Biomechanical Modeling and Simulation of the Spider Crab (*Maja brachydactyla*)

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***Abstract*— One line of research and development in robotics receiving increasing attention in recent years is the development of biologically inspired walking robots. The purpose is to gain knowledge of biological beings and apply that knowledge to implement the same methods of locomotion (or at least use the biological inspiration) on the machines we build. It is believed that this way it is possible to develop machines with capabilities similar to those of biological beings in terms of locomotion skills and energy efficiency. One way to better understand the functioning of these systems, without the need to develop prototypes with long and costly development, is to use simulation models. Based on these ideas, this work concerns the biomechanical study of the spider crab, using the SimMechanics toolbox of Matlab/Simulink. This paper describes the anatomy and locomotion of the spider crab, its modeling and control and the locomotion simulation of a crab within the SimMechanics environment.**

Keywords—spider crab; biomechanics; modeling; simulation; locomotion; SimMechanics.

I. Introduction

In recent years, significant advances have been made in robotics, artificial intelligence and others fields, allowing the creation of bio inspired machines. Scientists and engineers are using many of animals' performance characteristics for these advances. It is straightforward to see that even the most advanced robots reveal much inferior performances than their biological counterparts. Animal locomotion is much more versatile, efficient and elegant and, therefore, it is reasonable to consider studying biological systems in order to apply their schemes in the design and control of mechanical robots. For these reasons, there has been an investment in the development of robots that are mimics of animals. There exist already (or are under development) mechatronic mimics of various animals such as the cricket [1], the chicken [2], the gorilla [3,4], the dog [4,5], the Hermann Turtle [6] and the lobster [7].

Due to the desire to develop a walking robot able to move on the seashore, in sandy and rocky bottoms, it was decided to study animals that present good locomotion abilities in these terrains. The spider crab become a good choice for inspiration among the different animals analyzed, due to its living environment (that fits with the purpose of the intended study) and also since the structure of its body and its anatomy seemed interesting for the intended purpose. Based on these ideas, the aim of this study is to conduct a simulation study of the biomechanics of the spider crab.

The remainder of this paper is organized as follows. Section two presents a brief description of the spider crab and section three the determination of its biometric indices. Sections four and five present the kinematic and the dynamic model, respectively. Section six presents several simulation results obtained with the implemented model. Finally, section seven presents the main conclusions of this study and some ideas for future developments.

II. Spider Crab (*Maja brachydactyla*)

Maja brachydactyla (see Figure 1) (the European spider crab, spiny spider crab), a kind of edible crab belonging to the family *Majidae* arthropod decapod, is a species of migratory crab found in the north-east Atlantic and the Mediterranean Sea. *Maja brachydactyla* also supports commercial fisheries in northern Spain (Galicia), Portugal and in the Adriatic Sea [8].

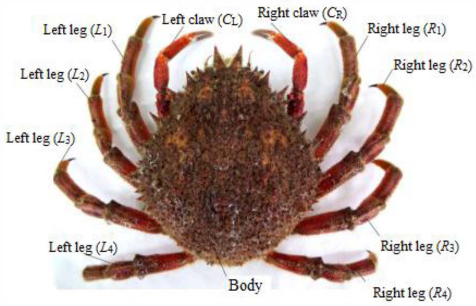

Figure 1. Photo of *Maja brachydactyla* with the legs numbered according to the nomenclature used on this work.

This crab's carapace presents a cord form and an irregular surface (with many nozzles), in general coated with algae, six spines on the longer side edges and two divergent large spikes at the front. It has five pairs of legs of which two strong clamps. Usually lives in sandy and rocky bottoms, where it hides among vegetation or in cracks. It feeds on algae, mollusks and echinoderms [8]. The spines are a protection against predators, but can also be dangerous to the unwary swimmers, if a carapace is trodden on. Fortunately they are not poisonous like some other organisms, such as the spider fish.

III. Determination of Biometric Indices

Measurements of the crabs were made in one of Estação Litoral da Aguda (ELA) laboratories. The used materials were 4 spider crabs (two of them were dead and two alive). Their overall dimensions are summarized in Table I.

