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 its 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 one of the most employed solutions. 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 to 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 work presents the design project and construction of the modular robot prototype Erekobot Alfa. The prototype consists of eight identical modules built in fiberglass and shaped in a semi-cylindrical form connected to an articulated arm. Components such as servomotor, batteries, microcontroller and communication system are embedded in the module which overall external dimensions reach 40 mm X 40 mm X 40 mm. Tests are performed for snake-like movement implemented with pitch-pitch and pitch-yaw configuration and results are compared with those obtained in the literature.*

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 to be 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 various 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, 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 forces, 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. Based previous results from the prototype ErekoBot β-5 (Souza et al, 2010), improvements in the project and different approaches in the kinematic topology and simulation have accumulated into the construction of a new module, the ErekoBot α. Using this model, apodal snake-like kinematics is simulated and implemented on a modular system with 8 modules. Finally, considerations are made about the results.

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 was a landmark work developed by Mark Yim who proposed in his PhD thesis a new approach to the problem of robot's locomotion (Yim, 1995, cited in Gomez, 2008). The solutions for locomotion of robots so far 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 a given time.

A modular robot could, for example, takes 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 in 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 of 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 possesses basic electrical elements - sensors, processors, memory and power supply - and have actuators for locomotion and mechanisms for connecting with 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 (Yim et al., 2001):

- *Low cost* - modular system already has an economic gain in the evaluation of the project. They decrease manufacturing costs and maintenance of complex machines are made of one or a few types of units mass-produced;
- *Versatility* - reconfigurable modular systems have a higher number of potential functions than the conventional robotics can offer. The variation in morphology of the robot allows new functionalities, which can be better or more efficient to complete a certain task, or even adapt 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 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 mobile robotics field, there is a line of compromise between conventional and modular, because the mechanical and computational complexities increase substantially with the modularity, configurability and speed that the system is required to have.

2.2. General Proprieties of a Modular Robot

Several research groups work on modular robotics, due to the advantages already mentioned. However, the solutions are still restricted to academic developing 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 concentrated much of the work in solutions tested in simulated environment 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 gains new components such as sensors, automatic docking system, 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 control of 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.
- C*hain* - 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 construction, but 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 to 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 which 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*: the modules are identical with regarding to the geometry, electronics, communication and functionality.
- *Heterogeneous*: 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 special communication link, 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 in the world who have explored the features and dynamics of various types of modular robots described above. Most have explored the chain architecture, mainly because it is easier to build; however, there are also significant advances in architectural designs based on the lattice, as well as some proposed projects in hybrid architectures. Systems such as MTRAN (Kurokawa et al, 2008), YAMOR (Dittrich and Ijspeert, 2004) and SuperBot are hybrid examples, whose design project and research have had advances in construction process and kinematics algorithm implementation. These systems, together with the latter developments with ErekoBot β-5 prototype (Souza et al, 2010) were the starting points in developing ErekoBot α module.

