EE599 Final Report

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***Abstract*—This paper presents the design, implementation, and evaluation of a novel snake-like robot capable of navigating through various terrains, with a particular focus on its ability to climb slopes. The robot's design incorporates unique scale-like structures to enhance its climbing efficiency. A series of experiments were conducted to test the robot's performance on different slope angles, analyzing the impact of factors such as swing amplitude, twisting frequency, and body design on its mobility. The results indicate that while the robot exhibits competent maneuverability on flat surfaces, its performance on inclined planes is hindered by certain design limitations. These findings provide valuable insights into the challenges of robotic locomotion in complex environments, highlighting areas for future improvement and potential applications in real-world scenarios. This study contributes to the ongoing research in robotic mobility, offering a foundation for developing more versatile and efficient robotic systems.**

Keywords: Snake robot, scale-like structures, slope climbing, obstacles

I. Introduction

In the field of robotics, mimicking the movement mechanisms of natural creatures has always been a captivating area of research, with snake-like robots, in particular, drawing significant attention. Our team has chosen the inclined obstacle terrain as our environment of focus, specifically investigating the climbing capabilities of scale-covered, snake-like robots on slopes with obstacles. Our study aims to explore the impact of scale structure and snake-like robot movement patterns on their ability to navigate such challenging terrains.

Recent research on snake-like robots, such as that by Changlong Ye and others[1], has primarily focused on the robots' turning and side motions, significantly advancing our understanding of their control and maneuverability. However, these studies reveal gaps in their application in more dynamic and unstructured environments, like slopes with obstacles, which are crucial for real-world applications such as rescue operations. Our research aims to fill these gaps by delving into the climbing abilities of scale-covered snake-like robots in inclined obstacle environments. We intend to investigate the impact of scale structure and movement patterns on their climbing efficiency, thereby extending the current understanding of snake-like robotic movement and its practical implications.

Additionally, we have evaluated literature on the modeling and path planning of snake robots in complex environments[2-5]. These studies underscore the importance of motion models and path planning for robots in cluttered, obstacle-rich environments. However, they do not fully address the specific challenges associated with varying terrain types, such as slopes with obstacles. Our study seeks to bridge this gap by focusing on the climbing ability of scale-covered snake-like robots on slopes with obstacles. We aim to extend the principles of path planning and obstacle interaction, as discussed in Singh's work[4], to the unique challenges presented by sloped terrains, thereby enhancing our understanding of snake-like robotic movement in more diverse and demanding environments.

We also read a research about scale design[6], which is valuable to our project on snake-like robots traversing inclined terrains with obstacles. It highlights the significance of scale placement and geometry for effective movement, offering insights for designing our robot's scales. However, the study doesn't directly address the unique challenges of navigating diverse obstacles on slopes. Additionally, it may not encompass the dynamic factors of varying slopes and obstacle characteristics, which are crucial elements of our project. Bridging these gaps is essential for advancing the understanding and capabilities of our snake-like robots in complex inclined environments.

Based on the advancements and gaps identified in the literature on snake-like robotics, particularly in terms of maneuverability and adaptability in complex terrains, our hypothesis is as follows- The integration of specially designed scale structures on snake-like robots, combined with optimized movement patterns, will significantly enhance their climbing efficiency and stability on slopes with obstacles. This hypothesis is grounded in the understanding that the physical attributes of snake-like robots, such as scale structures, play a crucial role in their interaction with various surfaces and obstacles. While existing studies have advanced our understanding of snake-like robot movement in controlled environments, they have not extensively explored the impact of scale structures in unstructured environments like sloped terrains with obstacles. Our hypothesis is testable through a series of experiments where we can compare the performance of scale-covered snake-like robots with different scale designs and movement patterns on slopes with various obstacles. The outcomes of these tests should reveal whether the specific scale designs and movement patterns employed lead to improved climbing ability, as measured by factors like speed, stability, energy efficiency, and adaptability to different obstacle types.

Our team chose the Inclined obstacle terrain traversal as our environment. Our team is researching the climbing ability of scale-covered snake-like robots on slopes with obstacles, attempting to explore the impact of scale structure and snake-like robot movement patterns on their ability to climb slopes with obstacles.

