

KINEMATICS OF A HEXAPOD MODULAR ROBOT

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Abstract. *Conventional mobile robotics is unable yet to offer locomotion solutions for overcoming real world obstacles. For instance, in a land collapsing situation, a wheeled robot has as much difficulties for climbing ladders as for crossing holes along its way. Meanwhile, modular robotics can create multitask robots with a wide range of configurations. This article is about the Erekebot Alpha, a modular robot provided with a hexapod locomotion system. The Erekebot Alpha has a cubic structure and a rod that offers one degree of movement freedom. The hexapod robot as a spine made of five rigid modules plus two more modules in each leg, which makes a total of seventeen identical modules. Each leg executes a constant and previously-defined trajectory. This research has concluded that the robot is capable of walking on plain surface, forward and back. Kinematics simulations were done based on previously developed movement equations. Hence, for comparison purposes of the real and theory models, the legs movements were tested. Modular robotics has already demonstrated more efficiency on different scenarios and, in the future, it is expected that the Ereko group's hexapod modular robot will be able of overcoming even more challenging surfaces.*

Keywords: *modular, robotics, hexapod, kinematics, simulation.*

1. INTRODUCTION

Mobile robots are the ones able of moving in any surroundings they are found, but this is not a trivial task. Besides the difficulty of maintaining balance and stability, obstacles can be found in the way. In order to predict such hardships, many researches on mobile robotics have been conducted. Another important factor that leads to the development of mobile robots is its applicability, including spatial exploration, rescue, speleology, tubing inspections, cargo transportation, and explosives deactivation.

The first mobile robots were built with wheels or tracks, demanding a lower computational power at routing processing. Such robots can move with ease and some regularity on rigid surfaces, but they are not so efficient on soft or bumpy surfaces, and neither are they on climbing ladders. To solve these problems and enable the exploration of not yet achieved terrains, researches about mobile robots with legs have been developed. They provide great versatility to robots, allowing them to achieve uneven terrains. However, the complexity of the system increases drastically, which complicates the control of the robot, since the legs need to move coordinately.

With help from the actual technological development and supported by the appropriated mathematical techniques, it is possible to calculate and determine individual trajectories of each leg with high precision. This way, it is possible to overcome the land irregularities, isolating the path of the leg and of the rest of the robot as well (Silva, 2005).

Stability is a crucial topic when talking about robots with legs, since it is essential for the robot to maintain its gait. There are two types of stability: static and dynamic. A robot is considered statically stable if it is able to maintain equilibrium at any given moment, even when its legs stop moving at the exact position in which they are found. The dynamic stability is achieved when the robot is moving. A biped robot is classified as dynamically stable, while quadruped and hexapod robots can achieve the static stability, since they are able to form a support polygon.

This polygon is defined by the vertices of the legs that touch the ground: if the center of gravity of the robot is positioned inside the support polygon, the robot remains stable. It was because of the static stability that the hexapod

robots were selected. The minimum amount of legs to create the support polygon is three, and therefore the hexapod can still remain statically stable even if it has half of its legs up in the air. There are, however, other characteristics that must be considered: the robot can move in many different ways, when relating to the gait's pattern; the quantity of legs provides security in case of the failure of a leg, and even allows one or more legs to be used as handlers for distinct tasks (Ding, et al 2010).

The desire to innovate and to make robots even more versatile inspired the idea of modular robots. A modular robot has a single basic component called module. There are three main benefits that promote studies on modular robotics: low cost, robustness, and versatility (Yim, et al, 2001). Since the modules are identical, they can be manufactured in large scale, which reduces the fabrication and maintenance costs. The robustness of modular robots results from the fact that the maintenance is given by replacing the defective modules with new ones. This process may be done automatically by the robot itself or by an external machine, which in both cases decreases the need of human intervention. The capacity of a modular robot to change its morphology allows a better adaptability to accomplish a task (Souza, et al, 2010).

This paper's objective is to study the movement of modular robot's legs using a hexapod configuration. It becomes necessary to develop a kinematic model to the hexapod robot in such manner that the robot can place each leg in a specific location, controlling only the joints angles. This way, through periodical movements of the legs, the robot can walk. First, the current state of the modules' development of the Ereko group, started by Souza, et al (2011), will be shown. Once a generic model for the module is defined, kinematic developments of four different modular robots and the results obtained through the simulations will be presented, as well as their respective analyses. Due to the practical difficulties, it was not possible to perform real tests with the complete robot, although tests were made to verify the individual legs' movements.

2. EREKO PROJECT

The ErekoBot $\alpha 1$ model described at Souza, et al (2010) already achieved success at locomotion tests in apodal shapes, but some improvements were identified as necessary: working with fiberglass demands an unusual knowledge and experience to the researchers, and its costs were not viable to the project.

These facts led to the development of a new module, the ErekoBot $\alpha 2$. It was resized to 50x50x50mm, making room to place more communication sockets, enabling the direct recording of the microcontroller program, and allowing battery tension measurement within the module. But, as the servomotors were not changed, the increased weight has caused the inability of one module to raise two others, precluding the requirements of some leg and apodal configurations. Solutions are being studied to avoid changing the servomotor, and subsequently the module's battery.

As the project lacked a completely functional module during the moment of the tests, a prototyping one, the ErekoBot $\alpha 0.5$, was used to achieve the experimental results presented on this paper. The ErekoBot $\alpha 0.5$ is designed for quick tests, and houses only the servomotor in its fiberglass case. An external microcontroller is responsible for controlling and connecting the modules.



Figure 1. Module ErekoBot $\alpha 0.5$ used in this Project

3. KINEMATICS OF HEXAPOD ROBOT

The set of modules developed by the group Ereko, in general, have cubic geometry and multiple connection faces, as it is seen on the previous section. Before proceeding to the development of the kinematics, a representative model for the module needs to be created, in order to be used as a base for calculations. Each module has the dimensions of the model shown in Fig. 2 (R_1 , R_2 and R_3 are equal). In the following calculations, numeric and non-literal constants were used in order to obtain equations independent to the size of the module. Thereby, the equations developed will remain valid even in case of eventual changes in the project, as long as the relationships between the dimensions of the module remain the same.