2.3.1. ErekoBot β-5

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

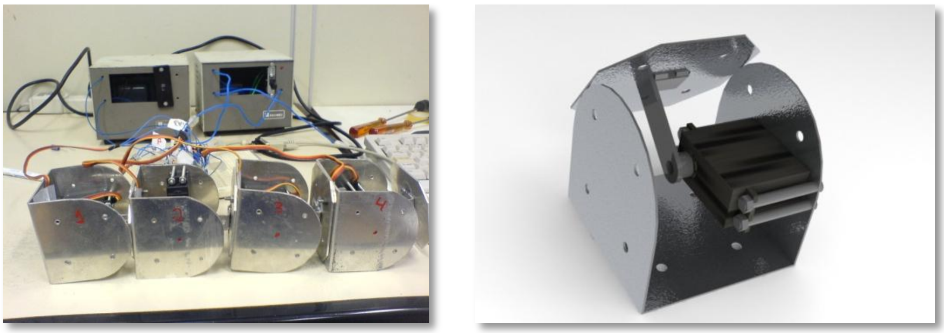


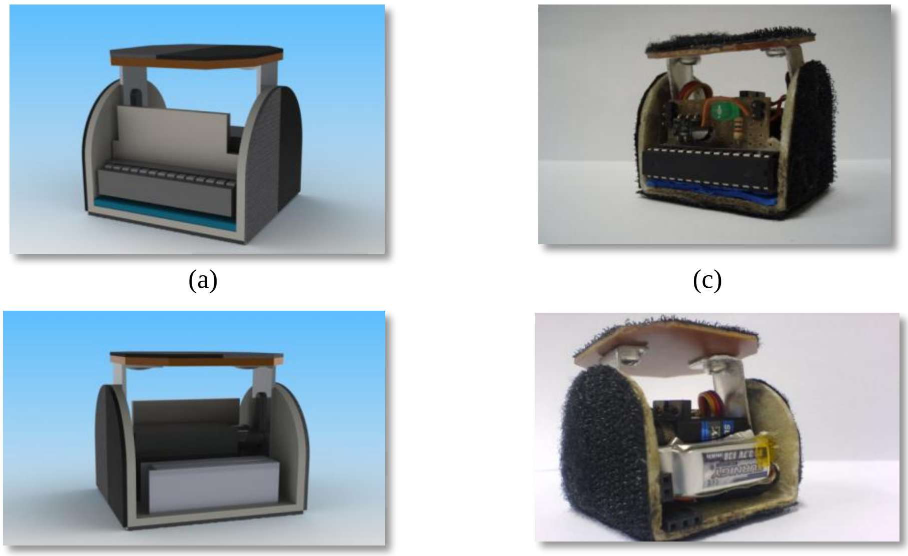
Figure 1. Modules ErekoBot β -5 (a) connected in series, bridge configuration. (b) detail of a module.

Figure 1.b shows ErekoBot β-5 modular encapsulation of aluminum embedded with servo motor HXT 12K Metal Gear (55 grams weight, with a torque capacity of 10-12 kg-cm). The ErekoBot robot on figure 1.(a), with four modules in series, has a considerable weight of 150 grams. This creates problems related to self-configuration and mobility on higher frequency transmissions. External cable is responsible for power supply 12V/6V DC 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 walking type *Sidewinding* or second pitch pitch (Gomez, 2008) having problems of support, inertia and vibration during movement. Limitations with locomotion, response time, precision and mechanical design made it impossible to continue this project and demanded it to be improved into a more reliable system to work the locomotion algorithms.

3. PROJECT EREKOBOT α

3.1 Design

The ErekoBot α was designed to apply new ideas and in order to overcome β-5 weight, connection and control problems. Furthermore, new materials, fixing ways and fabrication process were explored.



(a) (c)

(b) (d)

Figure 2. Module ErekoBot α (a) and (b) previous design, (c) and (d)actual implementation.

The new module has a smaller volume than β-5; 40mm X 40mm X 40mm, and is constructed of fiberglass (E-glass with AR-300 Epoxy from BarracudaTec ™). The change in size made it possible to reduce the module weight (ErekoBot α weighs 48 g). and still maintain the strength needed to support the requested efforts.

Modular faces of α are overlaid by Velcro ® fastner. In their paper (Dittrich, 2004), YAMOR Project classifies Velcro ® fastener "a very strong tissue which works with principal of cockleburs and screws". It can stand sheer forces up to 600 N if connected with enough pressure in the contact area. Each ErekoBot α modular face have male and female Velcro ® fastener tissues in order to always allow connection between modules.

As noted by Garcia (2008) and Dittrich (2004), MTRAN and YAMOR servo motors are selected by higher torques, with attention to the distance between the centers of rotation and gravity of adjacent modules. Figure 3.b shows Turnigy TGY-90s servo motor used in ErekoBot α due to its suitable weight-torque relationship. It has 1.5 Kg-cm of torque at 6 Volts and metal gears, which allows greater durability and resistance to impact compared to the TG-9, previously used. This servo, with 15 grams, is the heaviest component but is justified by its torque to weight ratio, higher than other analyzed, besides its low cost. Moreover, with the servo, one module is capable to raise two coupled modules without relying on inertial forces nor in an increase in current discharge.