Given the advancements and gaps identified in the literature on snake-like robotics, particularly in the context of maneuverability and adaptability in complex terrains, our hypothesis is as follows:

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II. EXPERIMENT PLAN

A. Robot Design

The morphology of our robot is a snake robot. The snake robot is mainly made of four links, four servo-motors, and a micro-controller Arduino Uno board. The initial unit design of the robot is presented in Figure 1. In the picture, in each unit structure of the snake, we put a XL-320 servo motor inside, and attach a number of scales on both sides, and each scale has a certain angle between the body and a spring is connected. The motor also serves as a joint to connect the units.

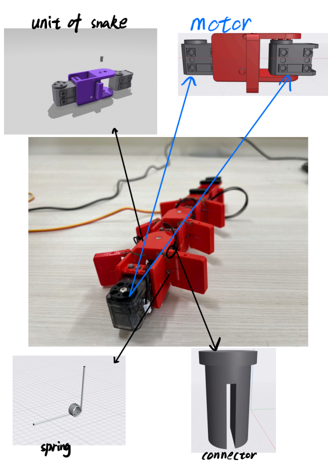

Fig. 1: The structure of Snake Robot part1

Figure 2 shows the components of scale structure. We use a fabric to play a role as a stopper to limit the maximum angle that the scale can be opened.

In Figure 3, when the snake is moving forward, if the scales meet an obstacle and are squeezed,the spring will be compressed causing the scales to contract to the sides of the body, and the θ will decrease, and when the snake hits an obstacle and cannot move forward, some of its scales will hang on the obstacles, and the θ will increase, preventing the snake from sliding down the slope. In order to prevent the θ from exceeding 90 degrees and not being able to catch the obstacles, we added a non-slip device(stopper) to the front of each scale to control the maximum θ value from exceeding a certain angle(e.g. 90 degrees).

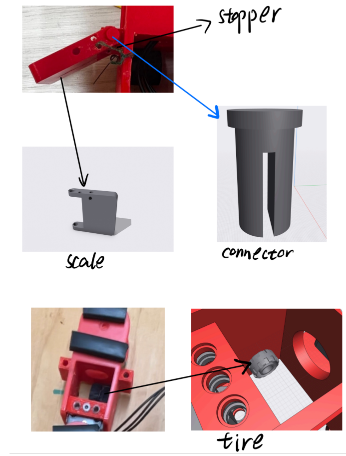

Fig. 2: The structure of Snake Robot part2

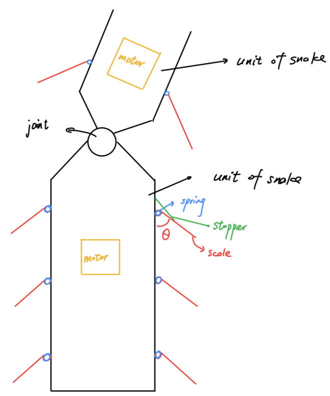

Fig. 3: The diagram of Snake Robot

We chose this morphology because snakes also use their scales in nature to help them climb and move forward. Moreover, through this morphological design, we can also study the influence of θ changes on adaptability and efficiency.

B. Experiment setup and parameter variation

Our research topic is to explore the impact of the snake robot's scale angle on its adaptability and energy efficiency

Assumption

Our team assume that:

1) the length of the snake l
2) the mass of the snake robot m
3) the total number of the scales n
4) the interval distance between adjacent scales d
5) the vertical distance of start and goal position h
6) the number of motors in the snake robot N

are constants.

The Dominance (Effect) of the snake scale angle

During the former experiments in Lab 3, the snake robots can move forward well on the flat ground. (slope = 0). However, when moving on the slope containing obstacles, the snake robot is too “slippery”, which means that the fraction of the robot cannot hold the entire robot body in a fixed position. Thus, snake “skin” structure, scales are necessary to create a fixed point to hold the robot body and to let the robot climb up to the goal position.

