

## EREKOBOT ALFA PROJECT: DESIGN AND CONSTRUCTION OF A MODULAR ROBOT PROTOTYPE

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**Abstract.** *Planning the mission's requirements is the first step in designing a robotic system. Conventional lines of robotics design, such as specialized robotics, are the best choice for specific missions, and their design depends on the variables of environment and actuation. However, in mobile robotics, multi-purpose and versatility are attributes highly desired and whenever versatility is a key element, self-reconfigurable modular robot design is an interesting solution. Modular robots are machines composed of autonomous parts, called modules, which are able to connect and arrange themselves into new shapes and forms, assuming new functions into each new structure. These kinds of robots can adapt to unanticipated circumstances in the environment they are situated in, as well as learn to execute new complex tasks and recover from damages that occurred in their mission. This paper presents the design project and construction of the modular robot prototype ErekoBot Alfa. The prototype consists of eight identical modules built of fiberglass and shaped into a semi-cylindrical form connected to an articulated arm. Components such as servomotor, batteries, microcontroller and a communication system are embedded in the module with overall external dimensions reaching 40 mm x 40 mm x 40 mm. Tests and simulation are performed for snake-like movement implemented with pitch-pitch and pitch-yaw configurations..*

**Keywords:** *Modular robots, Self-reconfigurable modular systems, snake-like movement.*

### 1. INTRODUCTION

Modular robots are autonomous reconfigurable machines that can change their shape to adapt to new circumstances, recover from damage, or accomplish a variety of tasks ordinarily designated for numerous specialized robots. They can reconfigure their structure to crawl through a narrow passage, roll like a hoop, or form a complex robot with many legs. Modular robots are versatile and have the potential of being applied to a wide range of applications. For instance, in conditions where payload volume is a constraint such as presented in a space mission, it is advantageous to have one set of modular robots execute the various tasks that several specialized robots would otherwise carry out. Also, since modular robots can be rearranged quickly, they offer the advantage of rapid robotic solutions in unpredictable and unforeseen conditions, such as an emergency search-and-rescue operation.

The basic component is called a *module* and consists of an enclosure, actuators, and specialized mechanisms such as hooks, magnets, wheels, cameras, payload containers and energy modules or processors. Each module has connection interfaces that let you transmit mechanical force, moments, power and data to other modules using the robotic system.

This paper presents the follow-up work done in the ErekoBot project at the University of Brasília, Brazil. Based on previous results from the prototype ErekoBot  $\beta$ -5 (Souza *et al.*, 2010), improvements in the project and different approaches in the kinematic topology and simulation have been accumulated into the construction of a new module, the ErekoBot  $\alpha$ . Using this model, apodal snake-like kinematics is simulated and implemented in a modular system with 8 modules.

The current model is still very simple: it has one degree of freedom, and neither the locomotion nor the reconfiguration is autonomous. About communication, the transmitters are not selective, and all the modules receive the same broadcast. Despite the simplicity of the model – if more modules were connected assuming different configurations, the system would acquire more degrees of freedom – it consists of a necessary step before implementing an automatic connection system, self-reconfiguration and self-locomotion, so it is appropriate to verify the parameters to be controlled in more complex systems.

## 2. MODULAR ROBOTICS

This special field of modern robotics presents interesting challenges in its mechanical aspects - motor drives, connectivity between the modules and new materials - communications and information processing. Technologies recently applied to robotics, such as intelligent actuators, magnetic connection and distributed control are often associated with projects in modular robotics.

Research on modular robots can be found in a landmark work developed by Mark Yim who proposed in his PhD thesis a new approach to the problem of robot locomotion (Yim, 1995, cited in Gomez, 2008). The solutions for locomotion of robots so far have been focused on designing a specific robot to move in a certain type of terrain. Yim proposed using robots based on modules that could change their form and locomotion by adopting different configurations according to the terrain they were operating in at a given time.

A modular robot could, for example, take the form of a snake, with its modules connected in a chain configuration and moving through a tube. Upon exiting the tube, it would change its shape again for quadruped or hexapod and traverse a rocky terrain with uneven surfaces. Arriving on a flat and uniform surface, he could change into another form that would allow a rapid movement (such as a wheel), then it could become a static object with some functionality.

The shape of the modular system depends on how many modules are needed, their types and how these modules are connected: it defines the system size and number of degrees of freedom it has. There may be several different types of modules, which possess basic electrical elements - sensors, processors, memory and power supply - and have actuators for locomotion and mechanisms for connecting to other modules.

