

Implementation of the Electronic and Communication System for a Snake-like Modular Robot

Santiago Melo Guayacan¹, Santiago Nougues¹, Hernando Leon-Rodriguez.

Industrial Engineering Department; Nueva Granada Military University, Bogota – Colombia.

(est.santiago.melo1@unimilitar.edu.co; est.santiago.nougues@unimilitar.edu.co; hernando.leon@unimilitar.edu.co*)

Abstract: Nowadays, engineers must have a wide variety of knowledge and techniques to apply them to different contexts, where robots play a fundamental role. Among the most useful are the snake-like robots which, thanks to their mobility, can adapt to different environments as needed. In this study a snake type robot was recreated to simulate the movement patterns providing a degree of freedom per joint so that it can adapt to the surface, where it was found that the mathematical expression that symbolizes this movement is a function of the amplitude of the wave and the phase shift of the movement of each joint, which can be recreated using servomotors. Having said this, it is demonstrated that the movement of a snake can be simulated by performing a mechanical coupling of joints, which is based on a formula that represents the sinusoidal kinematics of these animals. Also, by means of the Wi-Fi communication protocol, a function was implemented to vary the initial parameters of the SNAKE in order to adjust the movement according to the required surface.

Keywords: Sinusoidal motion, snake-like robots, IoT, modular robot.

1. INTRODUCTION

In general the snake-like robots are complying with a cylinder form modules, with active and passive wheels placed in each joint. On each module, there are one or two servo actuators with their mechanical assembly to generate the degree of freedom, ending up producing the motion.

The Unified Snake of Cornell Wright et al, proposed 16 DOF, with 180° max rotation, in this stand out it's the mechanical part, which is intergrade for a round cross section housing, provides a better contact, also in this the components as motor and gearbox, provide, a not recalibration when removed external forces. In another part, the parking brake present is a good system for save energy and facilitates its operation in addition to avoiding damage [1].

The bending and extending joint unit of Sugita, S. et al. presents a solution for the problems of a movement in uneven ground. When investigating the locomotion and surface contact, to improve the mechanical system of the ACM-S1 [2].

Hiroya, Y and Shiero, H, in a Study of a 2-DOF Joint for the Small Active Cord Mechanism, in this describe a mechanism of 2 servos and 4 rotational axes, which is opposite to other that presents 1 rotation axes by 1 servo. This is achieved by 6 miter gears, which form the mechanics of coupled drive. This provides a large range of motion and power [3].

From the above we can see that these are generally made up of joints which, depending on the designer, are given

a greater number of degrees of freedom, which makes their control more complicated, but at the same time allow versatility in the design motion. Servomotors are defined as a type of electric motor which, as its name indicates, includes a motor together with a set of gears and a control circuit which adjusts the position of the axis depending on the input signal, which allows this is positioned at a given angle regardless of external forces. This component is used to control the movement of a robot move like a snake. Now through servo motors to simulate the kinematics of a snake, we must use a theoretical analysis to define a mathematical expression that allows us to replicate the motion [14].

Within the robots inspired by the biological locomotion of snakes, these still do not reach the necessary requirements for mobility can adapt to changing environments where friction plays an important role and can be adjusted according to the obstacles that may arise. Hence the importance of the mechanism, these are generally composed of joints which depending on the designer are given a greater number of DOF which makes the control of these more complicated, but in turn allows versatility in the serpentine movement. Therefore, numerous mathematical expressions have been proposed according to 3 factors, the type of joints, the degree of freedom and whether they have wheels or not [5]. In the case of friction, it is generally considered in the mathematical model when there are no passive wheels in the system. On the other hand, it is worth mentioning that within the studies performed, the CMU modular snake robot has been used to test the effectiveness of the gait model for the generation of new behaviours by means of 3D body undulations to divide the serpentine motion into the even joints for horizontal motion (1) while the vertical ones are made the odd ones (2) as shown below. [4][13][15].

