to the axes "X, Y, Z "of the orthogonal projection.

To establish the characteristics of the movement of the front legs of the frog, three models were generated: the first through bars and cylinders, the second by geometrical planes, and the third with geometric solids and cylinders. In the bars and cylinder model, were determined the positions of the lines in space and identified the location and movements of the joints of the skeleton of the frog.

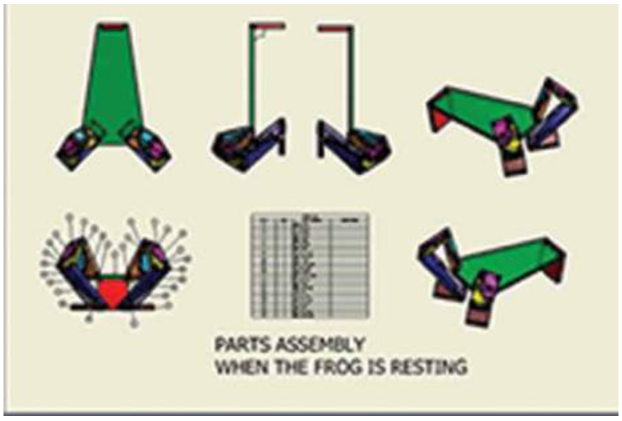

Fig. 25: Geometric planes.

In the geometrical plane model, realized in cardboard, were identified the movements of the oblique

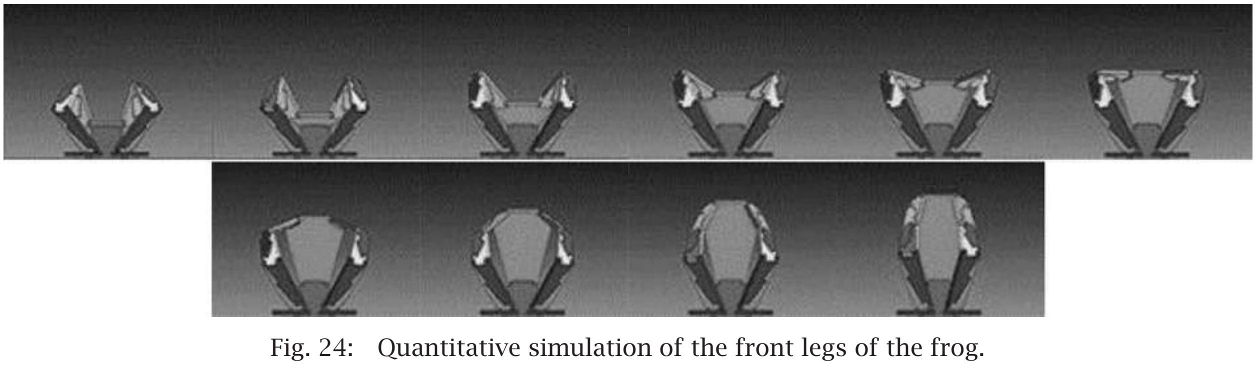

Fig. 24: Quantitative simulation of the front legs of the frog.

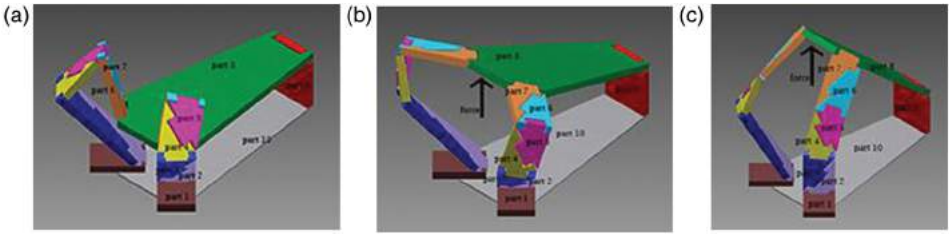

Fig. 26: Parties, frog, (a) resting, (b) raised 21°, (c) reaches 42°.

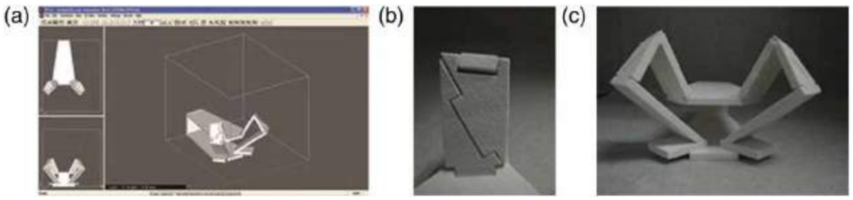

Fig. 27: (a) STL. File, (b) prototype, hinge detail, (c) front view.