TABLE I. METRICS OF THE CRABS

Spider crab	Mass of the body (*M*)	Length of the body (*L*)	Width of the body (*W*)	Thickness of the body (*T*)
First specimen	526.7 g	142 mm	117 mm	58 mm
Second specimen	891 g	160 mm	133 mm	80 mm

Length, weight and ratio of each animal's segment (see Figure 2) were measured and the average indices were calculated (see Table II for the case of the left legs).

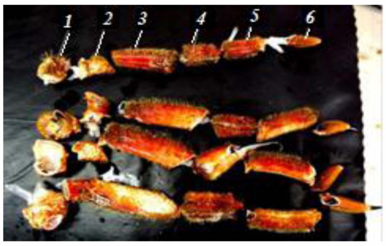

Figure 2. Legs of *Maja brachydactyla*, cut in the segments.

TABLE II. AVERAGE OF THE LEG CHARACTERISTIC VALUES OF THE FIRST SPECIMEN

Leg Number	Segments of leg n	Movement of the leg between joints around axis:	Amplitude of movement between joints α (°)	Length of the segment l_x (mm)	Diameter of the segment d_x (mm)	Mass of the segment m_x (g)
left leg L_4	1	*z*	90°	12.5	16	1.6
	2	*y*	90°	10.5	10	1.15
	3	*z*	20°	33.5	12	3.4
	4	*y*	120°	21.5	10.5	1.85
	5	*z*	75°	21.5	9.5	1.7
	6	*y*	90°	23.5	5	0.45
left leg L_3	1	*z*	85°	11.5	19	2.7
	2	*y*	90°	14.5	10.5	1.35
	3	*z*	25°	37.5	13	5.5
	4	*y*	120°	22.5	10.5	2.4
	5	*z*	80°	26	9.5	2.05
	6	*y*	90°	23.5	6	0.5
left leg L_2	1	*z*	90°	13	17	3.4
	2	*y*	100°	14.5	10.5	1.25
	3	*z*	25°	44.5	13.5	6.05
	4	*y*	120°	25	13.5	2.6
	5	*z*	80°	27.5	10	3.4
	6	*y*	90°	30	6	0.45
left leg L_1	1	*z*	90°	12	17	3.75
	2	*y*	90°	12	11.5	1.3
	3	*z*	20°	47.5	14	7.45
	4	*y*	115°	28	12	3.5
	5	*z*	65°	33.5	10	3.25
	6	*y*	90°	31	6.5	0.75

A. Locomotion of Maja brachydactyla

Walking is an automatic motor action which occurs as a result of complex coordinated activity of the skeletal muscles of the trunk and extremities. The motion of the individual units of the free leg is determined not only by muscle contraction but also by inertia [9]. A chronogram is a schedule displaying on a chart, for each operation, the amount of time it takes, and with all operations arranged in series according to their occurrence.

Videos made by filming live crabs in an ELA aquarium (see Figure 3), were used to make the chronograms of the locomotion of the crabs.

Figure 3. Filming *Maja brachydactyla* in ELA.

Figure 4 presents a chronogram depicting the locomotion of the spider crab sideways.

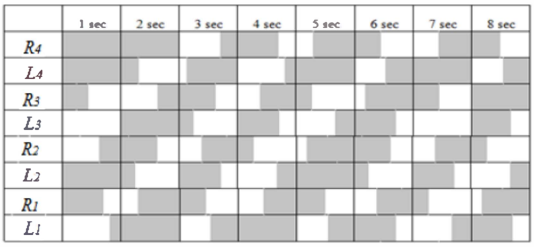

Figure 4. Crab`s locomotion chronogram.

The shaded parts of the chronogram represent the periods of time when a leg is on the ground (support phase); the white ones represent the periods of time when the legs make movements in the air (transfer phase).

The chronogram presented in Figure 5 was made using the same video, with the crab also moving sideways. The change of colors in this chronogram allows an easy interpretation of the movement of the legs during time intervals of one second.