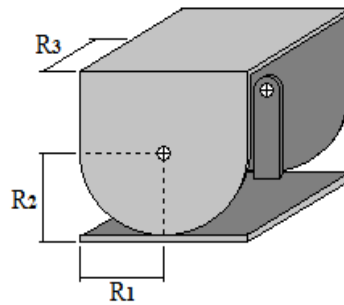


Figure 2. Module model used in the project

Each module has only one joint, with one degree of freedom (DOF). The motor operates in the joint of the module, giving an actuation angle between -90° and 90° to it.

By attaching multiple modules, it is possible to achieve shapes with more degrees of freedom, which allows the control over the assembly. In the following graphs and tables, it was considered that $R_1 = R_2 = R_3 = R = 25\text{mm}$. These are the measurements of the module *ErekoBot $\alpha 2$* , the initial objective of this research. However, while the proportions of the module are maintained, the shape of the movement will remain the same, and only the position that the leg can reach in space will be altered.

The configuration in study on this paper is the hexapod. Even if the type of configuration is restricted, there are several hexapod robots that can still be built in modular robotics. More usual configurations for hexapod robots were chosen, so that the least amount of modules would be used. Thus, four architectures were conceived: turtle robot, and robot soldier, with 2 and 3 degrees of freedom each. These models differ in module's positioning and quantity, since each module gives one degree of freedom. The common factor in all configurations is the body, composed by a row of modules with only a structural function as a rigid spine.

3.1 Turtle Robot with 2 Degrees of Freedom

The turtle robot is arranged as shown in Fig. 3(a). This nomination is inspired on the movement of its legs, which resembles a turtle when it walks, and on the fact that the body of the turtle remains close to the floor, but not touching it. This is given to the shape of the leg, which is composed by two modules (Fig. 3 (b)). The module that is attached to the body, called yaw module, is responsible for the range of the step, while the following module, called pitch module, controls the distance of the robot to the ground.

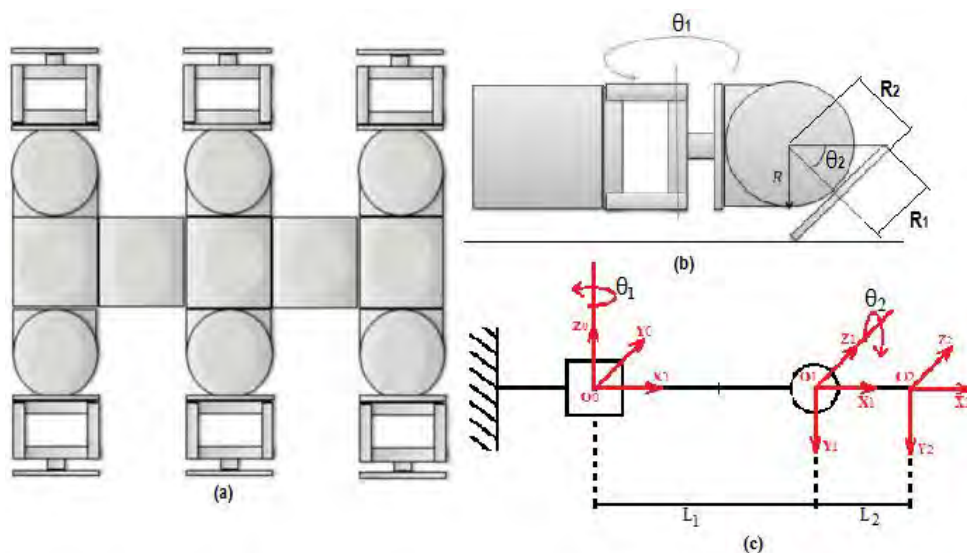


Figure 3. (a) Model of the complete turtle robot, (b) Approximation of the 2 DOF leg, (c) Leg simplification

The main problem of the forward kinematics can easily be solved using the Denavit-Hartenberg (DH) method (Craig, 1989). For this, it is necessary to assign coordinate systems to the joints. It is then possible to obtain the parameters of the joints, and determine the transformation matrix, from which the Cartesian position of the foot and the angles of each joint can be found. Note that Fig. 3(c) is the representation of the leg of the robot. The axis of the joint

represented by the square is parallel to the plane of the sheet, and the axis of the circular joint is perpendicular to it. The distance from one joint to another is $2R_2$, and the distance to the pitch joint to its surface is R_2 . That is, $L_1 = 2R_2$ and $L_2 = R_2$. The equations (1) – (3) express the results obtained with the transformation matrix and with the substitution previously mentioned, where θ_1 and θ_2 are the angles of the joints.

$$x = R_2 \cos(\theta_1) \{ \cos(\theta_2) + 2 \} \quad (1)$$

$$y = R_2 \sin(\theta_1) \{ \cos(\theta_2) + 2 \} \quad (2)$$

$$z = R_2 \sin(\theta_2) \quad (3)$$

Each leg will follow a single path repeatedly. The coordination of the movements of each leg will cause the robot to walk. During the project, it has been noted that the workspace of the leg used is quite limited, as it only deals with a tridimensional surface, without volume. Therefore, planning the trajectory in the operational space becomes very hard, since avoiding the singularities is not a trivial task. As result, it was feasible to plan the angles of the joints without calculating the inverse kinematics, which diminished the complexity of the project.