### 2.1. Benefits of Modular Robotic Systems

The use of modular robots instead of conventional robotic systems is based on three main motivations according to Yim *et al.* (2001):

- *Low cost* – modular systems already have an economic gain in the evaluation of the project. They decrease manufacturing costs and maintenance of complex machines and are made of one or a few types of mass-produced units;
- *Versatility* - reconfigurable modular systems have a higher number of potential functions than the conventional robotics can offer. Variation in the morphology of the robot allows new functionalities, which can be better or more efficient for completing a specific task, or even adapting to uncertain situations or uncontrolled environments;
- *Robustness* - the robot is made of identical modules and the possibility of replacing defective modules to be performed automatically by the robot or other machinery. This makes the modular robot less dependent on human intervention.

Even if the above aspects are motivating, a robot designed conventionally for a particular task will always perform better than a modular system in that specific task. Modular systems are to be seen as an alternative in which the requirements of the environment aspects in a mission may change the conventional robots range of application. A modular system would be better suited for missions where the robot must adapt morphologically to an environment susceptible to unforeseen changes, with multiple features to complete various tasks and independent of human intervention. They are redundant systems, and this characteristic is what makes the design robust and versatile in several situations. Although these qualities are important for the mobile robotics field, there is a line of compromise between conventional and modular, because the mechanical and computational complexities substantially increase with the modularity, configurability and speed that the system is required to have.

### 2.2. General Proprieties of a Modular Robot

Several research groups have been working on modular robotics, due to the aforementioned advantages. However, the solutions are still restricted to academic development and consist of few modules, with the exception of G3 Polybots Project, a system consisting of 56 modules (Garcia, 2008).

The current research projects in this area have concentrated much of the work on solutions tested in simulated environments where the complexities of electromechanical assembly of the modules are avoided. Among the projects that build physical modules, the first projects consist of identical modules whose connection to another module only occurs with external intervention. This manual docking system prevents the characterization of these robots as reconfigurable. As the projects become more sophisticated, the modules gain new components such as sensors, automatic docking systems, wireless communication, among other features.

Modular robots are classified according to the module's type, the geometric arrangement of its modules, the type of connection and the process of controlling their morphology. Below is a description of the main criteria for the classification of modular robots, according to Yim *et al.*, (2007). Depending on geometric arrangement, modular robots can follow lattice or chain architectures, or are hybrids of these two arrangements.

- *Lattice* - It is characterized by systems that feature modules arranged in a regular three-dimensional array. The control of morphology and locomotion of the robot can be performed in sequence or in parallel. This configuration has

the advantage of allowing a simpler reconfiguration, since the modules move only to neighboring positions and this kind of shift can be done without the need for closed loop control.

- *Chain* - It is characterized by systems whose units are connected in series, like a rope or chain. The structure may eventually bend to reduce the footprint, but the modules are still connected in series. Through joint modules, a robot architecture chain can reach any point in space, limited only by the size of the module. This makes it more versatile and easier to construct, but it increases the complexity and computational analysis, which makes it more difficult to control.

The modular robotic systems can also be classified according to the manner in which modules move to change the morphology of the robot:

- *Deterministic reconfiguration* – Present in systems whose modules are handled during the reconfiguration to a target position in the system. The exact position where the module should be positioned is known, even if the path for the module to reach this position can be changed. For this type of reconfiguration, a closed loop control is essential in chain architectures due to the wide range of positions within reach of the reconfiguration.

- *Stochastic reconfiguration* – Present in systems where modules move around randomly. The exact location of the module is known only when the module is connected to the main structure of the new morphology module and the trajectories are random during the reconfiguration process. The reconfiguration time can be determined only statistically. This type of reconfiguration favors smaller-scale systems. Another feature is that the environment usually provides the energy needed to transport the modules in the system.

For classifying the module's type in the project, there are:

- *Homogeneous types*: the modules are identical regarding the geometry, electronics, communication and functionality.

- *Heterogeneous types*: when there are modules that can be characterized as specific ones and have functionalities that will benefit the entire system during execution of a task. Examples are some robots that have built-in camera modules, while others have a central processing system. Other modules may have a special communication link, and may also contain wheels or even propellers.

### 2.3. State of Art

Currently, there are some designs of modular systems built by institutions and universities around the world that have explored the features and dynamics of the various types of modular robots described above. Most have explored chain architecture, mainly because it is easier to build; however, there are also significant advances in architectural designs based on lattice, as well as some projects proposed in hybrid architectures. Systems such as MTRAN (Kurokawa *et al.*, 2008), YAMOR (Dittrich and Ijspeert, 2004) and SuperBot are hybrid examples, whose design projects and research have had advances in the construction process and kinematics algorithm implementation. These systems, together with the recent developments with ErekoBot  $\beta$ -5 prototype (Souza *et al.*, 2010) were the starting points in developing ErekoBot  $\alpha$  module.