Table 1 is a summary of the main features of ErekoBot α:

Table 1. Features of the ErekoBot α module.

Specifications ErekoBot α	
Type	Homogeneous
Architecture	Hybrid
Reconfiguration	Deterministic
Self-Reconfigurable	Yes/Manual
Connectable sides	4
Degrees of Fredom (DOF)	1
Self-Locomotion	Sim (1D)

The ErekoBot α module is better designed than β-5 because it is smaller, lighter and cheaper. Figure 4 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 comparing with the nuts and bolts of the module β-5. It also damps the vibration on the link joints during locomotion.

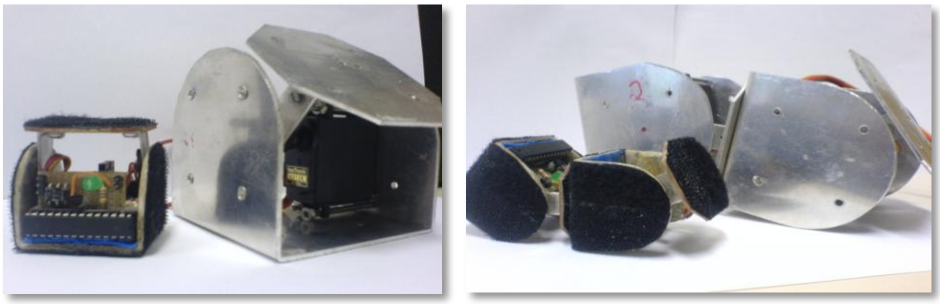


Figure 3. Comparison between α and β-5 modules.

3.2 Electronics & Communications

The electrical circuit embedded in α can be seen in Figure 5. Two rechargeable Lithium Polymer (LiPo) batteries with 7.4 V and 138mAh are the power supply. The three 1N4007 diodes protect the circuit of a reverse polarity and reduce the input voltage of 7.4V (or 8V) to the 6.35V on servo's VCC port. A 78L05 voltage regulator is used to provide power to the microcontroller, intermodular connection and to the wireless port(RF bus). The control circuit dissipated around 0.84W, showing that battery life depends more on servo's actuation(which power dissipates can go up to 2.5W).The Atmel ATmega 8 microcontroller is fed by 5V 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 35mA which is well below the maximum of 100mA supported by the voltage regulator.

The microcontroller output OC1A is connected to servo's signal input; where PWM signals (256 bytes) control the servo's position. For communication inter-module, there is a bus connecting two pins between the microcontroller and its RX and GND pins. To communicate via radio (RF) with other wireless device, there is a bus made from a mini-modu socket connected to the 5V, GND and RX pin of the microcontroller.