¹ All authors have contributed equally

$$A_c(n)\sin(\Omega n + \omega t) \quad (1)$$

$$eA_c(n)\sin(\Omega n + \omega t + \frac{\pi}{2}) \quad (2)$$

Analysing the equations shown above for the serpentine movement, it is obtained that as the movement is performed the ϕ of the robot will change due to the friction between the robot and the surface, therefore the rest of the parameters also vary. Therefore, if ϕ is properly controlled, the desired motion can be obtained taking into account that ω is the frequency with which the wave propagates through each of the joints and the values of β and γ determine the speed and direction of the robot according to a statement made by Hirose [6][12] and exposed in the following equation:

$$\phi_i(t) = a \sin [(wt + (i - 1)\beta) + \gamma i] \quad (3)$$

Within the different types of robots with serpentine movements these have different ways of carrying out their mechanical coupling as mentioned above, so in the first instance to classify these robots we have one of the most common which are those that have passive wheels that are used for both terrestrial and aquatic snakes and its use lies in helping the lateral movement of each of the joints of the robot. An example of this is the Michigan Snake 1 whose differentiating component is the use of linear solenoids and ball-shaped wheels for forward movement [7].

On the other hand, there are robots that use active type wheels in order to give propulsion to the snake and facilitate the movement of the same by surfaces that are not flat. Also within the main complications that this type of robot presents is that now they have to link the DOF of the wheels to each of the joints that the robot has, an example of this is the NTUA 2 which consists of six joints of which the first are to load goods and move it, the central ones provided the movement in the horizontal and vertical axis and finally the rotation was subject to the last two servomotors that allowed the control to each of the equipped wheels [8].

Finally, robots that move based on vertical waves are identified, where unlike those that use wheels, these move forward using only the undulation, within this category there are two types: those with rectilinear movement by vertical waves or rectilinear movement from segments that expand and contract [9]. A clear example of this is the inchworm robot whose movement allows climbing steel structures; this was composed of three joints that provided three degrees of freedom that by means of a fastening mechanism gave the strength and subjection for it to move along the surfaces [10].

2. MECHANICAL COUPLING

The representation of the serpentine movement the mechanical coupling of the robot was made with 8 modules, which were adapted to have two degrees of

freedom by servomotors, on the other hand this design was suitable to work in a modular way so that each joint has its own electronic components and respective power supply, covered by a rubber tube that protects the joints from the constant friction with the ground when moving the robot. Also, in order to simplify the locomotion, some metallic fastening points were fixed around the rings containing the servomotors, where passive wheels are incorporated as shown in figure 1.

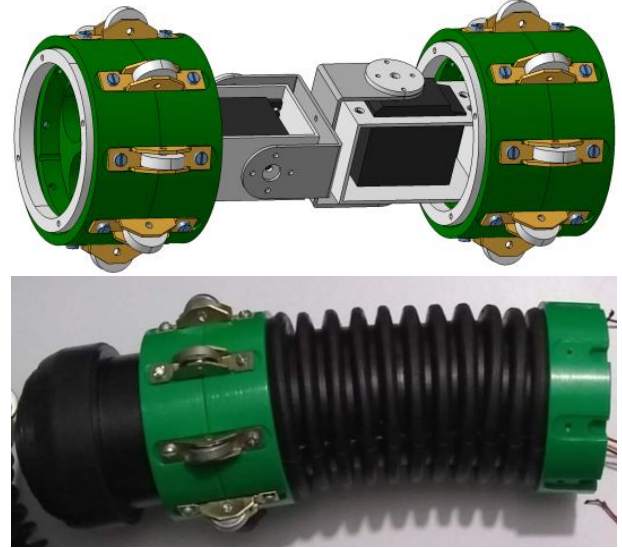


Fig. 1. Conceptual design and module of snake robot.

3. ELECTRONICS COUPLING

For the electrical part for the 8 servos, 2 power lines were used to connect the servos in parallel, as well as the control lines. The power lines were connected to a generic power supply with 5V and 32 A output; given a total consumption of the snake about 4 to 7 A. For the connection of the control lines, we used an ESP-32, using pins G13 to G32, also used the Wi-Fi module integrated in ESP 32 to send the commands, through IoT, as shown in the general diagram in Figure 2.