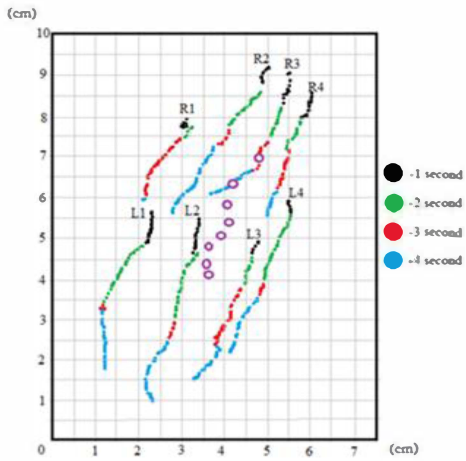

Figure 5. Chronogram of normal walk of *Maja brachydactyla* (scale 1:5).

Figure 6 shows the trajectory of the left leg (L_3) during a complete locomotion period (transfer phase plus support phase). First, the crab moves the leg up by rotating the “hip” joint; after this, starts the movement of the “knee” joint and, finally, using the “hip” joint, the crab moves the leg down and puts the foot on the ground. After this motion, the leg pushes the body and the crab “moves” the body sideways.

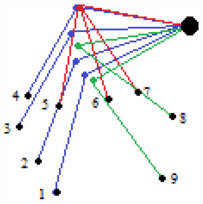

Figure 6. Locomotion of the leg during one period of locomotion.

Crabs crawl along the terrain by using four pairs of legs. Crabs bend and unbend their legs consistently. The leg consists of a series of movable articulated elements, whose mass is reduced towards the distal end. All joints allow movements around the *z* and *y* axis; this leads to leg flexion and rotation in plane. While walking the center of gravity of the crab is moving almost horizontally.

IV. Kinematic Model

Most walking robots are very complex mechanical systems, displaying variable structures and different number of legs. The available options in legged robots are enormous, with configurations varying among, for example, 2 legs (biped), 4 legs (quadruped), 6 legs (hexapod) and 8 legs (octopod) like spiders. In this paper the modeling and simulation of the spider crab, which has 8 legs (an octopod configuration) is described.

A. Number of Degrees of Freedom

The number of degrees of freedom in a mechanical system is the number of independent parameters defining the position of all elements of the system. Figure 7 presents the equivalent mechanism of a spider crab leg (simple kinematic scheme), presenting 5 degrees of freedom [10].

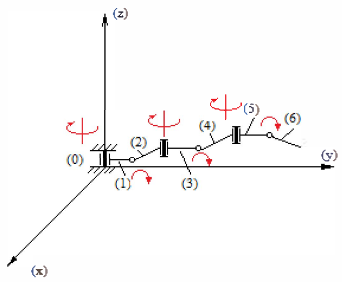

Figure 7. Equivalent mechanism of a spider crab single leg.

B. SimMechanics Kinematic Model

All legs of the crab were modeled in SimMechanics (a toolbox of Simulink [11], running on the MATLAB environment), and were connected to the body through revolute joints, as presented in Figure 8. The model presented in this figure is in its simplest form, without sensors, actuators, and control system.

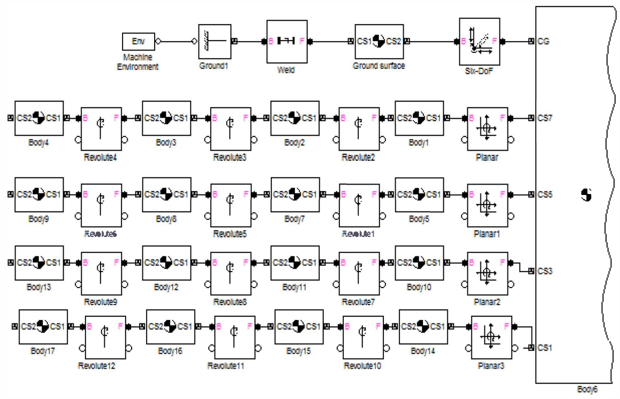

Figure 8. The kinematic model of the left part of the crab.

C. SolidWorks Model

SolidWorks [12] was used to model the geometry of the Spider crab, namely to draw all single parts of the crab’s body, and latter connect all parts in one model (see Figure 9). This model is made using original data and has a geometric dimension equal to the real size of the crab measured in ELA.