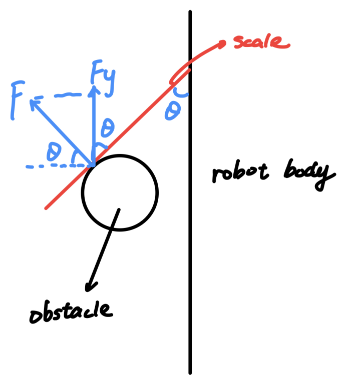

Fig. 4: Force Analysis of the single Scale

During the force analysis, according to the Fig. 2, we can have the following equation:

$$nFsin\theta = mg \tag{1}$$

$$F = \frac{mg}{nsin\theta} \tag{2}$$

indicates that n is the number of scales, m is the mass of the robot and θ is the scale angle. Equation (2) shows that with the increasing of the scale angle, the force that scale and obstacle needs to provide (F) is decreasing and the total robot are more likely to achieve the goal position. Based on the equation, it seems that the optimal angle need to be 90 degrees.

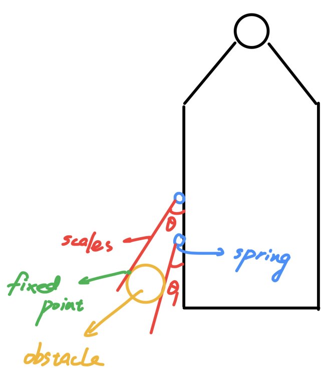

Fig. 5: Possible Moving Condition of Snake Robot

However, the angle value cannot be too large. According to Fig. 3 When the scales touch with the obstacles, the angle will be forced to decrease. Due to the fact that the value of angle θ is determined by spring, when the angle decreases, the motor needs to distribute more energy in the shrinking spring process. Thus, in this process, with a large angle value, extra energy will be distributed to deal with the scales instead of total body’s movement and the efficiency will probably decrease.

In conclusion, we assume the value of scale angle θ would dominate the locomotion of snake robot. When the θ was too small to offer force to against the gravity, the robot would likely have greater twisting amplitude to find more obstacles for support with scales at same time. On the contrary, the larger θ would result in fewer fixed points needed by snake for climbing.

Initial Experiment Design

Based on the hypothesis that the scale can significant improve the performance of snake climbing on slopes with obstacles. As the goal of our research, we want to investigate the value of scale angle θ. In order to achieve this, we design our plans with two steps. The first step is to obtain the relationship between the snake gait and the moving velocity. The second step is to find the relationship between Different Scale Angles and Efficiency and Adaptability.

A. *First Step* In this step, we consider the relationship between the swing amplitude and moving velocity of snake robot. We design to put the snake robot without scales on the flat with different amplitude settings. The amplitude angle is from 30° to 80°. In order to more intuitively reflect the speed of the snake robot crawling forward under different swing amplitudes, we stipulate that all tests are to let the robot crawl forward 10cm and then measure the time it takes for the robot to reach the specified distance.

TABLE I: Analysis of Swing Amplitude

Swing Amplitude (°)	30	40	50	60	70	80
Time(second)						

B. *Second Step* In this step, we design to hold two experiments. First, consider the connection between adaptability and scale angle. Due to the condition of the slope with random obstacles, it means that the the robot with specific scale angle will reach the high level of adaptability if the robot reach the goal position. In details, We will increase the value of θ slowly from 0 to 90 degree to find the range of the angle that can let the entire robot reach the goal position. The table of the result is presented in following table.

TABLE II: Climbing Experiment 1(Angle of Slope γ = 30°, 60°, 90°)

θ (°)	0	10	20	30	40	50	60	70	80	90
Height										

Based on the following table, In the ”Height” column, it will show the actual height of the snake robot can reach. If Height = h (the vertical distance of start and goal position), we can conclude that based on this scale angle, the robot has achieved adaptability performance goal.

C. Furthermore, consider the relationship between the efficiency η and scale angle θ. Based on the above experiment, the scale angle will be taken from the interval that satisfies the snake robot to reach the goal position. Assuming that based on the specific slope angle γ_0, the range will be $[\theta_{min}, \theta_{max}]$. Our teams will scan this range and find out the pattern between robot efficiency η and scale angle θ. The theoretical table has been presented as follow.