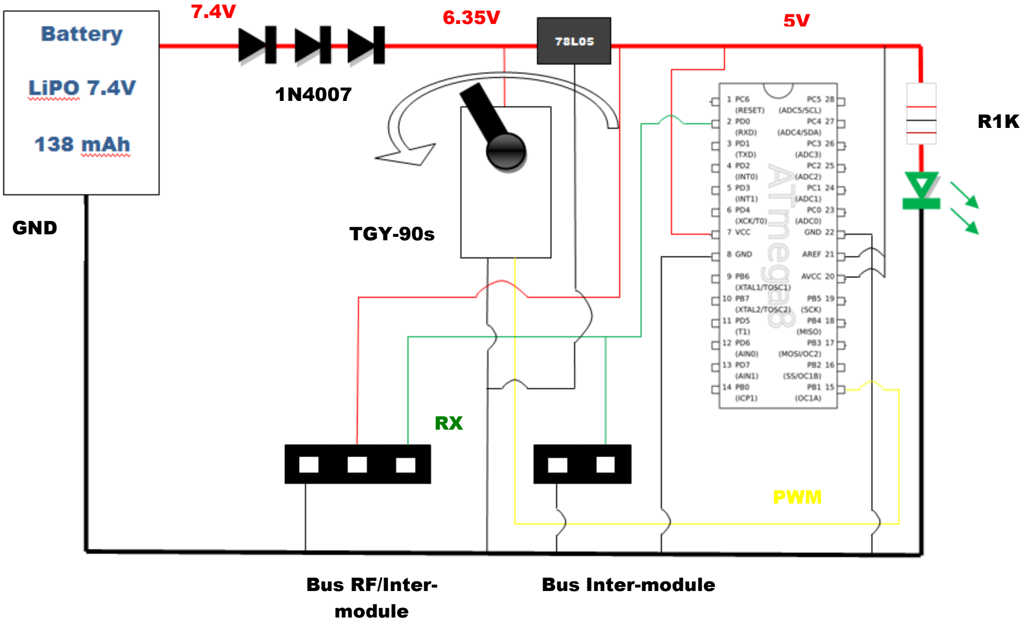


Figure 4. Electronic Circuit.

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. 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.

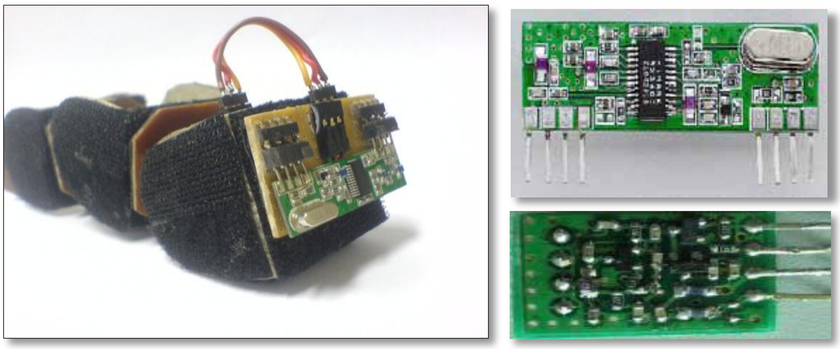


Figure 5. Transmitter module and receiver respectively.

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

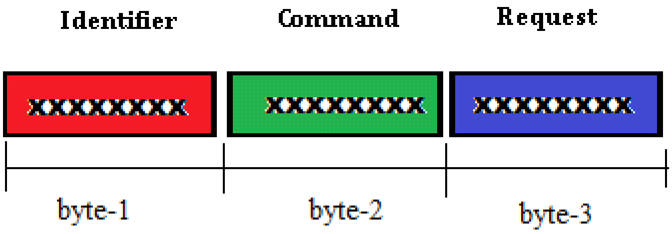


Figure 6. Communication protocol.

4. KINEMATICS OF ONE-DIMENSIONAL TOPOLOGY

Like in the animal kingdom, mobile robots are designed to perform tasks on a specific environment. It 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 appropriated. 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 dates from the seventies with the pioneering work of Hirose (Hirose, 1974, cited by Gomez, 2008), although they were applied to modular robots in the 90s. 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™ softwares and further simulated on OpenRAVE for dynamic analyses.

4.1 Serpentoide Wave

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

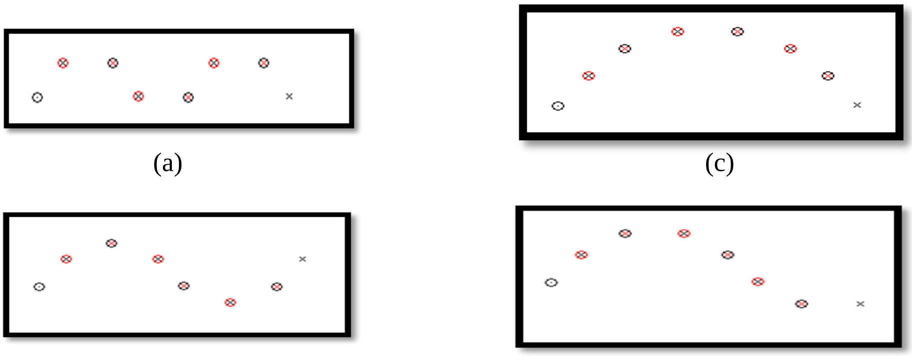
$$\varphi i \;\; t \; = A.\sin \frac{2\pi}{T}.t + \;\; i-1 \; \Delta\phi \; + \psi 1 \;\; , i \in \;\; 1 \ldots M \qquad (1)$$