#### 2.3.1. ErekoBot $\beta$ -5

The ErekoBot  $\beta$ -5 was the first functional prototype developed by graduate students in the *Ereko Group* at the University of Brasília (UnB). This prototype was designed to be used as a tool for studying important aspects of modular systems, such as assembly of different configurations and algorithms for motion and reconfiguration. The module ErekoBot  $\beta$ -5 has a shape similar to the MTRAN and PolyBot modules. Its dimensions are 70 mm x 70 mm x 70 mm and uses manual fitting nuts and bolts in the joints on the four sides of the connection.

The ErekoBot robot in Figure 1(a), with four modules in series, bridge configuration; Figure 1 (b) shows the module encapsulation of aluminum embedded with a servomotor that has a torque capacity of 10-12 kg-cm and 55 grams in weight. This creates problems related to mobility on higher frequency transmissions.

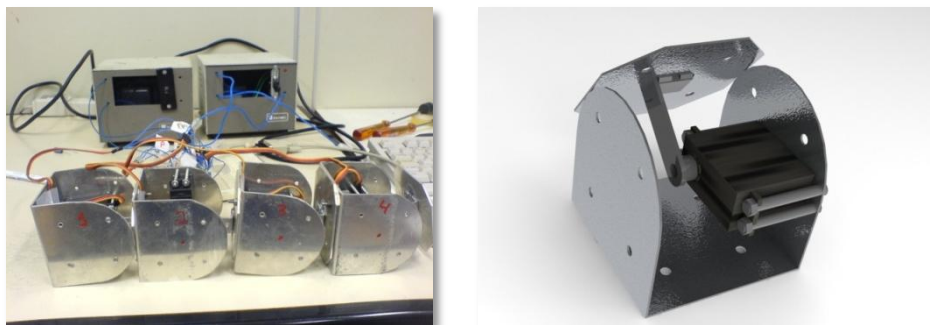


Figure 1. Modules ErekoBot  $\beta$ -5: (a) connected in series, bridge configuration; (b) detail of a single module.

An external cable is responsible for a 12V/6V DC power supply to the modules, also to the control circuit, based on microcontroller BasicStep BS1 and support circuitry. The programming and communication were centralized and controlled by the software *Basic Step*, programmed in TBASIC with serial communication throughout the bus. The prototype was able to run the algorithms with difficulties in the *sidewinding* walking type or second pitch-pitch configuration (Gomez, 2008) with problems such as support, inertia and vibration during movement. Limitations with locomotion, response time, precision and mechanical design made it impossible to continue this project and demanded that it be improved into a more reliable system for working with the locomotion algorithms.

### 3. PROJECT EREKOBOT $\alpha$

#### 3.1. Design

The ErekoBot  $\alpha$  was designed to apply new ideas and in order to overcome  $\beta$ -5 weight, connection and control problems. Furthermore, new materials, joining methods and fabrication processes were also explored.

Figure (2) shows the module design and final implementation. The module volume is 40 mm x 40 mm x 40 mm, and it is constructed in fiberglass. The change in size made it possible to reduce the module weight (ErekoBot  $\alpha$  weighs 48 g) and still maintain the strength needed to support the requested efforts.

The modular faces of  $\alpha$  project are overlaid by a Velcro fastener. In their paper, Dittrich and Ijspeert (2004), classified the Velcro fastener as a very strong tissue and used it in YAMOR project. It can stand shear forces up to 600 N if connected with enough pressure in the contact area. Each ErekoBot  $\alpha$  modular face have male and female Velcro fastener tissues in order to always allow connection between modules.

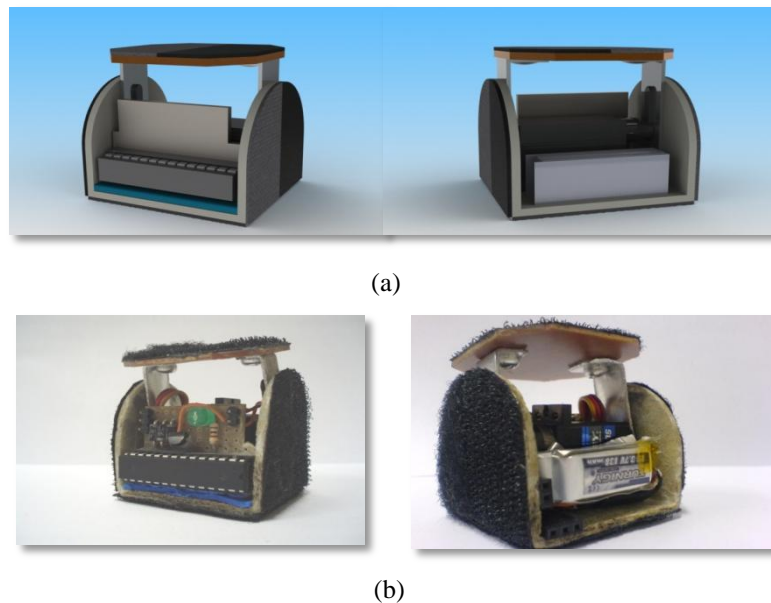


Figure 2. Module ErekoBot  $\alpha$ : (a) previous design; (b) actual implementation.