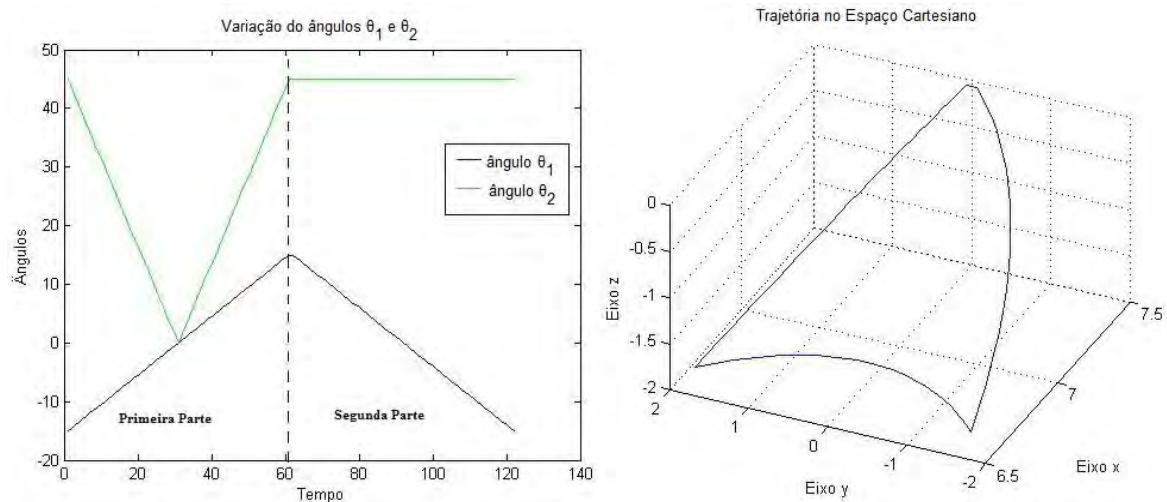


Figure 4.: Desired trajectory for turtle robot with 2 DOF leg

Two stages were defined when finding the desired trajectory: the stage when the foot is up in the air, and when it is touching the ground. In the first stage, both angles change linearly; θ_1 varies between -15° and $+15^\circ$ (this angle was chosen as to avoid collisions), while θ_2 ranges from 45° to 0° , and back to 45° . The second stage's goal is to maintain the body of the robot at a constant height, thus resulting in a flat trajectory parallel to the xy plane. The angle θ_2 remains constant at 45° , ensuring that the distance of the robot to the ground is the greatest possible distance. The angle θ_1 varies linearly with the same range, but in the opposite direction. The trajectory is then done. Figure 4 shows how the angles θ_1 and θ_2 , represented by the colors blue and green, respectively, vary in both stages. The figure also shows the trajectory in the Cartesian space.

3.2 Turtle Robot with 3 Degrees of Freedom

In this configuration, the movement of the leg is more complex, due to the addition of one degree of freedom. However, the robot gains more stability and more contact to the ground. This model is an extension of the robot with 2 DOF, having one extra module on each leg. This new module is on the same direction as the pitch module, so the robot can rise higher. Moreover, the robot can perform larger steps, without colliding with the other legs. Figure 5 shows an illustration of the complete robot, and it also shows a schematic drawing of the leg. The drawing is used to determine the DH transformation matrix. Because there is an extra joint, there are more parameters to be determined. L_1 and L_2 have the same length, $2R_2$, while L_3 is equal to R_2 . The equations for the variables x, y, and z were obtained according to the equations (4) – (6).

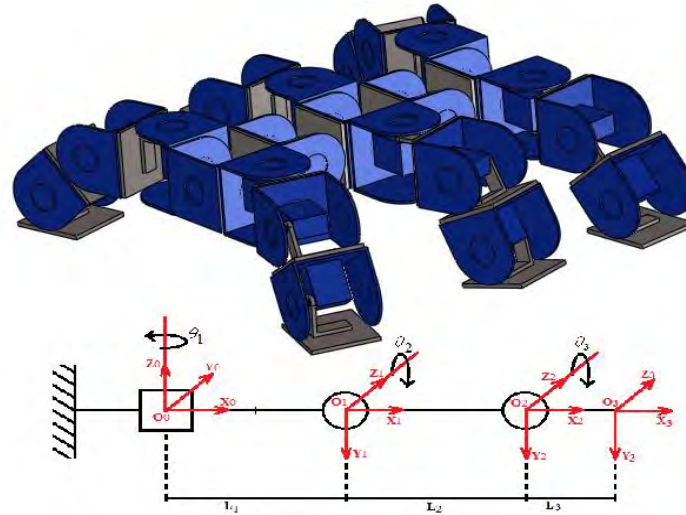


Figure 5. (a) Model of the complete turtle robot, (b) simplification of the 3 DOF leg

$$x = R_2 \cos(\theta_1) \{ \cos(\theta_2 + \theta_3) + 2 \cos(\theta_2) + 2 \} \quad (4)$$

$$y = R_2 \sin(\theta_1) \{ \cos(\theta_2 + \theta_3) + 2 \cos(\theta_2) + 2 \} \quad (5)$$

$$z = R_2 \{ \sin(\theta_2 + \theta_3) + 2 \sin(\theta_2) \} \quad (6)$$

The new configuration enables a greater freedom of movement. In this model, the workspace has increased considerably, no longer being just a surface, now becoming a complete solid with volume. However, in order to keep the development of the model with two degrees of freedom, it has been decided to plan the trajectory on the space of the joint, not on the Cartesian space. This new robot has a peculiarity: one of its modules has the capability to completely touching the ground with one of its faces, which grants more stability and friction, improving the impulse and reducing the chances of sliding. Planning the trajectory aims to achieve this scenario, so whenever the foot touches the ground, it is desirable that it remains in the described position.