, where *A* represents the amplitude of the movement, *T* the period, *t* the time, *ΔΦ* the phase between modules from the second one, *Ψ1* the first module phase and *M* the number of modules.

4.2 Differences between phases

The phase angle between modules is determined from the servo’s motor strength capability to lift adjacent modules. From the figures below, obtained with MATLAB™, it can be observed that the serpentoide wave pattern has less support point for smaller phase angles, which requires higher torque from the reference module (first point).

ErekoBot α servo capability limits phase angle to be less than 60° for efficient locomotion. For safety purposes, the phase angle settled was 90° in the paper's analysis.



(a) (c)

(b) (d)

Figure 7. Configurations: (a) Magnitude 60° - Stage 90°, (b) Magnitude 60° - Stage 60°, (c) Magnitude 60° - Stage 45°, (d) Magnitude 60 º - Stage 30 º.

4.3 Displacement

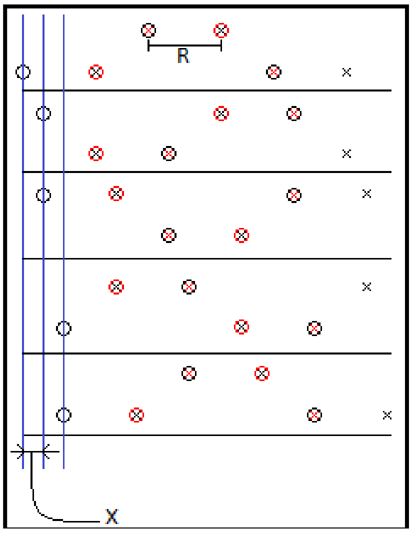


Figure 8. Module's position in sepentoide wave.

The snake's displacement is determined by the Eq. (2), where Ai is Amplitude and R is the distance between the two axis of rotation.

$$x = R.(1 - \cos Ai) \tag{2}$$

During a period, the angular displacement $\Delta\Phi$ is four times the amplitudeAi. Considering the angular velocity ω known from servo specification, the medium velocity should be defined as:

$$V_m = \frac{2.R(1-\cos \mathrm{Ai}).\omega}{4.Ai} \tag{3}$$

4.4 Analysis and Results

Servo motors are projected to normally work on a range of 30, 60 and 90 degrees of angular amplitude, which current and specific speed-to-voltage ratios are determined. Considering manufacture's data and optimal motion with 8 modules, an analysis of the systems configuration using 60 º and 60 º / 90 º are presented in the graphs below, where each point represents the center of rotation of the module.