As noted by Garcia (2008) and Dittrich (2004), MTRAN and YAMOR servomotors are selected by higher torque necessities, with attention to the distance between the centers of rotation and gravity of adjacent modules. The current servomotors used in ErekoBot  $\alpha$  were chosen due to their suitable weight-torque relationship. They have 1.5 Kg-cm of torque at 6 volts and metal gears, which allow greater durability and resistance to impact compared to the previously servomotors used. This servo, with 15 grams, is the heaviest component but is justified by its torque to weight ratio, higher than others analyzed, besides its low cost. Moreover, with the servo, one module is capable of raising two coupled modules without relying neither on inertial forces nor on an increase in current discharge.

Table 1 gives a summary of the main features of ErekoBot  $\alpha$ .

The ErekoBot  $\alpha$  module is better designed than the  $\beta$ -5 because it is smaller, lighter and cheaper. Figure 3 shows the two ErekoBot versions. The first one has high moments of inertia leading to small angular accelerations due to servo motor torque limitations and loss of precision. The Velcro overlay makes the assembly and disassembly easier compared with the nuts and bolts of the module  $\beta$ -5. It also dampens the vibration on the link joints during locomotion.

Table 1. Features of the ErekoBot  $\alpha$  module.

| ErekoBot $\alpha$ specifications |               |
|----------------------------------|---------------|
| Type                             | Homogeneous   |
| Architecture                     | Hybrid        |
| Reconfiguration                  | Deterministic |
| Reconfigurable                   | Yes/Manual    |
| Connectable sides                | 4             |
| Degrees of Freedom (DOF)         | 1             |
| Locomotion                       | Yes (1D)      |



Figure 3. Comparison between  $\alpha$  and  $\beta$ -5 modules.

### 3.2. Electronics & Communications

The electrical circuit embedded in  $\alpha$  can be seen in Figure 4. Two rechargeable lithium polymer batteries with 7.4 V and 138 mAh are the power supply. Three diodes protect the circuit from reverse polarity and reduce the input voltage of 7.4 V (or 8V) to the 6.35 V on servo's VCC port. A voltage regulator is used to provide power to the microcontroller, intermodule connection and to the wireless port (RF bus). The control circuit dissipated around 0.84 W, thus showing that battery life depends more on servo's actuation (in which power dissipates can reach up to 2.5 W). The ATmega 8 microcontroller is fed by 5 V input voltage in parallel with a LED that is used to verify if the microcontroller is on. The consumption of microcontroller and LED is around 35 mA which is well below the maximum of 100 mA supported by the voltage regulator.

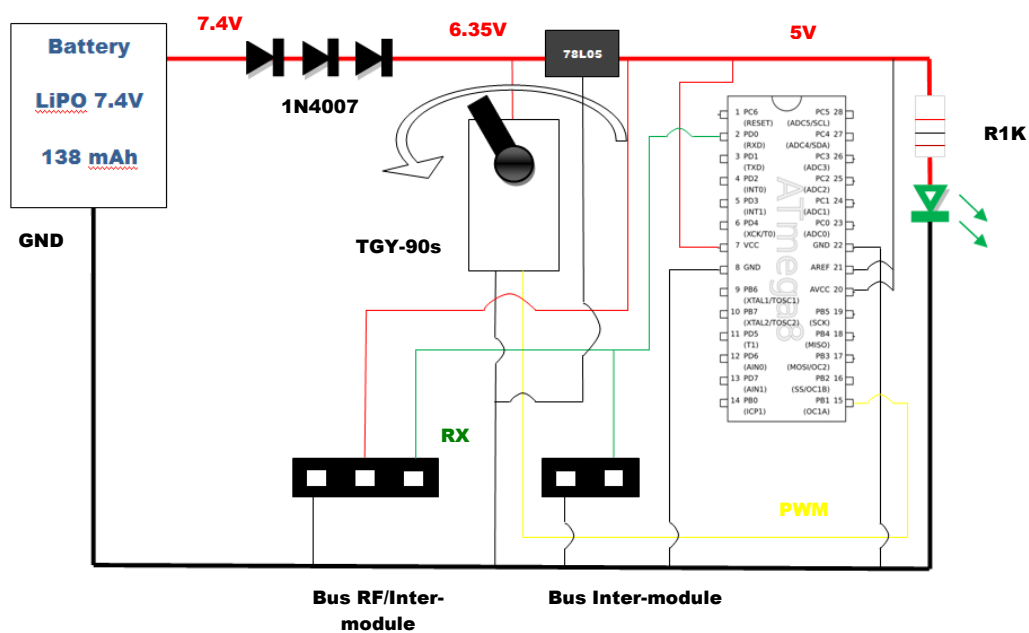


Figure 4. Electronic circuit.