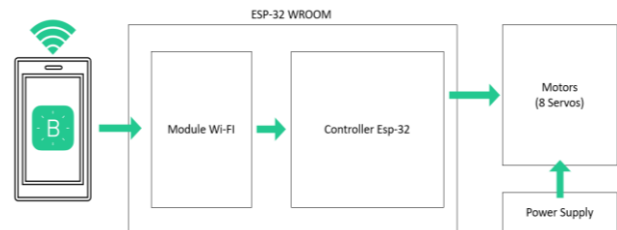


Fig. 2. Block diagram of connection with the main controller.

4. MATHEMATICAL EXPRESSION FOR SERPENTINE MOTION

In order to optimize the movement of the snake, it was identified that to generate the sinusoidal movement it was necessary to have an equation that would allow the correct control of the angles of each of the servomotors,

from which the following equation was obtained depending on the number of servo motors used [11]

$$\emptyset = 2\alpha \sin [(wt + (i - 1)\beta) + y]$$

Where:

\emptyset : Angular position of the servomotor

α : Range of motion

w : Angular frequency

t : Time since the beginning of the movement

i : Servomotor number (1-8)

β : Offset

y : Initial angle

Given this expression is adjusted for the mechanical model made, taking into account our number of servomotors which were 8, Having said this, the displacement for each servo is found using the displacement equation from which we obtain the following:

$$\beta = \frac{-c}{n}$$

$$\beta = \frac{-45}{8}$$

$$\beta = 5,625$$

Where:

c = initial position of the servos

n = number of servos

Finally, to obtain the last of the constants to be used, the amplitude of the desired wave is found by clearing the amplitude from the equation and obtaining the following value for α .

$$\alpha = 2 * 30 * \sin\left(\frac{11.25}{2}\right)$$

$$\alpha = 22.18$$

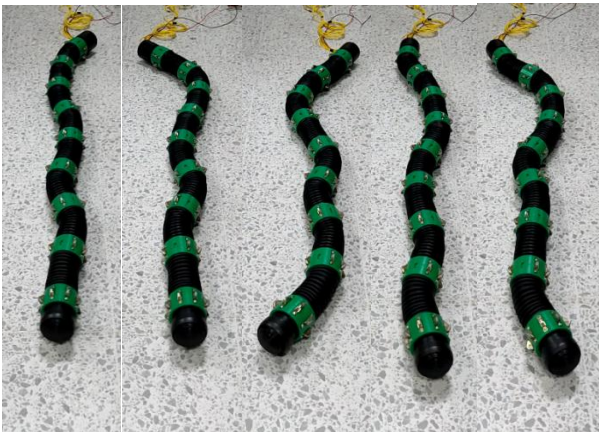


Fig. 3. Sinusoidal motion of the snake like robot.

Once these constants are obtained, they are defined within the code in order to use them in the equation and perform the corresponding movement in each of the servos, in addition to this it should be noted that for the SNAKE to have such movement was necessary to

divide the modules into groups, the servo motors numbered 1, 2 and 3 are grouped to perform the beginning of the wave, modules 4 and 5 represent half of the wave and the remaining 6, 7 and 8 symbolize the termination of the cycle giving a movement similar to the expected, results in the trials are showing in figure 3.

5. DYNAMIC ANALYSIS AND UNDULATION

For the kinematic analysis is performed for one of the joints of the robot, where it is obtained that the main forces that exert the movement are those that come from the servomotors, also takes into account that the forces that oppose this movement is the friction force from the surface on which it is located and it should be noted that the angle from the joints also plays an important role in distributing the momentum to the direction that moves the snake robot.

Figure 4 is showing the kinematic diagram with the forces that interact in the joints of the robot with snake movement, we have the tension force represented by the letter T which allows the union between two servomotors which in turn generate a force so that the snake moves forward and are represented by the letter F1 and F2, finally, it must be taken into account that being a robot that moves on surfaces the weight of the robot (W) will also influence its movement and thus will have a normal force in the system.