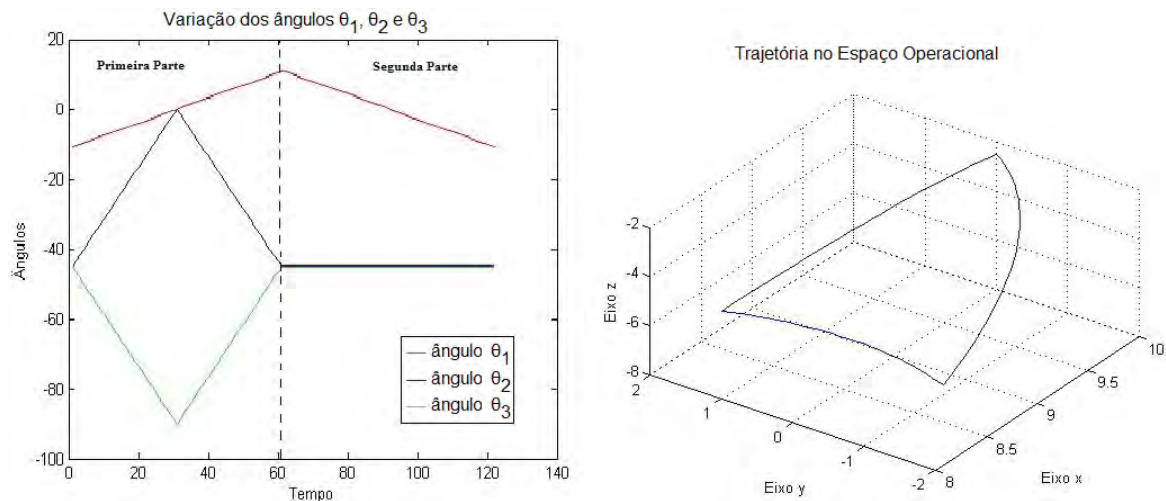


Figure 6. Desired trajectory for turtle robot with 3 DOF leg

Figure 6 shows a trajectory similar to that of the previous configuration, with the difference that, due to the inclusion of the extra module, the maximum value on the x axis was increased. Once more, the course was divided into two stages. The angles θ_1 and θ_2 vary in the exact same way as before, but the new angle, θ_3 ranges from 45° and -90° , in a way that the face of the module that touches the ground will always be parallel to it.

3.3 Soldier Robot with 2 Degrees of Freedom

The arrangement of the soldier robot's joints, shown in Fig. 7(a), is fairly recurrent in literature of robots with legs. Because of the geometry of the module, this configuration cannot maintain the center of the robot stable, but the arrangement of this model allows it to safely walk forward, backward, and turn around, although it does not make it possible for the robot to walk to the side like a crab. Another drawback generated by the shape of the module is that the length and height of the step are very limited.

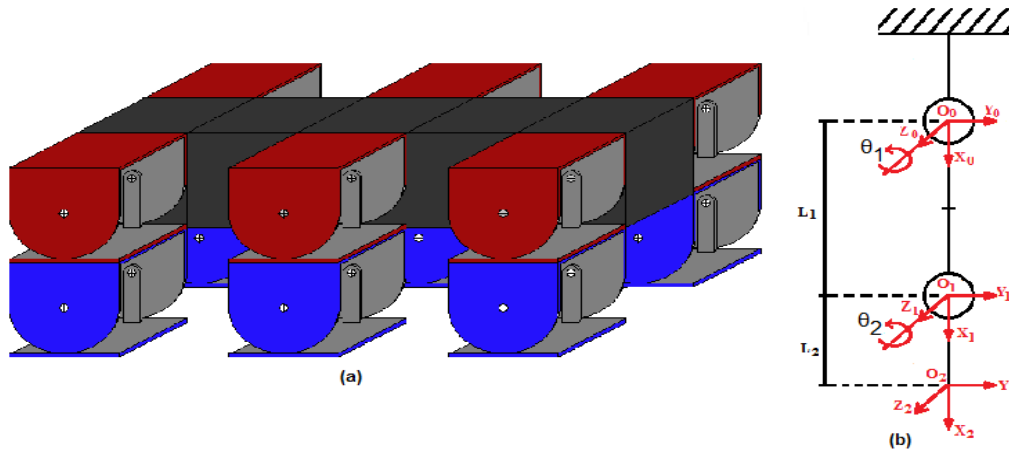


Figure 7. (a) Model of the complete soldier robot, (b) simplification of the 2 DOF leg

The leg resembles a planar manipulator, whose direct kinematics is well known. Another advantage of using this configuration is that it is not necessary to calculate the variable z of the position of the foot. In Fig. 7(b), a sketch of the leg with the assignment of the coordinates systems, following the Denavit-Hartenberg method, is shown. The measures of L_1 and L_2 are the same as they were in the turtle robot with two degrees of freedom. The equations (7) and (8) were obtained, as a result.

$$x = R_2 \{ 2 \cos(\theta_1) + \cos(\theta_1 + \theta_2) \} \quad (7)$$

$$y = R_2 \{ 2 \sin(\theta_1) + \sin(\theta_1 + \theta_2) \} \quad (8)$$

In the beginning of the study, it was evident that the leg's trajectory should be described in the Cartesian space, since foreseeing the movement of the leg from a set of angles is not as trivial as it was with the turtle robot. Thus, it was necessary to use the inverse kinematics, which calculates the joints' angles based in the position of the manipulator's foot. There are several techniques for solving the inverse kinematics. Aiming to simplify the project, the solution was approximated by the Equation (9), where \mathbf{q} represents the set of angles in the discrete amount of time k , \mathbf{r}_1 represents the position, also in the amount of time k , and \mathbf{J}^\dagger represents the pseudo inverse matrix of the manipulator's Jacobian (Souto, 2007).

$$\mathbf{q}_{(k)} \approx \mathbf{q}_{(k-1)} + \mathbf{J}^\dagger (\mathbf{r}_{(k)} - \mathbf{r}_{(k-1)}) \quad (9)$$

All legs must perform the same movement in a synchronized way, so that when 3 legs are up in the air, the other three remain on the ground. The movement has to be simple, since it will be repeated numerous times. Following this idea, the trajectory was divided in two parts: When the leg is up in the air, it will make a parabola whose vertex is in $(R_2 \sqrt{5}, 0)$. The second part is a line that defines the length of the step, $2R_2$. These values avoid singularities in the workspace and collision between legs.