The microcontroller output is connected to servo’s signal input; where PWM signals (256 bytes) control the servo’s position. For inter-module communication, there is a bus connecting two pins between the microcontroller and its RX and GND pins. To communicate via radio (RF) with other wireless devices, a bus connected to the 5 V, GND and RX pins of the microcontroller is used.

For communication, the modules were tested to receive data via radio frequency by “RF backpack” hardware and to pass the data through inter-modular wired connections.

The RF transmitters are not selective and all the modules receive the same broadcast communication, Fig. 5. So, at the beginning of each message an identifier was added to specify the module to which the command is addressed. As all the modules must begin to move at same time, in the end of the received message there is a command indicating the immediate request to execute the predetermined movement.

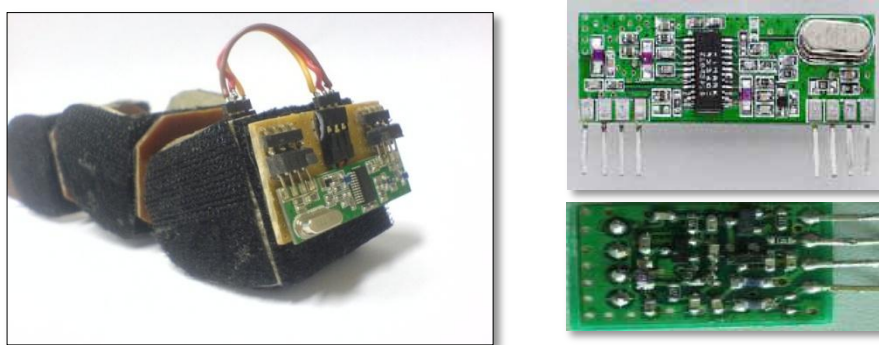


Figure 5. Transmitter module and receiver, respectively.

Figure 6 illustrates the communication protocol with the first byte defined as the identifier followed by one byte of command and the last byte representing the request.

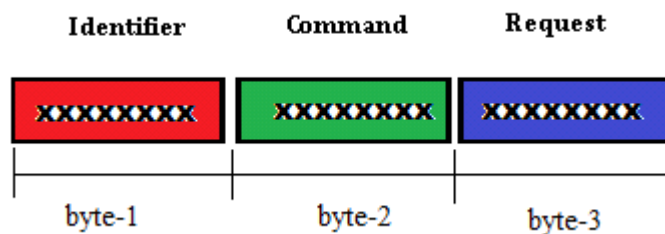


Figure 6. Communication protocol.

#### 4. KINEMATICS OF ONE-DIMENSIONAL TOPOLOGY

Like in the animal kingdom, mobile robots are designed to perform tasks in a specific environment. The design sets robot configuration and therefore its pace. Thus, if the robot moves on flat smooth surfaces, where there is no need to overcome obstacles, the use of wheels may be more appropriate. In his PhD thesis, Dr. Gomez states:

“One of the biggest challenges is to develop a robot that is as versatile as possible and is able to move from one place to another over various types of terrain, even the roughest and most broken. This is of special importance where the environment is unknown, such as the exploration of the surface of other planets, navigation in hostile environments or in search and rescue operations.”

Biomechanical studies of the snake’s motion for use in robots date back to the seventies with the pioneering work of Hirose (Hirose, 1974, cited by Gomez, 2008), although they were applied to modular robots in the 1990s. An important contribution of their studies was the "Serpentoid Curve" formulation which represents the shape adopted by the snake to move around.

The movement analysis of pitch-pitch and pitch-yaw modular hybrid system models is presented. The calculations were developed in MATLAB and SIMULINK software and further simulated on OpenRAVE for kinematic analyses.

##### 4.1. Serpentoid Wave

In a snake configuration, each module's relative position is determined by the "Serpentoid Curve" (Gomez, 2008), presented in Eq. (1):

$$\varphi_i(t) = A \sin\left(\frac{2\pi}{T}t + (i - 1) \Delta\phi + \psi_1\right), \quad i \in \{1 \dots M\}, \quad (1)$$

where  $A$  represents the angular amplitude of the movement, with units in degrees,  $T$  is the period, in seconds,  $t$  is the time, in seconds,  $\Delta\phi$  is the phase angle variation between modules, in degrees,  $\psi_1$  is the first module phase angle and  $M$  is the number of modules.

#### 4.2. Differences between phases

The variation of the phase angle between modules is determined from the servo's motor strength capability of lifting adjacent modules. From Figure 7, obtained with MATLAB, it can be observed that the serpentoid wave pattern has less support points for smaller phase angles, which requires higher torque from the reference module (first point).

ErekoBot  $\alpha$  servo torque capability requires the phase angle to be greater than  $60^\circ$  for efficient locomotion. For safety purposes, the phase angle decided upon was  $90^\circ$  in the paper's analysis.