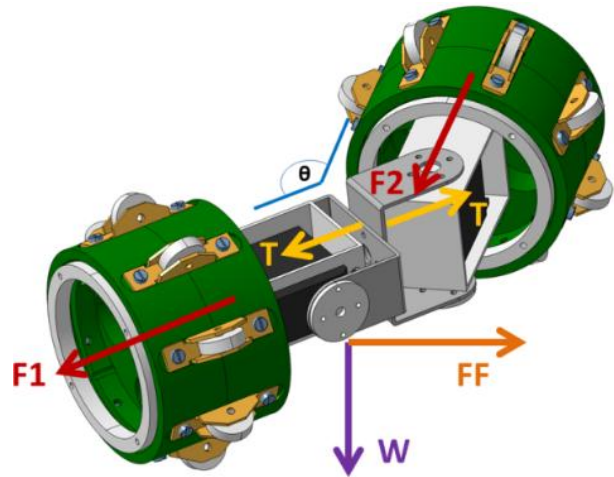
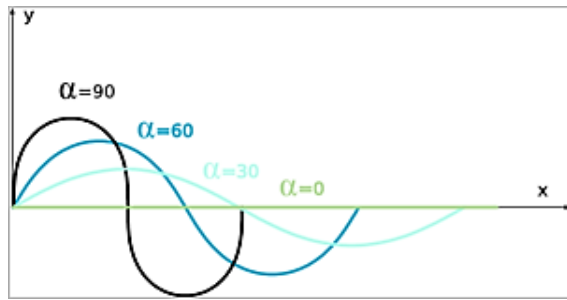


Fig. 4. Kinematic analysis for one single joint.

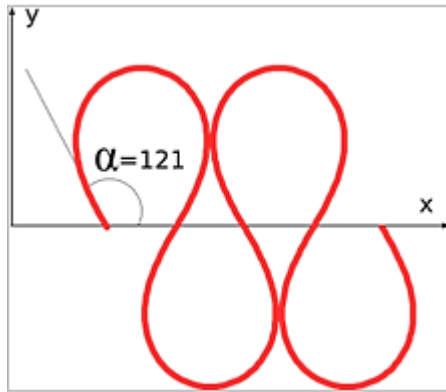
In 1976 Professor Hirose developed an algorithm which has become important for the study and construction of a-pedal robots, in order to apply it to the locomotion of this type of robot.

$$K(s) = \frac{2\pi k}{l} \alpha \sin\left(\frac{2\pi k}{l} s\right)$$

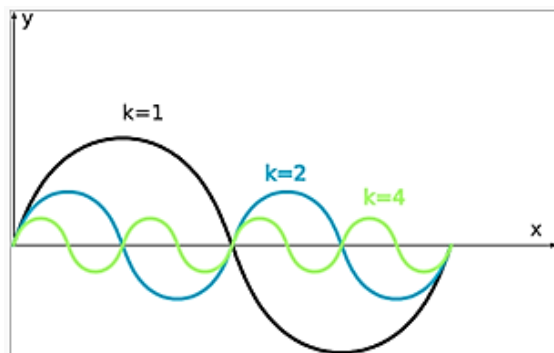
In this study the serpenoid wave is described, which varies its curve sinusoidally with the distance along the curve in different cases represented in figure 5.



Case 1. ($\alpha = 90^\circ, 60^\circ, 30^\circ$)

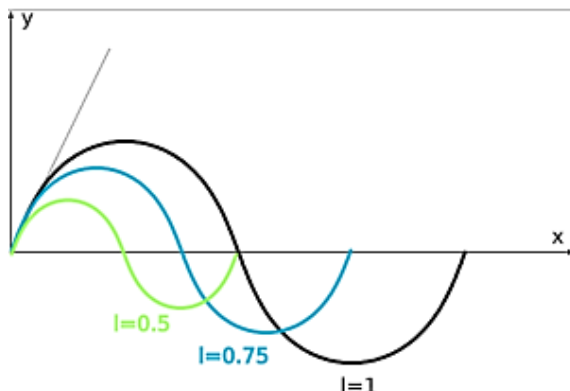


Case 2. ($\alpha = 121^\circ$)



Case 3. ($k = 1, 2, 4$)

The number of undulations (k), have the same length, but different values of k , so the height decreases but the width remains constant.