TABLE III: Relationship Between η and Scale Angle θ

$\theta(°)$	θ_{min}	$\theta_{\text{min}} + \delta_0$	$\theta_{\text{min}} + 2\delta_0$	...	θ_{max}
Efficiency (η)					

δ is the sampling interval and it is a constant. To figure out the efficiency, first the system needs to lift the robot from initial position to the goal position vertically. In this process, the necessary mechanical work is:

$$W_{need} = mgh \tag{3}$$

m is the mass of snake robot, h is the vertical distance between the start position and goal position. g is the gravitational acceleration.

Assuming that each motor's output power (P) will be a constant and the time the root takes to reach the goal position will be t. Therefore, the total mechanical work that the motors generate will be:

$$W_{total} = NPt \tag{4}$$

Thus, the efficiency (η) will be

$$\eta = \frac{W_{need}}{W_{total}} = \frac{mgh}{NPt} \tag{5}$$

While the time used to reach the goal position longer, the lower efficiency of the robot will get. By measuring time t, we can roughly calculated the current efficiency the robot obtains.

In conclusion, the adaptability can be measured by the result if the snake robot can reach the goal position or not. The efficiency can be measured by the time which the robot takes from the start position to the goal position.

We expected after above experiments, we would get the results that show snake like robot's moving velocity increasing with the swing amplitude growing up and will reach a peak at a specific amplitude then go down. Also, the larger maximum angle of scale would result in the higher place the snake can reach and the higher efficiency the robot can obtain.

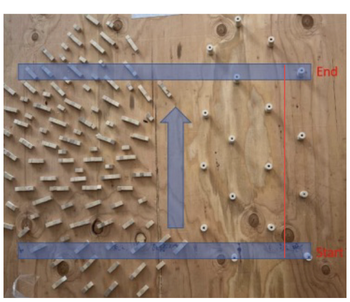

Fig. 6: Experiment environment

We hold our climbing experiment on the right side of the board in Figure 5. In order to ensure that the obstacles encountered in each experiment are the same as much as possible, we set the robot at the starting point of the blue horizontal line at the bottom aligned with the red vertical line during the experiment.

Extra Experiment Design

Through the the initial experiment we designed, we found some unexpected results and issues worthy of research. Hence we designed extra experiments to explain them.

Unexpected results:

1. In the analysis of swing amplitude, we found out that when the amplitude beyond 60°, the snake robot's locomotion showed a trend of changing moving direction, which means it may spend more time in getting same forward distance.

2. Nevertheless, we also noticed the snake slides when it is moving on the flat. Since the gravity was not pulling the snake down, just like it did when the snake was on slope. Our team realized that there is more potential parameters that affecting the friction between snake robot and slope.

3. Based on the experiment we held on slope, the snake showed obvious friction lacking on the slope. The scale structure did not perform expected function that help snake robot overcome lack of friction on slope and climb up continuously.

4. The scale sometimes could not be squeezed and be a obstacle preventing the snake robot moving forward.

The more detailed results will be discussed in next section.

Based on above unexpected results, we designed other experiments to figure out the reasons and potential parameters:

D. To detect the turning direction pattern, we change the constant from -20 to 20. Here is the equation that we used for developing algorithm for snake locomotion.

$$\beta_i = \beta_0 sin(2\pi i/N - 2\pi f t) + c \tag{6}$$

β_i indicates the instant angle for motor i. β_0 indicates the maximum instant angle that each motor can reach. N indicates the number of motors we use in the experiment and f is the frequency of each motor's turning. Thus, by adding a constant offset c in each of motor's instant angle, we are testing the relationship between the snake turning and the value of c.

TABLE IV: Analysis of Turning Pattern By Changing Offset

constant offset (°)	-20	-10	0	10	20
Turning Pattern					

E. We assumed that the twisting frequency also make a role in the moving performance of snake robot, which may affect the friction between snake robot and ground. We used the algorithm as follow to control the twisting frequency.

```
for(float i = 0; i <= 10; i += 0.01){
}
```

our team developed an experiment that set the forward target distance of the robot to 10cm and obtain the time required for different i-value intervals.