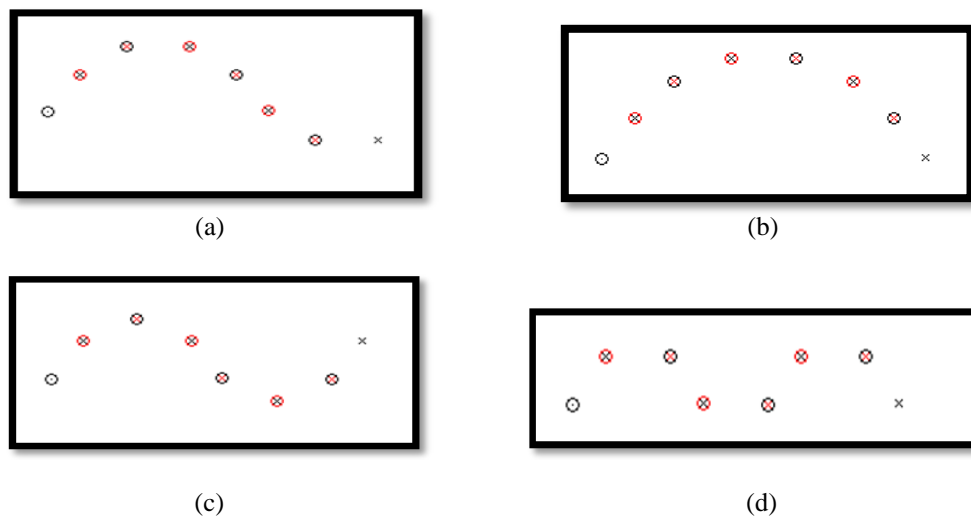


Figure 7. Configurations: (a) Amplitude ( $A$ )  $60^\circ$ , Phase ( $\Delta\Phi$ )  $30^\circ$ ; (b)  $A = 60^\circ$ ,  $\Delta\Phi = 45^\circ$ ;  
 (c)  $A = 60^\circ$ ,  $\Delta\Phi = 60^\circ$ ; (d)  $A = 60^\circ$ ,  $\Delta\Phi = 90^\circ$ ,

#### 4.3. Displacement

According to Gomez (2008), the snake's displacement,  $x$ , is determined by Eq. (2), where  $A_i$  is Amplitude and  $R$  is the distance between the two axes of rotation, as shown in Fig. 8.

$$x = R(1 - \cos(A_i)) \quad (2)$$

During a period, the angular variation  $\Delta\Phi$  is four times the angular amplitude  $A_i$ . Considering the angular velocity  $\omega$  known from servo specifications, the medium velocity should be defined as:

$$V_m = \frac{2R(1 - \cos(A_i)) \omega}{4A_i} \quad (3)$$

#### 4.4. Analysis and Results

Servo motors are projected to normally operate in a range of  $30^\circ$ ,  $60^\circ$  and  $90^\circ$  of angular amplitude, in which current and specific speed-to-voltage ratios are determined. Considering manufacturer data and optimal motion with 8 modules, an analysis of the system's configuration using  $60^\circ$  and  $60^\circ / 90^\circ$  are presented in Fig. 9, where each point represents the module's center of rotation.

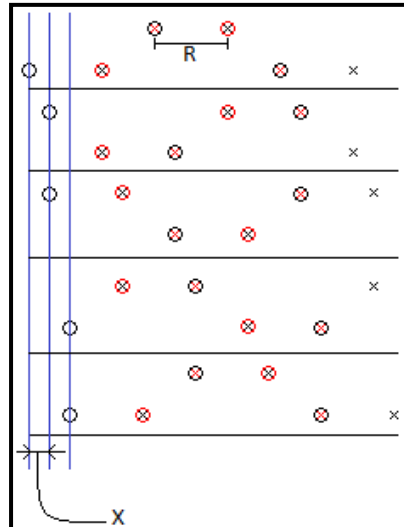


Figure 8. Module's position in serpentine wave.

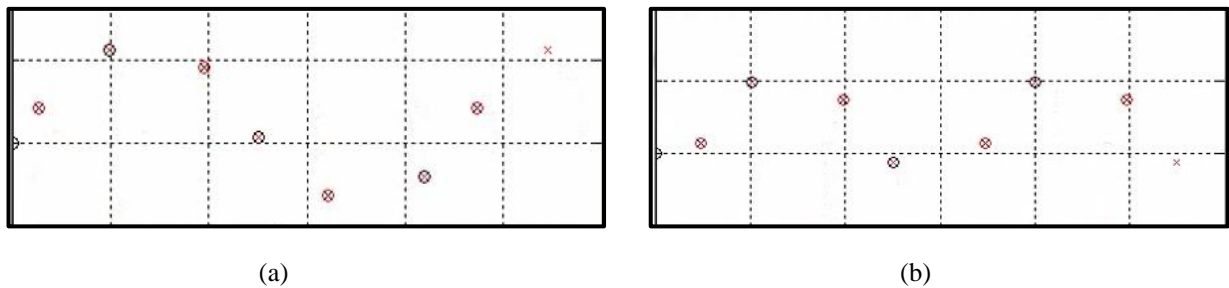


Figure 9. (a) Chart for angular amplitude,  $A = 60^\circ$  and variation of phase angle,  $\Delta\Phi = 60^\circ$ ; (b)  $A = 60^\circ$  e  $\Delta\Phi = 90^\circ$ .