Case 4. ($l = 0.5, 0.75, 1$)

The length (l) determines the scale, where the angles are fixed and the shape is the same but scaled.

Fig. 5. Serpenoid wave is described for different modifications of variables.

To achieve these motions in the snake prototype the sequence of sending data where perform via PWM or Pulse Width Modulation. It is a very basic method of open loop control that reduces the average power delivered by an electrical signal, chopping it into discrete parts. This is also a very common technique used to control servomotor via the variation of duty cycles from the signals; where, the proportion of a signal is on and off into a specific period of time and a high duty cycle corresponds to a high power, such as the low duty cycle

6. IOT APPLICATION AND SOFTWARE

Several IoT platforms and open source hardware and software can be used to program and control a very large number of things, it's composed by a microprocessor and a controller, the hardware (board) is composed with sets of digital and analogue input/output pins and other circuits, also serial communication interfaces including Universal serial bus. This type of microcontrollers are programming in a mixed of languages such as C, python, HTMLs, C++, etc. additionally it has an integrated development environment based on the processing language project.

For the communication system, IoT was used, using the Wi-Fi intergrade over ESP32 and the Blynk platform, in which an interface of switches was implemented to indicate the movement in forward, backward, right and left direction in both directions, as shown in figure 6.

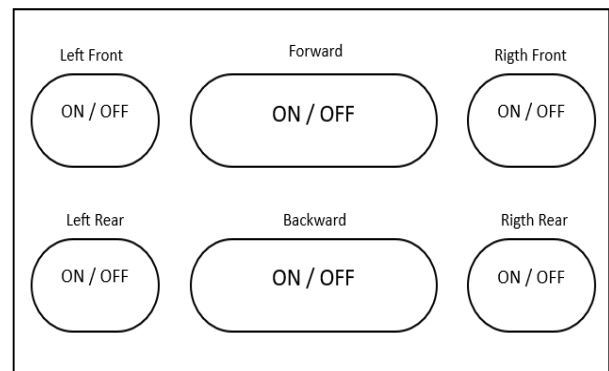


Fig. 6. Graphic user interface from IoT-Blynk.

For the movement in the different directions, send a digital variable from Blynk to ESP32, any for each direction, where for front movements use the positive beta and negative for rear directions. Again, for the movements to the right, add an offset to angles of only 45° to the odd joints and even joints with 90° ; meanwhile the opposites movements to the left.

Table 1. Movement Direction

--	--	--

7. MOTION ANALYSIS

For the motion analysis, a video was recorded with the movement of the Snake robot and decomposed using the Tracker Video Analysis tool, from which the practical data of the movement and the theoretical part were obtained, to finally get the equation of motion and thus be able to calculate the error at each of the points and weight them to get an overall error

Table 2. Data obtained in practical trial

Data				
t	X	Practice	Theoretical	Error
6,69E-02	4,13E-03	9,29E+00	4,23E+01	78%
1,00E-01	6,27E-03	-6,76E+00	4,08E+01	117%
1,34E-01	6,27E-03	-4,42E+01	3,88E+01	214%
1,67E-01	6,27E-03	-4,42E+01	3,64E+01	221%
2,01E-01	6,27E-03	-6,29E+01	3,37E+01	287%
2,34E-01	7,34E-03	-6,03E+01	3,07E+01	296%
2,67E-01	9,48E-03	-5,76E+01	2,73E+01	311%
3,01E-01	9,48E-03	-5,22E+01	2,37E+01	321%
3,34E-01	1,27E-02	-5,49E+01	1,98E+01	377%
3,68E-01	1,91E-02	-5,49E+01	1,57E+01	449%
4,01E-01	2,34E-02	-5,22E+01	1,15E+01	554%
4,35E-01	2,66E-02	-5,22E+01	7,16E+00	830%
4,68E-01	3,30E-02	-5,76E+01	2,74E+00	2202%
5,01E-01	3,19E-02	-5,76E+01	-1,71E+00	3275%
Avr.Error				344%

Once the results are obtained and recorded in table 2, both the theoretical and practical values are plotted in order to compare how faithful the movement is to the proposed equation and this can be seen in Figure 7.