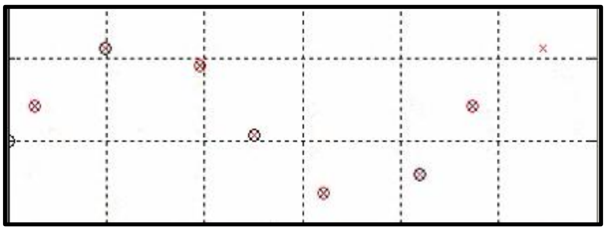


Figure 9. Chart for A = 60º e $\Delta\Phi$ = 60º

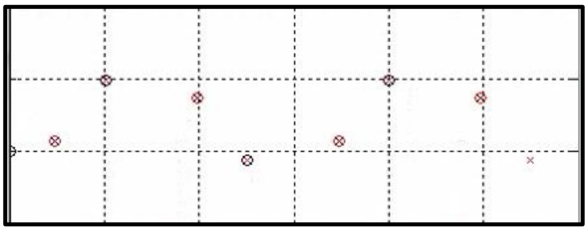
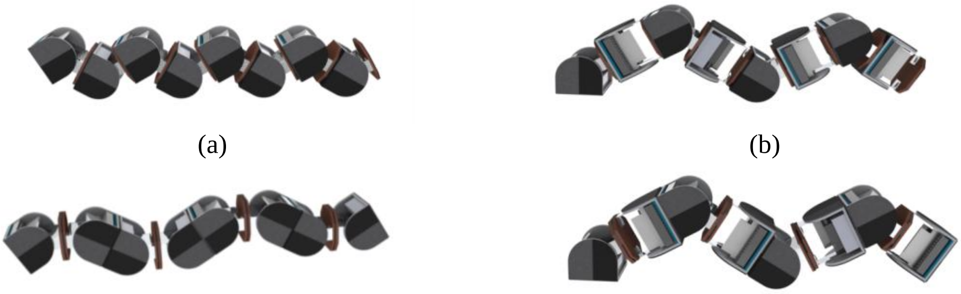


Figure 10. Chat for A = 60º e $\Delta\Phi$ = 90º

This data was then introduced into SIMULINK ™ block system, using Simscape's Simmechanics Block Library, to model the modular robot. The Simulink body model and data was imported from SOLIDWORKS ™ assembly file and tested with the sepentoid 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 dynamics analysis.



(a)

(b)

(c)

(d)

Figure 11. Reproduction for A = 60º e $\Delta\Phi$ = 90º (a) Pitch-Pitch. (b) Pitch-Yaw.

5. SIMULATION

Simulators are essential tool in robotics, allowing initial experiments with hardware design and controller programming to be performed at a relatively low cost (Christensen, 2008). A suitable simulator to ErekoBot must support modular robotic and be in use and 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 (Diankov, 2008). There is a plug-in named OpenMR which makes modular robots 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).

Figure 12. Simulation model of the module and the Pitch-Pitch serpentoid system.

The ErekoBot α was implemented in *OpenRAVE*. Figure 14 shows pitch-pitch (a) and pitch-yaw (b) eight-module-snakes locomotion evolution. An ErekoBot α CAD design was converted on numerical file in which the modules one by one were added and simulated to achieve final configuration. 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 straightforward on serpentoid movement and pitch-yaw moving laterally.