Figure 8 shows the desired trajectory, but note that the arrangement of the x and y axis is on the coordinate system O_0 of Fig. 7 (b). By analyzing the variation of the angles, the conclusion is that the trajectory was not planned in the space of the joints, and therefore there was no effective control on the angles. This explains why they did not have a linear behavior, as it did in the two previous cases. The figure also shows the variation of the angles so that the leg can develop the desired trajectory. The blue and red lines represent, respectively, θ_1 and θ_2 .

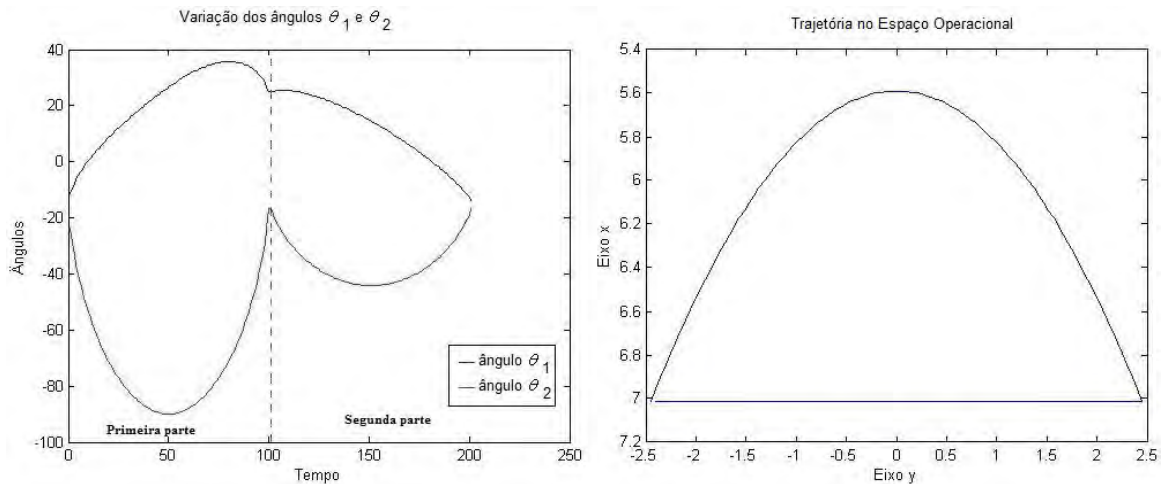


Figure 8. Desired trajectory for soldier robot with 2 DOF leg

3.4 Soldier Robot with 3 Degrees of Freedom

This configuration, presented in Fig. 9(a), is very usual when dealing with robots with legs, especially when talking about quadrupeds. In other studies, the same configuration for the leg's joints is used, but the size of the link is different (Silva, 2005, and Souto, 2007). The distance between the joints 1 and 2 is much shorter, and can even be considered zero at times, approaching a spherical wrist. The other two links are larger and have the same size. This model is based on a few animals, and even on human beings. It can be said that the junction of the femur with the pelvis would be a spherical wrist, and the knee the joint that is left.

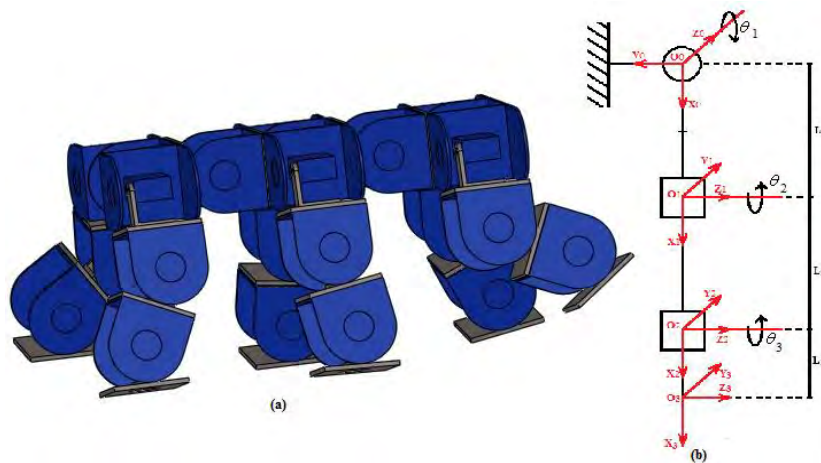


Figure 9. (a) Model of the complete turtle robot, (b) simplification of the 3 DOF leg

During the development of the kinematic model of this robot, an interesting fact was noted and deserves to be mentioned. In Fig. 9(b), it is possible to observe that this arrangement of the joints is exactly the same as in the turtle robot with 3 degrees of freedom. If all the coordinate systems and their respective joints were to be rotated in -90° in relation to the x axis, the result would be the configuration of the leg in Fig. 5. For this reason, it is not necessary to repeat the development of the direct kinematics. The variables x , y , and z can be calculated according to Equations (4) – (6).

Compared to the foot of the soldier with two degrees of freedom, the new foot has a much greater freedom of movement, which does not need to remain in the xy plane. However, when planning the trajectory, it is better to choose something simple and easy to repeat. In short, the trajectory presented on this section is the same as the one from the soldier robot with two degrees of freedom, but the new size is taken in consideration, which explains the translation of $2R_2$ in the x axis. This is not the only change; the trajectory is performed in the xz plane instead of the xy .

4. RESULTS AND DISCUSSION

Using the formulas obtained in the previous section, it was possible to perform experiments to evaluate various aspects of robot's walking. Before the simulations, each variation to the joint's angles through time calculated. The results were written in separate files for each joint, which were used in the simulation and implementation with the real leg. This approach avoided performance problems associated with real-time calculus.

To perform the simulation, the software V-Rep was used. Besides building a 3D model of the robot, the simulator requires a Lua script. Its implementation was divided into reading and execution. The reading runs when the script starts and is responsible for saving each joint's angle file in a vector. During the execution process, a counter is used to access each vector positions, assuring the correct joint's angles combination. The counter restarts when a movement cycle is complete, creating a loop. The software also provides graphical and measurement tools. It is possible to track changes in the positions and to show the trajectory on screen or to save it in a file. After data acquisition, it is possible to evaluate the results using softwares like Matlab.