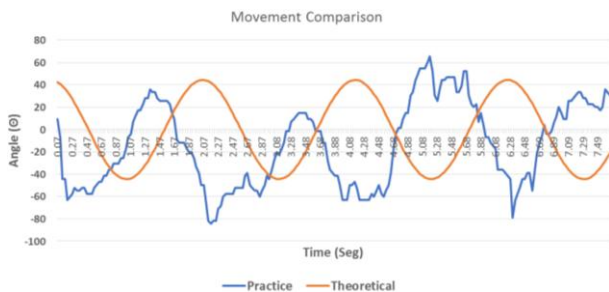


Fig. 7. Comparison between theoretical and real motion of the snake-like robot.

Given the graph shown in figure 7, the sinusoidal line obtained theoretically and the practical line are contrasted, where it is corroborated that there is an error which was previously calculated in table 2. This error is due to several factors, the first one is the friction factor of the surface which makes the sinusoidal movement not completely constant, likewise, it is also taken into account that there could be errors in the mechanical construction more specifically in the wear that can present the servomotors due to the continuous use that have been given as to the passive type wheels. On the other hand, it is taken into account that the mathematical model is not perfect so that some of the calculated constants are not necessarily influencing the behaviour

of the serpentine motion so that some of the servomotors may be limiting the range of motion of the adjacent servos.

Also to corroborate that the movement of the snake-like robot moves with constant velocity we proceed to plot the displacement of the robot on the X-axis as shown in figure 8.

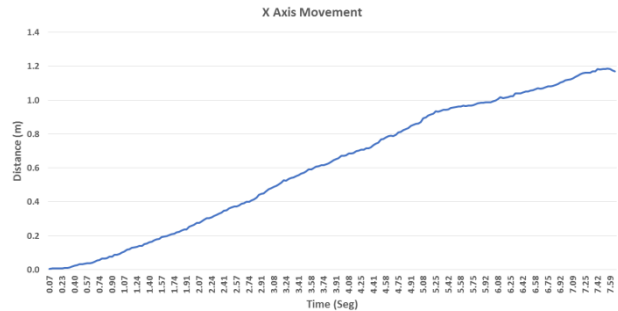


Fig. 8. Movement of the snake in the X-axis.

8. CONCLUSIONS

This study has shown that snake robots have a great advantage compared to other types of robots because of their great mobility and ability to adapt to different environments. With this it was demonstrated that by means of a mathematical expression it is possible to represent the movement of these animals using servomotors and so that they can adapt to different situations, Wi-Fi communication is used to adjust the values of the equation and thus adjust the movement of the robot as needed.

Given the percentage of error the 344%, to minimize it, it must evaluate new algebraic expressions that represent a sine wave as a function of servo motors, also to consider the variation of the characteristics as amplitude, phase shift, among others. To give a greater precision of the angles for generating a sinusoidal movement, also is necessarily a greater flexibility and adaptability to the environment required and friction conditions.

9. FUTURE WORK

In the power supply of the robot it is suggested to connect each of the servomotors not to an external source but to a Li-Po battery so that it can travel a longer distance and be independent of the system.

For the Snake motion, it is suggested to rethink some of the mathematical expression parameters found in order to be able to improve the fluidity and representation of the expected sine wave.

Further research, it is suggested to reuse the mathematical expression proposed using a different number of servomotors so that the movement of the same is more faithful to the theoretical one.

