iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: III Month of publication: March 2025

DOI: https://doi.org/10.22214/ijraset.2025.67434

www.ijraset.com

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue III Mar 2025- Available at www.ijraset.com

Robotic Snake Locomotion

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Abstract: This research explores the development of a robotic snake designed with a PVC structure, secured with screws, and powered by MG995 servo motors for enhanced flexibility. The robot is controlled using an ESP32 microcontroller, which integrates various sensors, including an ultrasonic sensor, motion sensor, temperature sensor, and a camera module, enabling real-time data collection and environmental awareness. The primary objective of this project is to overcome challenges in navigating complex terrains, where conventional robots often struggle due to their rigid structures. The snake-like design allows for smooth maneuvering through tight spaces and uneven surfaces, making it well-suited for applications such as search and rescue missions, pipeline inspections, and environmental monitoring.

The project emphasizes efficient locomotion through a strategic combination of hardware and algorithmic control. MG995 servo motors provide precise movement for the robot's segments, while the ESP32 facilitates seamless sensor integration and communication. The onboard sensors deliver critical data on obstacles, temperature fluctuations, and real-time video feedback, improving the robot's adaptability across different environments.

Key findings highlight that this flexible, multi-segmented design significantly enhances maneuverability and energy efficiency compared to traditional wheeled robots. Furthermore, the modular structure allows for easy maintenance and scalability. This robotic snake presents a practical solution for real-world challenges requiring navigation in restricted or hazardous environments.

Keywords: Robotic SnakeESP32 Microcontroller, MG995 Servo Motor, Undulatory Movement, Obstacle Detection, Battery Management System (BMS), Search and Rescue, Pipeline Inspection

LIST OF ABBREVIATIONS

BMS	Battery Management System
PVC	Polyvinyl chloride
USB-C	Universal Serial Bus C
V	Voltage
SoC	System on Chip
IOT	Internet Of Things

I. INTRODUCTION

Robotics has made significant strides, particularly in navigating complex environments. Traditional wheeled and legged robots, while effective on flat surfaces, face limitations in confined or irregular spaces [4, 2, 12, 13]. These challenges are particularly relevant in areas such as search and rescue, pipeline inspections, and hazardous material handling, where robots must maneuver through tight or cluttered spaces [4, 9]. The concept of a robotic snake offers a solution with its segmented, flexible design, allowing it to access areas that are typically inaccessible to conventional robots. Motion patterns of snakes, inchworms and caterpillars are used as an inspiration for how the snake robots should move [2].

Inspired by biological snakes, robotic snakes replicate their undulating movements, providing greater adaptability in uneven terrains [7]. However, the development of such robots involves overcoming challenges related to flexibility, stability, and energy efficiency, while ensuring precise control of each segment [12, 13]. Previous models often relied on basic hardware and lacked the precision needed for real-world applications, leading to inefficient movement and limited environmental awareness.

Fig 1.1 Snake Model

This project seeks to address these limitations by utilizing advanced components, including MG995 servo motors, an ESP32 microcontroller, and sensors such as ultrasonic, motion, temperature, and a camera module. These components allow for improved obstacle detection, real-time environmental monitoring, and better control. The MG995 motors offer high torque and precision, while the ESP32 microcontroller ensures efficient communication between the segments, significantly enhancing the robot's performance [13]. Additionally, the robot can be operated through a dedicated application, allowing remote control of its movement and functionality. This feature ensures that the robotic snake can be deployed in hazardous or hard-to-reach environments while being controlled safely from a distance [9]. there are still many challenges to face both on the modelling and control of snake robots in order to make them able to locomote intelligently through unknown terrain [2]

This project aims to enhance robotic performance in confined spaces, with potential applications in disaster relief and industrial inspections, where traditional robots often fall short.

II. OBJECTIVES

The primary objectives of the Robotic Snake project are as follows:

1) Design and Construction: Develop a robotic snake equipped with multiple servo motors to enable realistic lateral undulation. The design will emphasize compactness and lightweight construction, ensuring smooth functionality for slithering and motion [11]. Materials for the body will be selected to balance flexibility, strength, and durability. Each segment will house a servo motor, allowing for precise control of individual movements.
2) Control System Integration: Implement an ESP32 microcontroller to serve as the central control unit. ESP32 is powerful SoC (System on Chip) microcontroller with integrated Wi-Fi, dual mode Bluetooth version 4.2 and variety of other peripherals [5]. The ESP32 will process inputs from sensors and actuators, ensuring precise control of the robotic snake's movements. This system will enable seamless communication between sensors and servo motors for smooth operation.
3) Obstacle Detection: Integrate an ultrasonic sensor to autonomously detect and navigate obstacles. The robotic snake will halt after one complete undulation to measure the distance to nearby obstacles. If a clear path is detected, it will proceed forward. When an obstacle is too close, the robot will take additional measurements by rotating the sensor, reverse its movement, and turn in the direction of the clearer path [10].
4) Camera System: Incorporate a camera for real-time video feedback, assisting in navigation and task execution. The camera will provide live streaming of the surrounding environment, offering valuable data for both autonomous and manual control operations [10].
5) Movement Pattern Programming: Develop movement algorithms that simulate natural snake movements. The robotic snake will feature multiple movement modes, including U-bend and slithering, tailored for navigating different terrains.
6) Energy Optimization: Design the system for efficient power consumption, maximizing operational periods. Batteries will supply power to the servo motors, while a Battery Management System (BMS) will monitor charge levels and prevent overcharging or undercharging, ensuring long-term stability.
7) Remote Control: Enable manual control via a wireless interface for direct human oversight when necessary. This feature will provide users with an intuitive control interface, offering flexibility in issuing commands to the robotic snake.