The leg implementation was made using a vertical support in which it was fixed. The modules are controlled by an Arduino, which uses the simulated angles with a discretization on behalf of keeping experimental data uniformity. Sensors were not used during tests given the module simplicity, thus the analysis was based on recorded video observation.

Every robot configuration presented in this section used this same approach.

4.1 Turtle Robot with 3 Degrees of Freedom

Figure 10 shows the 3D model of the leg of the turtle robot with 2 degrees of freedom in four distinct moments during the movement cycle. The yellow tracing represents the leg's trajectory relative to the joint fixed on the support. It also shows the real leg results in the same positions. The physical robot results were greatly similar to the simulated ones, despite a certain movement discontinuity due to the discretization and hardware limitations. Even with these discrepancies, the resulting motion was considered good enough to develop a satisfactory movement.

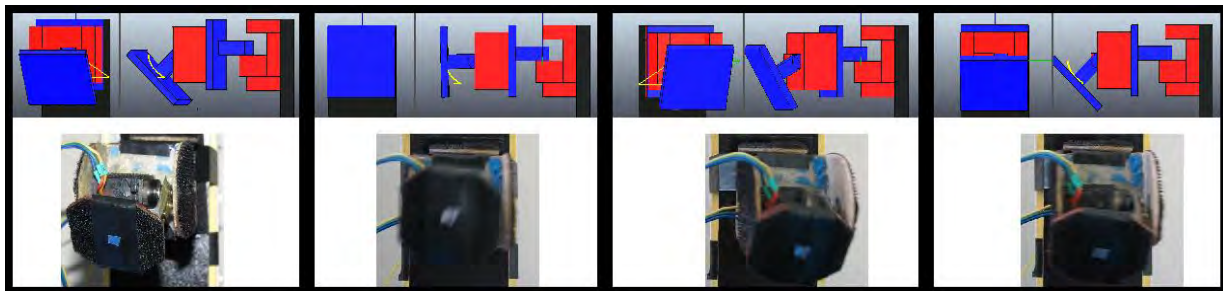


Figure 10. 3 DOF turtle robot leg movement

The graph generated from the simulation is found in Fig. 11(a). Comparing it to Fig. 4 shows that both trajectories have a lot in common, disregarding a scale contrast. Such statement validates the kinematics model obtained.

To verify this configuration performance, a 3D model of the whole robot was developed as well. In Fig. 11(b), the column was replaced by a solid block equivalent to five aligned modules. As the column modules do not perform any active role on the movement, serving exclusively for structural purposes, this exchange does not cause relevant differences to the proposed model. During the simulations, it has been noted that the robot walked with ease. It is possible to observe a yellow line in the image that represents the trajectory. Unlike the expected, its trajectory was not a straight line, but this does not relate to the leg's kinematic model as it was most probably caused by a lack of synchronization between the legs. This problem may be caused by the script, as the joints are coded in sequence, one at time. A possible solution would be a script running threads for each leg.

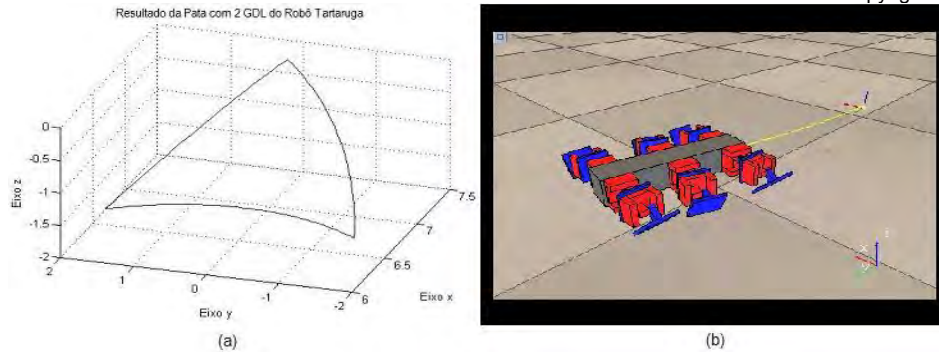


Figure 11. (a) Graph of the trajectory of the leg with 2 DOF of the turtle robot, (b) Simulation of the whole robot

4.2 Turtle Robot with 3 Degrees of Freedom

In Fig. 12, the leg movement can be seen in different instants, both in the simulation and physical implementations. It is possible to see that the lack of precision in the module construction had great impact on the movement. The use of Velcro as coupling agent resulted in spacing between the modules, preventing the correct alignment among them. The previous configuration was not visibly affected due to the lighter weight. However, even using this module, it would be possible to implement a complete robot able to walk normally.