Also for the interpretation of the movement it is suggested to represent the movements of the sine wave by fragments, that is to say to make groups of consecutive servomotors that represent the beginning, intermediate and final part of the wave assigning a different number of servomotors in each case to observe how this influences in the behaviour of the same one

REFERENCES

- [1] C. Wright et al., "Design and architecture of the unified modular snake robot," 2012 IEEE International Conference on Robotics and Automation, Saint Paul, MN, USA, 2012, pp. 4347-4354, doi: 10.1109/ICRA.2012.6225255.
- [2] Sugita, Saori et al. A study on the mechanism and locomotion strategy for new snake-like robot active cord mechanism slime model 1 acm-sl. Journal of Robotics and Mechatronics. (2008). 20. 302-310. 10.20965/jrm.2008.p0302.
- [3] H. Yamada and S. Hirose, "Study of a 2-DOF joint for the small Active Cord Mechanism," 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, 2009, pp. 3827-3832, doi: 10.1109/ROBOT.2009.5152837.
- [4] Gong, Chaohui & Travers, Matthew & Astley, Henry & Li, Lu & Mendelson III, Joseph & Goldman, Daniel & Choset, Howie. (2015). Kinematic gait synthesis for snake robots. The International Journal of Robotics Research. 35. 10.1177/0278364915593793.
- [5] Transeth, Aksel & Pettersen, K.Y.. (2006). Developments in Snake Robot Modeling and Locomotion. 9th International Conference on Control, Automation, Robotics and Vision, 2006, ICARCV '06. 1-8. 10.1109/ICARCV.2006.345142.
- [6] P. Liljeback, K. Y. Pettersen, Ø. Stavdahl and J. T. Gravdahl, "Hybrid Modelling and Control of Obstacle-Aided Snake Robot Locomotion," in IEEE Transactions on Robotics, vol. 26, no. 5, pp. 781-799, Oct. 2010, doi: 10.1109/TRO.2010.2056211.
- [7] J.S. Gray. *The Mechanism of Locomotion in Snakes*. Journal of Experimental Biology, vol. 23, 1946.
- [8] K.J. Kyriakopoulos, G. Migadis and K. Sarrigeorgides. The NTUA Snake: Design, Planar Kinematics, and Motion Planning. Journal of Robotic Systems, vol. 16, 1999
- [9] Hopkins JK, Spranklin BW, Gupta SK. A survey of snake-inspired robot designs. Bioinspir Biomim. 2009 Jun;4(2):021001. doi: 10.1088/1748-3182/4/2/021001. Epub 2009 Jan 22. PMID: 19158415.
- [10] K.D. Kotay and D.L. Rus. *The Inchworm Robot: A Multi-Functional System*. Autonomous Robots, vol. 8, 2000
- [11] Gómez, D. A. (s). *Progression of electronic and communication system for motion control of modular snake-like-robots*; Source: <http://hdl.handle.net/20.500.12495/5365>.
- [12] Zhang, P.; Zang, Y.; Guan, B.; Wu, Z.; Gao, Z. *Analysis and Optimization Based on Factors Affecting the Spiral Climbing Locomotion of Snake-like Robot*. Electronics 2022, 11, 4002. <https://doi.org/10.3390/electronics11234002>
- [13] Wang, K.; Gao, W.; Ma, S. *Snake-Like Robot with Fusion Gait for High Environmental Adaptability: Design, Modeling, and Experiment*. Appl. Sci. 2017, 7, 1133. <https://doi.org/10.3390/app7111133>
- [14] Du, Z., Fang, H. & Xu, J. *Snake-worm: A Bi-modal Locomotion Robot*. J Bionic Eng 19, 1272–1287 (2022). <https://doi.org/10.1007/s42235-022-00197-x>
- [15] Z. Bing, L. Cheng, K. Huang and A. Knoll, "Simulation to Real: Learning Energy-Efficient Slithering Gaits for a Snake-Like Robot," in IEEE Robotics & Automation Magazine, vol. 29, no. 4, pp. 92-103, Dec. 2022, doi: 10.1109/MRA.2022.3204237.