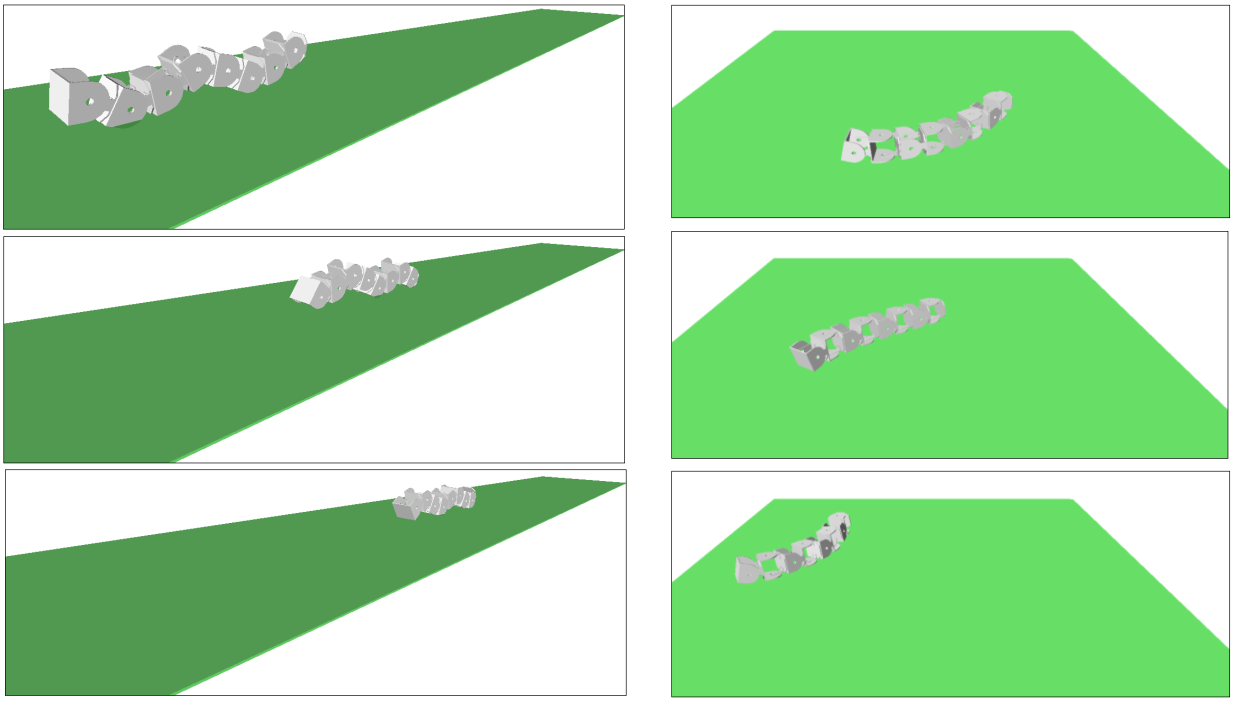


Figure 13. Pitch-Pitch (right side) and Pitch-Yaw(left side) serpentoid motion simulation in the OpenRAVE environment.

5. TEST

After simulation and construction of modules, it was possible to perform the first tests in order to make a validation 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.

- Distance between axes: R = 5 cm;
- Angular Velocity: $\omega \cong 60^\circ/0.9s$ or $\omega \cong 1.164 rad/s$ (The speed is approximated to have been calculated by using a stopwatch, because the program does not control the quality of the angular velocity);
- Using the equation for average velocity(Eq. (3), Pg. 7):

Table 2. Test results.

Pitch-Pitch			
	1° Test	2° Test	3° Test
Amplitude	60°	30°	45°
Fase	90°	90°	90°
1° Round	Distance: 30 cm	Distance: 30 cm	Distance: 30cm
	Time: 57,7 s	Time: 46,06 s	Time: 38,04 s
	Average Speed: 0,520 cm/s	Average Speed: 0,651 cm/s	Average Speed: 0,781 cm/s
2° Round	Distance: 28 cm	Distance: 30cm	Distance: 30cm
	Time: 52,2 s	Time: 45,08 s	Time: 39,25 s
	Average Speed: 0,536 cm/s	Average Speed: 0,655 cm/s	Average Speed: 0,764 cm/s
3° Round	Distance: 31,5 cm	Distance: 30cm	Distance: 30cm
	Time: 59,9 s	Time: 44,43 s	Time: 39,51 s
	Average Speed: 0,526 cm/s	Average Speed: 0,675 cm/s	Average Speed: 0,759 cm/s
	Overall Average Speed:	Overall Average Speed:	Overall Average Speed:

	0,527 cm/s	0,660 cm/s	0,768 cm/s
	Theoretical Overall Average Speed: 1,389 cm/s	Theoretical Overall Average Speed: 0,745 cm/s	Theoretical Overall Average Speed: 1,085 cm/s
	Loss of expected speed: 62,06%	Loss of expected speed: 11,40%	Loss of expected speed: 29,21%

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. Decreasing the amplitude - test 2 - the snake was able to almost reproduce the theoretical speed. It is observed that the modules slipped only slightly on the surface, but a new problem arose, the need for a higher speed you should use a larger range. The test with the mean value between the previous two amplitudes - Test 3 – modules also slipped, but not as much for the range of 60 °. His speed has been greater than for 30 °, even slipping on the surface.

Performing this test, came to the conclusion that it is necessary to modify the part of the module that comes in contact with the surface to increase friction. This can be done by adding a material 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 of a modular prototype, ErekoBot α, and a side-by-side design comparison to its predecessor, the ErekoBot β-5 module. Hardware system was described and kinematic analysis discussed. The system's feasibility was demonstrated through simulation.

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

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