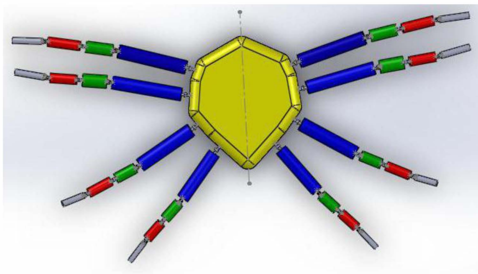

Figure 9. SolidWorks model of the crab.

V. Dynamic Model and Visualisation

SimMechanics was also used to make a dynamic simulation. The dynamic model is based on the kinematic model, and on the real measurements of the spider crabs. This means that the variables length, radius and mass of the legs and body of the robot are parametrically programmed in the dynamic model.

A. SimMechanics Dynamic Model

The “Robot Kinematics” block model, shown in Figure 10, is based on the kinematic model developed in SimMechanics. Here the main central Body block (gray) represents the body of the crab, the eight surrounding subsystems (blue) represent legs, and the smaller blocks connected to the latter are subsystems representing the ground contact blocks (green). The ground is fixed at $z = 0$ and the position of the robot center of gravity is connected through a 6 DOF block to the ground.

Each leg has the same structure, being one of the dynamic models of a leg presented on Figure 11. Body blocks represent links (blue blocks), and Revolute blocks are revolute joints (green blocks), with joint sensors and actuators. There is also a PD (Proportional-Differential) controller for each join (block PID).

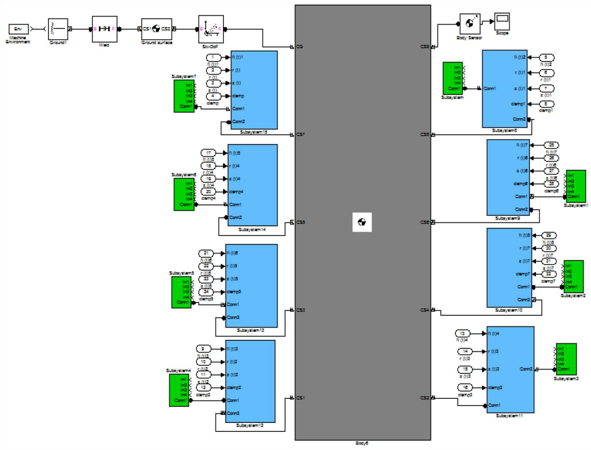

Figure 10. SimMechanics representation of the crab.

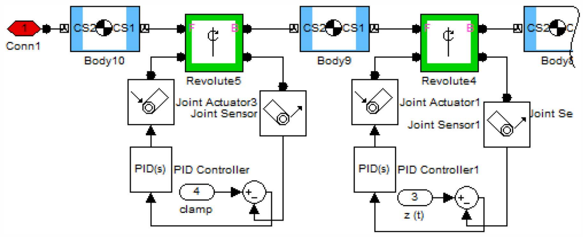

Figure 11. Dynamic model of a crab's leg in SimMechanics.

B. Ground Contact

The coordinate system in the simulator is, at t = 0, directly linked to the neutral point in the frame (0, 0, 0), meaning that the robot starts with a preset body height directly centered above the zero frame point.

The legs of the robot are connected to the body frame and to the robot's coordinate system. On the contrary, the feet of the robot are observed in the world coordinate system to determine the world z. If the z is equal or smaller than zero it means that there is a contact with the ground and the forces of the ground should reflect to the feet, as shown in Figure 12.

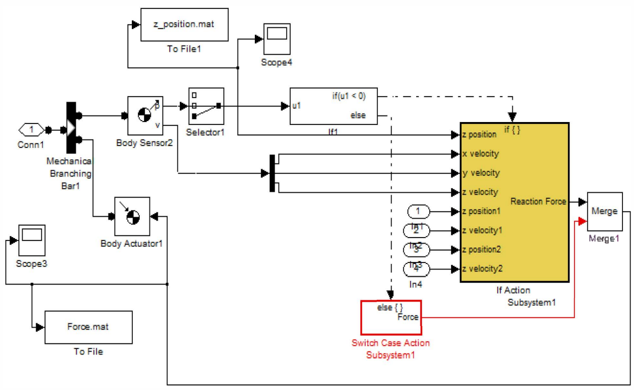

Figure 12. SimMechanics implementation of the ground contact model, which determines if the leg is on the ground or in the air and the corresponding contact force.