This data was then introduced into the SIMULINK block system, using Simscape's Simmechanics Block Library, to model the modular robot. The SIMULINK body model and data were imported from SOLIDWORKS assembly file and tested with the serpentine equation in pitch-pitch and pitch-yaw configurations, Fig. 10. This analysis only determines the angular settings and the "wave flow", which are input data for kinematic analysis.

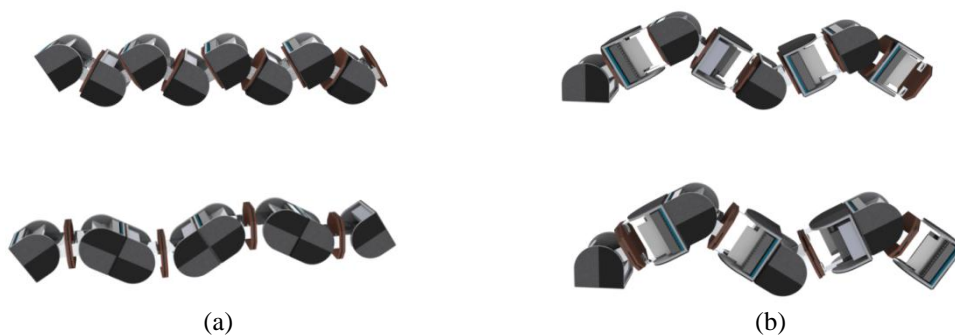


Figure 10. Reproduction for  $A = 60^\circ$  e  $\Delta\Phi = 90^\circ$ : (a) pitch-pitch; (b) pitch-yaw.

## 5. SIMULATION

Simulators are essential tools in robotics, allowing initial experiments with hardware design and controller programming to be performed at a relatively low cost (Christensen, 2008). A suitable simulator for ErekoBot must support modular robotics and be in use and under development. The simulator named Open Robotics Automation Virtual Environment, OpenRAVE, is targeted for real-world autonomous robot applications, and includes a seamless integration of 3-D simulation, visualization, planning, scripting and control. There is a plug-in named OpenMR which makes modular robot implementation easier. Indeed, OpenRAVE has been driven primarily by the need for a general-



purpose planning and scripting layer to be used in conjunction with low-level robotic packages such as ROS and Player (Diankov, 2008).

The ErekoBot  $\alpha$  was implemented in *OpenRAVE*. An ErekoBot  $\alpha$  CAD design was converted into a numerical file in which the modules were added one by one and simulated to achieve final configuration as shown in Fig. 11. Eight hinge joints were set based on nominal servo specifications. The controller follows the kinematic study, so a different equation drives each configuration. Locomotion follows what was expected with pitch-pitch moving straight forward in a serpentine movement and pitch-yaw lateral movements. Figure 11 shows pitch-pitch (a) and pitch-yaw (b) eight-module-snake locomotion evolution.