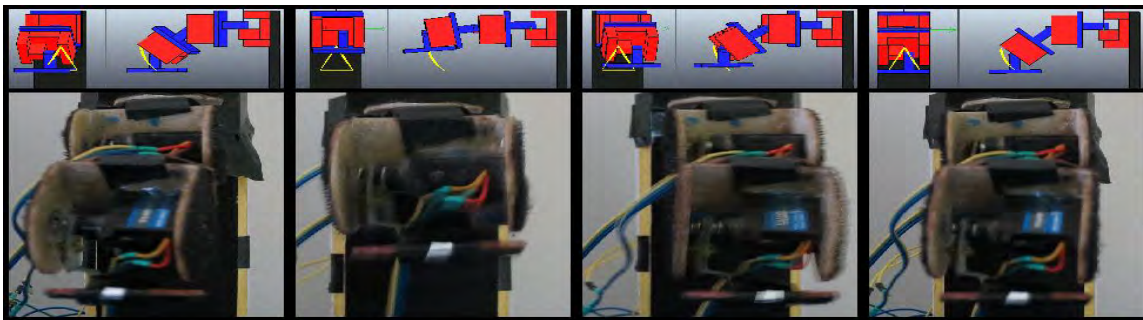


Figure 12. 3 DOF turtle robot leg movement

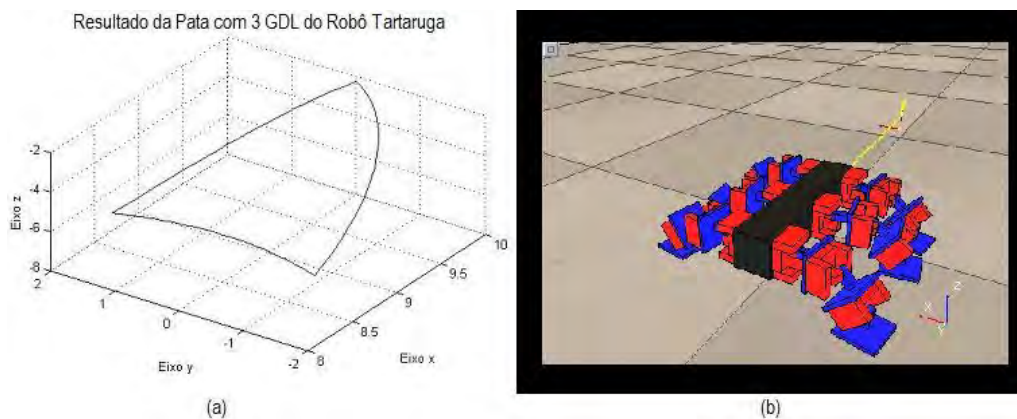


Figure 13. (a) Graph of the trajectory of the leg with 3 DOF of the turtle robot, (b) Simulation of the whole robot

The yellow line drawn by the simulator in Fig. 12 is rather continuous. Comparing the trajectory obtained in the simulation (Fig. 13(a)) and the desired (Fig. 6), it is possible to confirm the kinematic model developed.

The result of the whole robot's walking is presented in Fig. 13(b). The robot's movement in this configuration has shown to be better than the one with two degrees of freedom, with clearer steps and a greater linear progress. This is assigned to the fact that the leg's modules have its arm surfaces touching the ground completely, decreasing the sliding and assuring more stability to the movement. Another important observation is the increased height of the robot body in relation to the ground, an important characteristic when avoiding obstacles.

4.3 Soldier Robot with 2 Degrees of Freedom

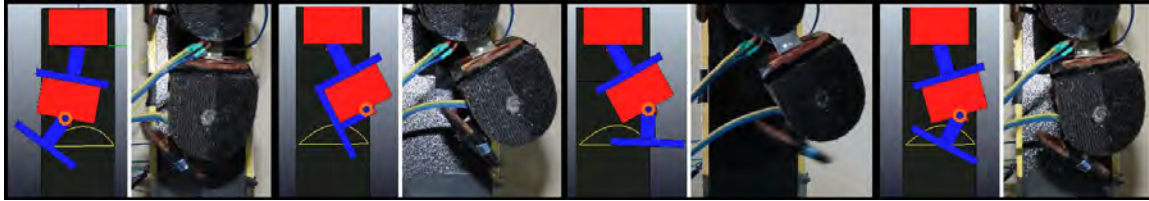


Figure 14. Movement of the leg with 2 degrees of freedom of the soldier robot

As it can be seen in Fig. 14, on the yellow line, the resulting trajectory made by the real leg was similar to the simulated one. The black support in which the leg is fixed has a width of $2R_2$. This way, the second stage of movement, described in section 3.3, approaches the desired length. Thus, the leg implementation of the soldier robot with 2 degrees of freedom appears to follow the defined model. It was not possible to make measurements to determine the fulfillment of the trajectory, but visual observation led to the conclusion that the kinematics development is appropriate.

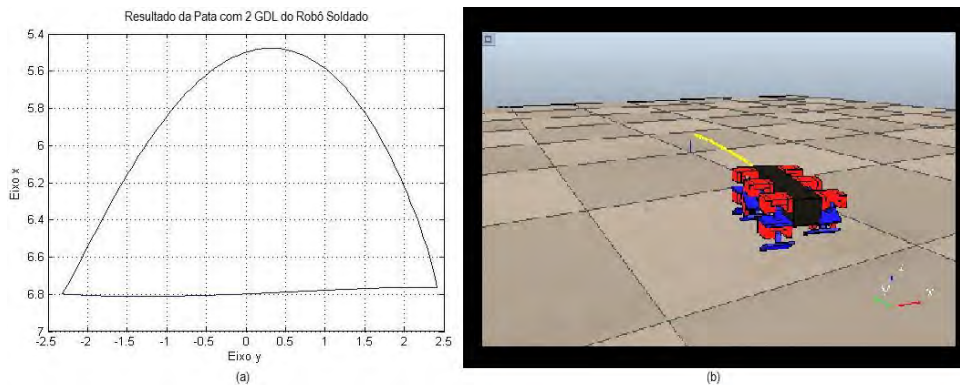


Figure 15. (a) Graph of the trajectory of the leg with 2 DOF of the soldered robot, (b) Simulation of the whole robot

The detours in the trajectory of the leg, evident in Fig. 15(a), may be attributed to a numeric error resulted from the approximated equation used to estimate the reverse kinematics. However, it seems not to be a limiting factor to the robot locomotion, as Fig. 15(b) shows. During the movement, a certain peculiarity was seen. It was expected of the robot to walk on the positive direction of the y axis, but it went on the opposite direction. This happened because of the module geometry that does not maintain the foot of the robot completely in contact to the ground. The contact was occurring prematurely during the descendant movement of the leg, boosting the robot to the opposite side.

It was noticed that the chosen trajectory was not appropriate for this configuration. If a punctual ground contact was used, the result would be satisfactory. It is expected that the model could generate a movement able to make the robot move in the desired route with a trajectory change. Even if the robot moves in the wrong direction, it is still possible to determine its walking ability. It was expected for it to walk in a straight line, but it is possible to see instability in the movement, characterized by a detour on the route. The apparent reason for this is a lack of synchronization between the legs.