The ground is modeled as a spring-damper contact. The values for the spring and damper are $K_{contact}$ = 15 N/m and $D_{contact}$ = 5 Ns/m. The crab can stand at the ground at level z = 0. Only when the leg is in contact with the ground do the reaction forces act on the leg (see Figure 12, red subsystem block).

In order to let the robot walk in a given direction, friction has to be introduced when the feet touches the ground, according to equation (1).

$$F_n = \begin{cases} -z \cdot K_{contact} - \dot{z} \cdot D_{contact} \\ 0 \end{cases} \quad \text{if } z \le 0, \text{ otherwise}$$

$$F_{wx} = \begin{cases} -\left(2/(1+e^{-10\dot{x}})\mu \cdot F_n\right) \\ 0 \end{cases} \quad \text{if } z \le 0, \text{ otherwise} \qquad (1)$$

$$F_{wy} = \begin{cases} -\left(2/(1+e^{-10\dot{y}})\mu \cdot F_n\right) \\ 0 \end{cases} \quad \text{if } z \le 0, \text{ otherwise}$$

Basically $F_w = V\mu F_n$, with $F_n = -z \cdot K_{contact} - \dot{z} \cdot D_{contact}$ being V a Sigmoid step function $2/(1+e^{-10\dot{x}})$, depending of the contact speed but with a (0, 0) crossing.

C. Discrete-positional Planning of the Crab Motion in Simulink

Let us consider the structure of the motion planning subsystem (see Figure 13). The input signals (except for control signals) are combined through a multiplexer and fed to the input subsystem functional analysis of the current mismatch and terminal coordinates. The control signal is supplied to the unit of comparison, that analyzes the enabling or disabling of the sensor interrogation procedures, etc. If the signal is equal to +1, the job passes to the next subsystem. If the signal is zero, then no change occurs in the system.

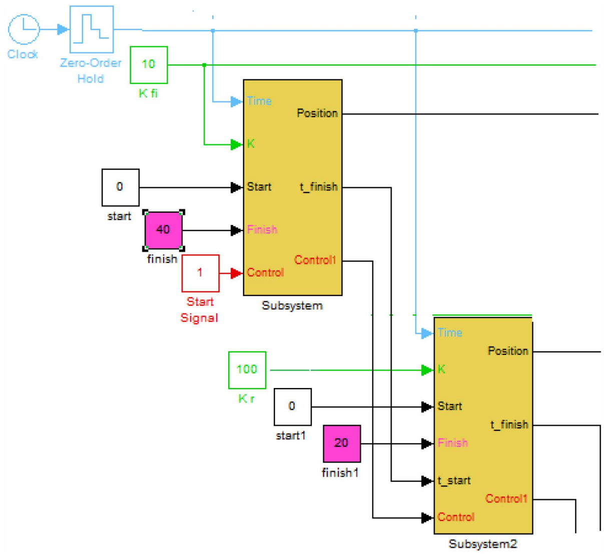

Figure 13. The integrated simulation model of the motion planning of the start point.

To confirm the validity of the model, this system was connected to the model of the robot, which was made in SimMechanics. Simulation results are presented in the next section.

VI. MODEL SIMULATION

This section presents the results of simulation tests performed on the developed model.

A. Simulation of One Leg

The first test of the mechanism model was made with only one leg (see Figure 14), to check what occurs to the body while one foot is in contact with the ground surface.

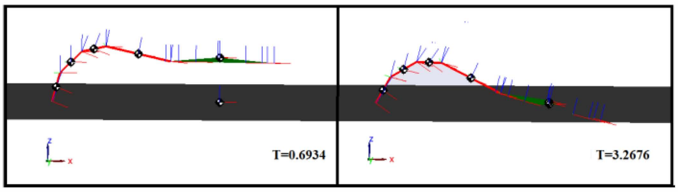

Figure 14. Simulation ofthe crab with one leg.