Parties	Resting	Raised 21°	Reaches 42°
One and two	133.65°	39.92°	56.96°
Two and three	1.98°	170.73°	174.44°
Three and four	94.73°	133.52°	123.58°
Four and five	13.64°	22.19°	156.82°
Five and six	66.18°	99.26°	177.45°
Six and seven	177.28°	176.23°	173.77°
Seven and eight	105.92°	170.38°	105.65°
Eight and nine	90°	111°	132°
Nine and ten	90°	90°	90°

Tab. 7: Result of the angles between the parties.

planes in space. And, in the model of geometric solids and cylinders, printed in 3D, were analyzed the behavior of the hinges, of each of the parties.

When we perform triangulation of oblique planes, the movement of the parties was gradually resolved in the first two models and when we generate the simulation with the third model, using the hinge mechanism, the result we got was that when turned upwards and downwards the body of the frog, each of the parties of the front legs of the frog, besides moving upwards and downwards, also rotate about the axis of the cylinders to the right and the left.

In the quantitative simulation of the front legs of the frog (Fig. 24) we can observe that the movement of the legs is synchronized, this tells us that the assembly is well resolved and the pieces do not collide when performing movements simultaneously. Through the simulations, we analyze the behavior of the oblique planes and hinges when a force is applied, the results that we can see in Tables 8, 9 and 10, (the data that are in the tables correspond to the left front leg of the frog, the body and the part nine of the model) shows the displacements and angles of each of the parties with respect to the origin (the origin is located at the top of the part number nine).

parties	X offset	Y offset	Z offset	X angle	Y angle	Z angle
partie_one_2	−201	−1341	−400	0	0	45
partie_two_2	−149.8	−1289.8	−371	−143.4	−30.8	−34.5
partie_three_2	−555	−1695	226	−145	31.8	−35.5
partie_four_2	−585	−1723	185	−39.4	32.5	35
partie_five_2	−405	−1430.4	504.1	−24.3	37.57	32.4
partie_six_2	−433.7	−1479.7	470.1	68.2	−39.9	29.3
partie_seven_2	−294.7	−1432.4	−6.9	68.6	−42.9	14.9
partie_eight	0	0	0	0	0	0
partie_nine	0	0	60	90	0	0

Tab. 8: Displacements and angles of each of the parties with respect to the origin, the frog is resting.

parties	X offset	Y offset	Z offset	X angle	Y angle	Z angle
partie_one_2	−201	−1341	−400	0	0	45
partie_two_2	−149.8	−1289.8	−368.8	−146.2	29	−36
partie_three_2	−564.4	−1688.8	220.5	−134.3	20.7	−30.9
partie_four_2	−566.9	−1698.7	196.5	−96.9	34.6	−12.9
partie_five_2	−664.5	−1587.6	632.1	−83.8	58.2	−14
partie_six_2	−657.2	−1606.6	575	18.6	6.4	59.1
partie_seven_2	−256.9	−1309.7	515.1	17.4	3.56	44.8
partie_eight	0	−8.7	12.7	21	0	0
partie_nine	0	0	60	90	0	0

Tab. 9: Displacements and angles of the parties with respect to the origin, the frog raised 21°.

parties	X offset	Y offset	Z offset	X angle	Y angle	Z angle
partie_one_2	−201	−1341	−400	0	0	45
partie_two_2	−150.4	−1290.4	−378.8	−132.5	36.3	−28.5
partie_three_2	−461.7	−1595.3	322.1	−126.9	31.9	−25.4
partie_four_2	−477	−1616.2	293	−59.6	37.1	15.9
partie_five_2	−388.5	−1361.5	665.6	−30.3	51.8	26.1
partie_six_2	−387.9	−1361.9	664	−26.9	50.7	28.7
partie_seven_2	−253.6	−1012.5	996.3	−25.7	42.7	15.5
partie_eight	0	−12.3	27.7	42	0	0
partie_nine	0	0	60	90	0	0

Tab. 10: Displacements and angles of the parties with respect the origin, the frog reaches 42°.

8. CONCLUSIONS

Perform a locomotion system is a challenge, since it depends on many factors, among which we mention the proper handling of adaptation, the geometrical description and the mechanisms.

This paper presents the simulation of a system of locomotion via oblique planes. From the triangulation of oblique planes, the front legs of the frog they moved simultaneously when it rotated upward and downwards the horizontal plane, ie the body of the frog, since each of the parties of the front legs of the frog, besides moving upwards and downwards, also rotates about the axis of the cylinders to the right and the left.

The results show that the design process that was carried out in this project, contributes to the solution of geometric structures to simulate the movements of the animals with the handling of the oblique planes without losing sight of the concepts of physics.

ACKNOWLEDGEMENTS

To Jesús Hernández Cadena professor at Metropolitan Autonomous University, Cuajimalpa in Mexico City, that with all his knowledge is helping us with the solution of the mechanism.

To Enrique Garcia Salazar, student of the Bachelor of Design at Autonomous Metropolitan University, Cuajimalpa in Mexico City, who with all his enthusiasm, is supporting us in this project as an intern.

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