4.4 Soldier Robot with 3 Degrees of Freedom

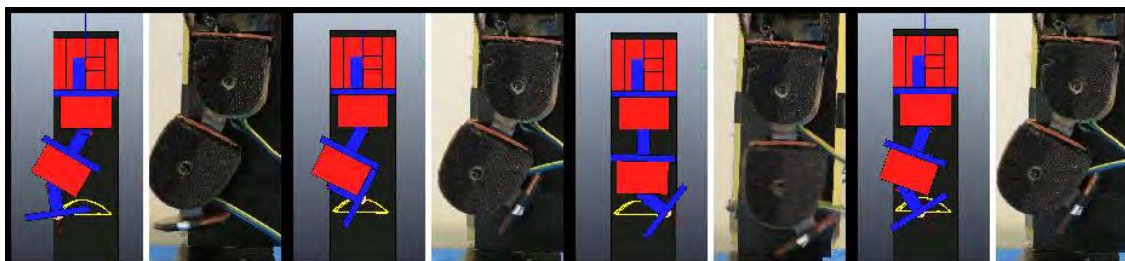


Figure 16. Soldier robot 3 DOF leg movement

Apparently, the leg developed its trajectory as it should, as is presented in Fig. 16. Although both soldier robots' legs follow the same trajectory, the angle variation differs between them. Comparing figures 14 and 16, it is credible that the same path is being followed in different directions, but that not happens. The trajectory in both cases is performed in clockwise direction. Based on the Soldier with 2 DOF, it is visible that the resulting trajectory would not follow the model presented in section 3.4 once the reverse kinematic calculations used the same approximation. Figure 17(a) shows a detour on the second part of the trajectory, which should be a straight line.

The leg implementation showed that, in general, the movement was very similar to the simulated. Still, in certain moments, the movement was not precise and the leg trembled while going from a position to another. This may have been caused by the angles discretization that in some occasions generates abrupt movements from one position to another.

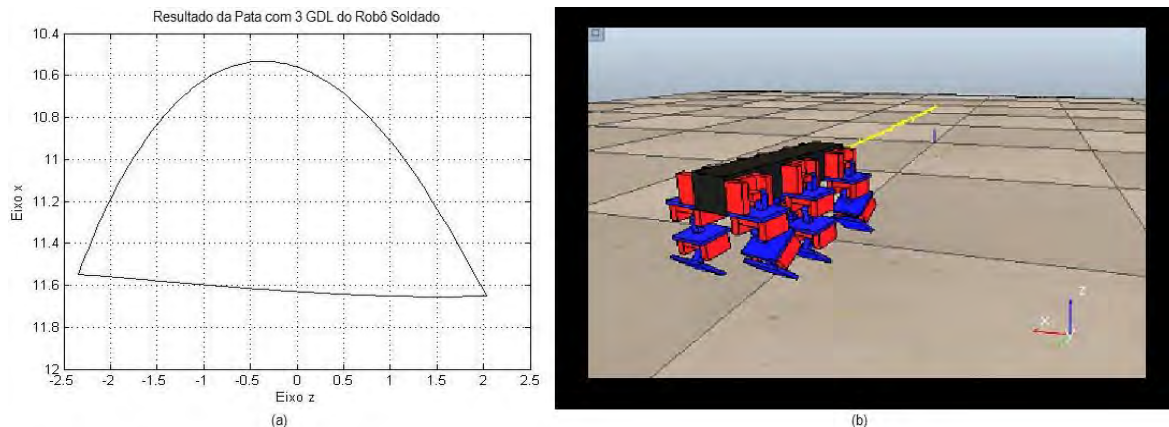


Figure 17. (a) Graph of the trajectory of the leg with 3 DOF of the soldered robot, (b) Simulation of the whole robot

Unlike the robot with less degrees of freedom, this one moved in the positive direction of the y axis due to the different angle variation. Similarly to the Turtle with 3 DOF, its trajectory was stable and practically linear during a considerable amount of time, showed by the yellow tracing of Fig. 17(b). However, the synchronization between legs did not occur as hoped. Legs touched the ground before the ideal time, causing a small regression on the trajectory. This, as all before, may be attributed to the irregular module geometry.

5. CONCLUSION

In this work, the state of development of the Ereko project, a group that has already built several prototypes of modular robots, was presented. It has been found that the use of legs is one of the most efficient methods of terrestrial locomotion. A few characteristics of hexapod robots were presented. Such robots are appropriate for movement on uneven grounds. During the research, the found conclusion was that it is possible to model each leg of the robot as an industrial controller, which allows the establishment of any given position within its reach. Kinematic models for four different legs' configurations were developed: turtle with 2 DOF, soldier with 2 DOF, turtle with 3 DOF, and soldier with 3 DOF. All of them presented relevant results that, in general, show proof to the obtained kinematics.

This work did not focus on comparing the types of legs as to judge which one is better, but to create possibilities for the hexapod movement of the modular robot, even though a few comparisons are inevitable. The soldier robot with two degrees of freedom did not obtain satisfactory results. It was difficult to find a single point of synchrony between the legs with the projected trajectory, and that is why the movement was given to the wrong direction. Despite the great similarity, the same has not happened with the soldier robot with three degrees of freedom. The turtle robots clearly had better results.

When dealing with the soldier robots, it became quite visible that, even of the desirable trajectory is acquired, the model project must be reformulated, and its construction made systematic. The face of the foot was supposed to completely touch the ground, and when it did not happen, an improper movement of the robot was generated. In order to solve this problem, two solutions were found: to remake the model considering that the foot is on the edge of the one before it, and that only it must touch the ground or to re-plan the trajectory, now considering the orientation of the leg.

The walking simulation of the complete robot revealed another mistake originated from equation (9). The obtained result for the joints' angles was approximated using the pseudo inverse Jacobian matrix. The calculation of the reverse kinematics, when done this way, generates a growing error that, with a synchronization problem, is very likely the cause of the detours presented in the trajectory of the simulated robots.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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