For this test, it was used the three-dimensional animation functionality of SimMechanics, and also "Scope" blocks to depict the graphics of several variables. There is a leg contact with the ground, and the leg does not go through the surface. Forces acting on the leg make the body move and fall down on the surface. This result was expected, because the crab's body is standing just on one leg and there is no support.

The plots depicted in Figure 15 show the movement of the body in the *x*, *y* and *z* axis. *z* position (red line, right plot) shows that the body actuated by the gravity force, moves from the position 50 mm and falls down to the ground.

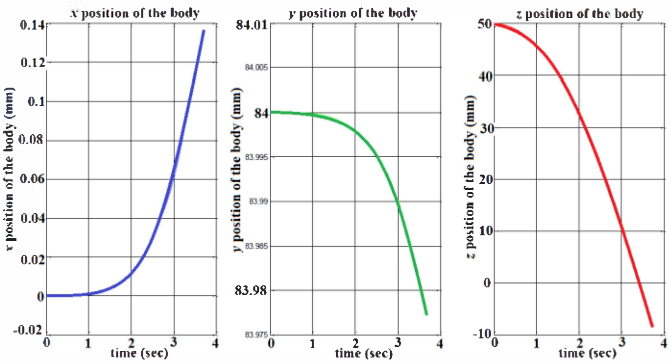

Figure 15. Plots of the *x*, *y* and *z* positions of the crab's body during simulation with just one leg

B. Simulation of the Spider Crab Locomotion

The pictures depicted in Figure 16 are screenshots of the simulation of the spider crab locomotion during 10 seconds. In this case, the model of the crab has eight legs. The legs are positioned in relation to the body, according to their positions on a real spider crab. The pictures show the movements of the legs, and body, relatively to the surface. For this simulation, amplitudes of motion of the segments used were equal to the ones measured in laboratory and the same locomotion movement of the leg was implemented. In Figure 16 it is possible to see that the center of mass of the crab moves against the center of mass of the ground. There are four main moving legs, namely L_4, L_2, R_2 and R_3. While these legs are moving (transfer phase), the other legs are being used as a support for the body (support phase), but they are also moving with the entire body. This conclusion was taken from studying the crab's locomotion, and through the chronograms' analysis.

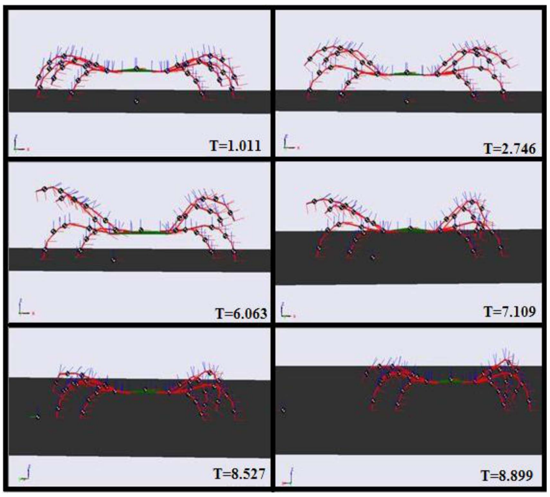

Figure 16. Simulation of the spider crab (0-10 sec)

The force plot presented in Figure 17 shows that there are forces acting on the leg during its motion, being the maximum value 0.9 N. To get this plot the "Scope" was connected to the lower extremity ("foot") of the moving leg (L_4). Theoretically the ground reaction force should be about 0.6 N, because the crab's body weight (526.7 g) is equally distributed in all contact points (eight legs).

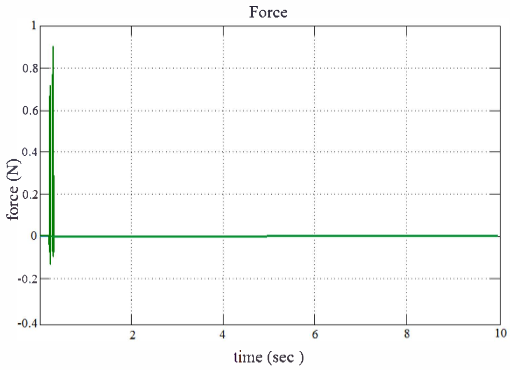

Figure 17. Plot of the ground reaction force acting on leg L_4

In Figure 18 it is presented the *z* coordinate of the foot of leg L_4. It is possible to conclude that there is ground contact only in the beginning of the simulation. The scope is connected to the distal part of the leg, and from this plot it is possible to see the trajectory of the moving leg.