TABLE V: Analysis of Different Sampling Interval With 10cm Moving Distance

Sampling Interval(Δi)	0.1	0.05	0.025	0.01
Time(second)				

III. Result and Discussion

A. Results Corresponding to Snake Locomotion

Swing Amplitude

First, we hold our experiments on the flat ground to exclude the influence of gravity. The results are as follows. α indicates the swing amplitude.

TABLE VI: Analysis of Swing Amplitude

Swing Amplitude (°)	30	40	50	60	70	80
Time(second)	12.5	8.7	5.3	3.8	4.9	5.7

According to the former table, when the swing amplitude is increasing from 30° to 60°, the moving velocity of the snake robot is increasing significantly. However, when the amplitude over 60°, with continuous increase, the moving velocity is decreasing. After carefully evaluating the moving locomotion, our team found out that when the amplitude beyond 60°, the snake tends to change its moving direction, which means that it may spend more time in getting same forward distance.

Turning Direction

TABLE VII: Analysis of Turning Pattern By Changing Offset

constant offset (°)	-20	-10	0	10	20
Turning Pattern	CCW	CCW	Move Forward	CW	CW

CCW indicates counter-clockwise turning and CW indicates clock-wise turning. Based on the analysis table, we can conclude that when the constant offset c is negative, the snake tends to do counter-clockwise turning and when c is positive, the snake tends to do the clock-wise turning. Therefore, the turning problem shown in the former swing amplitude evaluation can be solved by adding a relatively small value of constant offset.

Twist Frequency

TABLE VIII: Time Analysis of Different Sampling Interval With 10cm Moving Distance

Sampling Interval(Δi)	0.1	0.05	0.025	0.01
Time(second)	3.8	3.3	2.6	2.1

According to the given result table, we can conclude that with the range of sampling interval from 0.01 to 0.1, with the decreasing of sampling interval, the velocity of the snake robot will increase.

B. Climbing Result

D indicates the distance between the point that the snake can get and the start position (unit is centimeter) and θ indicates the scale angle. The distance between the start and goal position is about 65cm.

TABLE IX: Climbing Experiment 1(Angle of Slope γ = 0°, 10°, 20°, 30°)

D(cm) θ(°) / γ(°)	0	10	20	30	40	50	60	70	80	90
0	65	65	65	65	65	65	65	65	65	65
10	0	1.2	3.4	2.7	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0

Based on the former robot, we initially tested the climbing ability of the snake robot. We conducted a series of slope crawling tests based on different slope angles (γ = 0°, 10°, 20°, 30°). When testing on the flat ground (γ = 0°), the snake could obviously move to the goal position successfully with suitable settings. Unfortunately, the snake robot we have designed performed far from expectation when γ = 10°. When γ was greater than 10°, the robot could not climb from the start position to the goal position successfully. Compared with the hypothesis before, we got unexpected results that the scale structure could not always grab the obstacles to be a fixed point which was supported to hold the snake to climb. The scale can not fold while squeezed well by the obstacles that disturb the snake from moving forward. It may suggest we need to consider the strength of strings, structures of scales or the locomotion like different settings of amplitude. Another unexpected result was that the snake robot could easily slide down on slope with small degrees. This result suggests the lack of fraction between the robot and slope or the robot need to grab more obstacles at one time. On the other side, there were some positive and interesting results, sometimes the scales could grab obstacles and help the snake robot to climb, which suggests that the scales did its expected function that offer a fixed point for climbing in optimized situation. In order to better understand measurement and results, we did the following analysis of the performance on flat and 10-degree slopes of the robot.

After careful consideration, our team realized that stiffness coefficient of the springs we used may too large to hind the snake body from climbing up. Considering the fatigue performance on a 10 ° slope, we refined the angle variation to attempt experiments on lower slopes. Thus, after changing the springs, we did the experiment again. Here is our final results for snake climbing.

TABLE X: Climbing Experiment 2(Angle of Slope γ = 0°, 10°, 20°, 30°)

D(cm) θ(°) / γ(°)	0	10	20	30	40	50	60	70	80	90
0	65	65	65	65	65	65	65	65	65	65
5	10	13	25	16	15	15	16	9.6	9	10
10	0	1.8	4	2	1	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0

The diagram above shows that, up to 5 degrees, snake robot can do climbing process. However, beyond 5 degrees, the performance of snake deteriorates significantly. Therefore, 5 degrees may be the upper bound of slope angle that our snake robots can tolerate.