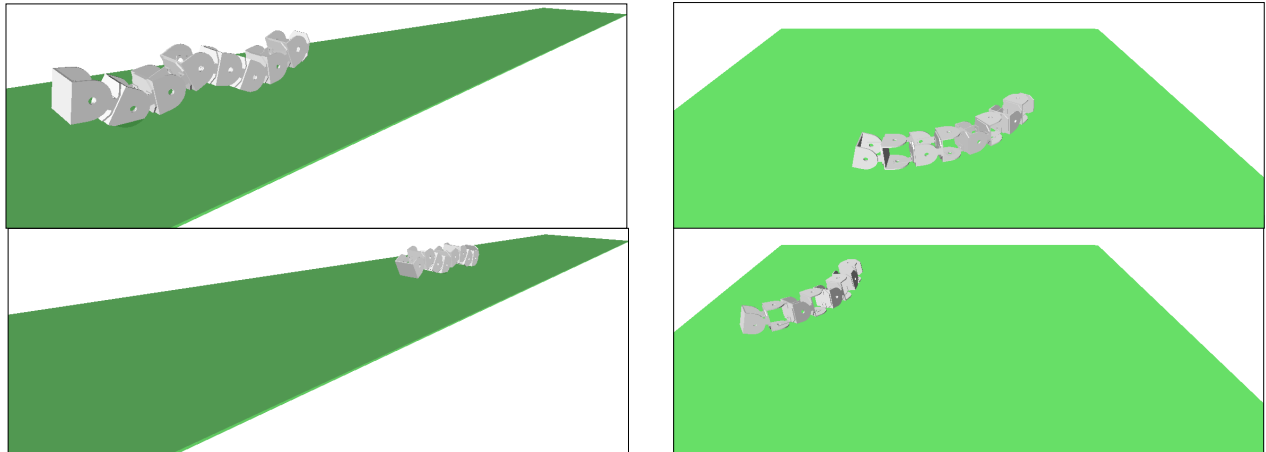


Figure 11. Pitch-pitch (right side) and pitch-yaw(left side) serpentine motion simulation in the OpenRAVE environment.

### 5. TEST RESULTS

After simulation and construction of modules, it was possible to perform the first tests in order to make a validation to confirm if all studies had a practical application for our purpose. For this, we used a standard procedure, with some elements previously determined due to the geometry of the module and a characteristic formula. The results are shown in Tab. 2,

Table 2. Test results.

| <b>Pitch-Pitch Configuration</b> |  |  |  |
|----------------------------------|--|--|--|
|                                  | 1° Test  | 2° Test  | 3° Test  |
| Amplitude                        | 60°  | 30°  | 45°  |
| Phase                            | 90°  | 90°  | 90°  |
| 1° Round                         | Distance: 30 cm<br>Time: 57.7 s<br>Average Speed: 0,520 cm/s   | Distance: 30 cm<br>Time: 46.1 s<br>Average Speed: 0,651 cm/s | Distance: 30 cm<br>Time: 38.0 s<br>Average Speed: 0,781 cm/s |
| 2° Round                         | Distance: 28 cm<br>Time: 52.2 s<br>Average Speed: 0.536 cm/s   | Distance: 30 cm<br>Time: 45.1 s<br>Average Speed: 0.655 cm/s | Distance: 30 cm<br>Time: 39.3 s<br>Average Speed: 0.764 cm/s |
| 3° Round                         | Distance: 31.5 cm<br>Time: 59.9 s<br>Average Speed: 0.526 cm/s | Distance: 30 cm<br>Time: 44.4 s<br>Average Speed: 0.675 cm/s | Distance: 30 cm<br>Time: 39.5 s<br>Average Speed: 0.759 cm/s |
|                                  | Overall Average Speed:<br>0.527 cm/s                           | Overall Average Speed:<br>0.660 cm/s                         | Overall Average Speed:<br>0.768 cm/s                         |
|                                  | Theoretical Overall Average<br>Speed: 1.389 cm/s               | Theoretical Overall Average<br>Speed: 0.745 cm/s             | Theoretical Overall Average<br>Speed: 1.085 cm/s             |
|                                  | Loss of expected speed:<br>62.1%                               | Loss of expected speed:<br>11.4%                             | Loss of expected speed:<br>29.2%                             |

considering:

- Distance between axes:  $R = 50$  mm;
- Angular Velocity:  $\omega \cong 60^\circ/0.9$  s or  $\omega \cong 1.164$  rad/s. The speed is approximated as if calculated by using a stopwatch)
- The equation for average velocity, Eq. (3).

Comparing the three tests, it is observed that when the amplitude of the modules was high, they slipped a lot –first test – and the expected speed was not reached, creating the idea that it is better to decrease the amplitude when it comes to a smooth surface. When decreasing the amplitude – test 2 - the snake was almost able to reproduce the theoretical speed. It is observed that the modules slipped only slightly on the surface, but a new problem arose, if there is a need for a higher speed you should use a wider range. The test with the mean value between the previous two amplitudes – Test 3 – modules also slipped, but not as much as in the range of  $60^\circ$ . Its speed was greater than in the  $30^\circ$ , even slipping on the surface.

In performing this test, we came to the conclusion that it is necessary to modify the part of the module that comes into contact with the surface in order to increase friction. This can be done by adding a material for such ends, like sandpaper, and / or making a chamfer or fillet these machines to increase the area of contact with the surface.

## 6. CONCLUSION

This paper presents a novel design for a modular prototype, ErekoBot  $\alpha$ , and a side-by-side design comparison with its predecessor, the ErekoBot  $\beta$ -5 module. The hardware system was described and a kinematic analysis was discussed. The system's feasibility was demonstrated through simulation.

There are several important issues remaining in the ErekoBot project under development. Implementing a self-reconfigurability is a major step in a hybrid modular robot scale, and research is required for inserting a controllable connection mechanism in a future version. Sensors, feedback ports and processing power are also issues for enabling the module to perform more complex motions and reconfiguration algorithms. Also, a distributed control algorithm for autonomous actuation is an objective for future work, in order to explore the capability of self-repair in the field, which is an important quality present in modern modular robot architecture.

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