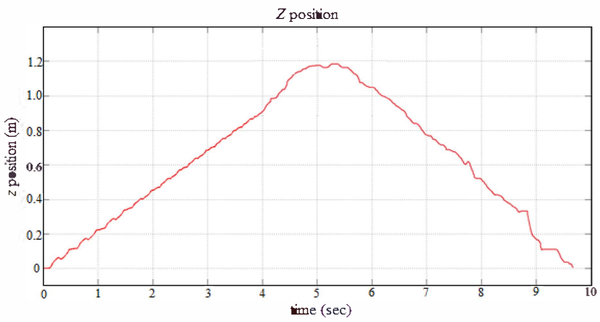

Figure 18. Plot of leg L_4 foot *z* position during simulation

During this simulation the crab moves. On Figure 19 are presented plots of the crab's *x*, *y* and *z* body position (blue (left) is the *x*-axis, *y*-axis is the green (center) plot and red (right) is the *z*-axis).

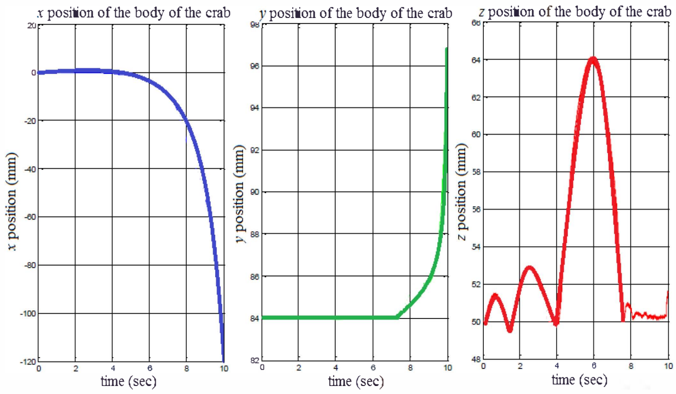

Figure 19. Plots of *x*, *y* and *z* positions of the crab's body during simulation

VII. Conclusion and Perspectives for Future Developments

A. Conclusion

This paper presents the modeling, simulation and control of the spider crab, which might be an option for a new type of biologically inspired robot. The strategy has been to use the animal's kinematic and dynamic characteristics and behavior as the default in the design and control of a robot model.

In laboratory, the parts of the crab's body were measured, the locomotion and trajectory of its movements were studied, to implement a more realistic, and based on real data, simulation model. The crab model was implemented and programmed in Matlab/SimMechanics and in SolidWorks. The legs are all individual controlled, but the robot legs are not equally constructed in shape, size and mass. In the dynamic environment, gravity and mass are affecting the model. Model parameters (mass, length, diameter, motion amplitudes) are the same as the ones of the real crab. The kinematic model has been slightly changed, to make a less complex model, without significantly changing the biomechanical properties of the Spider Crab. The dynamic model includes the ground contact effect, implemented in order to make the robot stand on the ground surface. This model is implemented to give the feet a reaction force to the ground and, to make the robot move in the desired direction, a discrete-positional control system was used. Closer attention was given to the spider crab's biology and biomechanical aspects in the design of this robot model. Concerning the locomotion, the algorithm presented in this paper allows the crab to walk sideways. As a result, a robot model that is moving in an "animal like" manner was obtained.

B. Perspectives for Future Developments

To further develop the simulation programs described in this paper towards a realistic spider crab model, the following development steps are needed:

- Investigate the dynamic algorithms and tune the PD controller parameters for each joint, to make the model walk with better performance and faster;
- Design an algorithm for the general path planner in order to make the robot walk according to a desired trajectory, to climb rocks, walk on the sand surface, and enter to the water, as a real spider crab does. These extra features will reduce the stability of the robot, so it is necessary to investigate dynamic stability algorithms;
- The development of a real robot biologically inspired in the "*Maja brachydactyla*", will be the final objective for future work.

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