Besides, based on the 5-degree slope, when the scale angle increases from 0 to 20, the distance also increases correspondingly. It means that in this range of scale angle, the scale help the snake body climb forward. However, beyond 20 degrees, with the increasing of the scale angle, the climbing distance of the snake decreases considerably, which means that the scales may hinder the snake body from climbing up. The possible reason for this situation is when the angle is increasing, the snake need to distribute more energy to the spring potential energy, which is far from our expectation.

C. *Efficiency Analysis*

In our experimental study, a significant challenge was encountered with the snake-like robot's lack of sufficient friction while maneuvering on slopes, hindering its ability to reach the goal position effectively. The robot's performance on inclines was nearly negligible, with an inclination angle close to zero degrees. Consequently, in our efficiency formula,

$$h = l \sin\theta \tag{7}$$

where θ = 5°, the resulting value of sin5° is approximately zero, leading to a minimal 'h' value. This small value made it impractical to differentiate and compare the efficiency of different scale angles as originally planned in our experimental design. Therefore, the planned experiment to calculate and compare the efficiency of various scale angles was ultimately not conducted. Instead, we resorted to using a height comparison experiment to observe the performance of the snake-like robot under different scale angles. This approach allowed us to assess the robot's climbing capabilities, albeit in a more limited scope than initially intended. The findings underscore the critical need for optimizing friction in snake-like robotic designs, especially for tasks involving inclined surfaces. Future research should focus on enhancing the traction capabilities of these robots to enable more comprehensive and conclusive efficiency evaluations.

D. *Discussion*

The findings suggest a need to revisit the robots' design specifications. The unexpectedly high elastic force of the spring mechanism caused the unstable performance of scales. It may require an adjustable mechanical design of scale with spring or spring constant. Nevertheless, defective design of scale and the lack of friction between the snake robot and the slope both contribute to the poor performance of climbing on the slope of snake robot resulted in the big difference between experimental results and hypothesis. The lack of fraction may due to the tires, their size are so small that can not offer enough horizontal fraction when snake was climbing. Also, the results shows that the imitation of lateral body movement of snake is far from enough to achieve the slope climbing task. We may need introduce the muscle contraction of snake to offer more more diverse gaits, and the scale structure on the ventral side which help grip the surface and produce high friction.

The newly acquired knowledge from the robotic design challenges underscores critical insights into three main areas: 1. Material and Design Adaptability: The unanticipated high elastic force of the spring mechanism suggests that materials and designs need to be more adaptable to variable stresses encountered in diverse terrains. 2. Traction Optimization: The insufficient friction of the wheels has highlighted the importance of optimizing tread patterns and possibly incorporating adhesive materials for enhanced traction, especially when increasing the robot's weight is not a viable solution. 3. Precise Movement Control: The deviation in the robot's movement trajectory due to servo control parameters indicates a need for highly precise movement algorithms that can dynamically adjust to maintain the desired path, emphasizing the complexity of kinematic control in robotic systems. These findings are pivotal for advancing robotic mobility and stability in complex environments, providing a foundation for designing more resilient and efficient robots.

Based on the above findings, we could reduce the influence of the lack of friction, which is a congestive defects for snake robots on climbing tasks. It helps us to have a better experimental condition for a suitable scale angle.

To evaluate the relationship among swing amplitude, twisting frequency, constant offset and robot velocity, our team can determine a relatively optimal locomotion, which help us to have better research on the relationship between scale and climbing efficiency of snake robots on a slope with obstacles.

IV. Conclusion

In this paper, our research goal is to design a snake-like robot with scales with optimized movement patterns that can climb slopes with obstacles. According to the whole research, our team find out that only implementation of snake-scale structure cannot be meet the need of snake climbing movements and more detailed snake locomotion, such as swing amplitude, twist frequency and turning pattern. For the realization of the snake-shaped robot's climbing task, future design directions may need to consider and incorporate more bionic designs about snakes (such as the contraction of snake scales and muscle movement in the abdomen) to achieve our experimental purposes.

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