8) Environmental Testing: Conduct rigorous testing in various environments to assess the robotic snake's capabilities and limitations. These tests will help evaluate its adaptability, reliability, and overall performance across diverse operational conditions.
9) Durability and Reliability: Ensure the robotic snake is built to endure environmental stresses and function reliably over extended periods. The construction will emphasize the use of lightweight, durable materials capable of withstanding impacts, abrasions, and environmental factors such as moisture and temperature fluctuations. The joints and segments will be designed for repetitive movements without degradation, and the electronic components will be protected from potential damage.
10) Exploration Capabilities: Design the robotic snake to explore environments that are inaccessible or dangerous for humans. Its flexible and advanced movement capabilities make it ideal for applications such as pipeline inspections, disaster recovery, and navigating confined spaces where traditional robots may fail [9, 10].

III. PROBLEM STATEMENT

The work proposed in this paper addresses the following issues:
1) Navigating Narrow and Confined Spaces: Traditional wheeled or legged robots struggle to navigate confined spaces like pipes or collapsed structures, limiting their utility in such environments [7,9].
2) Search and Rescue in Disaster Areas: Locating and rescuing trapped victims in disaster areas is challenging due to debris and unstable structures that hinder access [7]-[9].
3) Inspection and Maintenance of Industrial Pipelines: Inspecting and maintaining long, narrow industrial pipelines often require halting operations, which can be time-consuming and costly [9].
4) Environmental Monitoring in Hard-to-Reach Areas: Monitoring remote or difficult-to-access areas like forests or caves is inefficient with conventional robotic systems due to terrain challenges [9].
5) Difficulty in Traversing Rough or Uneven Terrain: Traditional robots face instability and reduced manoeuvrability on rough, uneven, or rocky surfaces, increasing the risk of mechanical failure.
6) Overheating of Motors and Sensors in Extreme Temperatures: Servo motors and sensors can overheat in extreme temperatures, leading to reduced performance or complete system shutdown [12].
7) Limited Battery Life in Prolonged Operations: Prolonged operations, especially in remote environments, can quickly drain the snake robot's battery, limiting its effectiveness.

IV. LITERATURE SURVEY

1) *Robotic modelling of snake traversing large, smooth obstacles reveals stability benefits of body compliance*

Snake robots are discussed for their potential in hazardous, narrow, and hard-to-reach environments, such as inspections, rescue missions, and firefighting. Unlike wheeled or legged robots, snake robots excel due to their superior terrain adaptability, mimicking biological snakes' movement.

Fu Q, Li C. 2020 Robotic modelling of snake traversing large, smooth obstacles reveals stability benefits of body compliance. R. Soc. open sci. 7: 191192.http://dx.doi.org/10.1098/rsos.191192

2) *Developments in Snake Robot Modeling and Locomotion*

This paper reviews the kinematics and dynamics modeling, mechanical design, and control approaches used to recreate snake-like locomotion. It also compares features of various snake robots and evaluates simulators for testing models and designs, providing insights for researchers new to the field [1]

Aksel Andreas Transeth and Kristin Ytterstad Pettersen Department of Engineering Cybernetics Norwegian University of Science and TechnologyO.S. Bragstadsplass 2D, NO-7491 Trondheim, Norway

3) *Motion Estimation of Snake Robots in Straight Pipes*

Snake robots, with their high terrain adaptability, redundancy, and potential for complete sealing, are poised to enhance search and rescue and firefighting operations. Despite a significant increase in literature over the past decade, there is a lack of comprehensive reviews on mathematical modeling and locomotion techniques for these robots. This paper aims to fill that gap by reviewing both kinematic and dynamic models and linking these methods to design characteristics and locomotion approaches. The study also explores various biologically inspired locomotion strategies.

Florian Enner, David Rollinson and Howie Choset "*Motion Estimation of Snake Robots in Straight Pipes*" 2013 IEEE International Conference on Robotics and Automation (ICRA) Karlsruhe, Germany, May 6-10, 2013

4) Flexible Snake Robot: Design and Implementation

Mazda Moattari and Mohammad Amin Bagherzadeh (2013) developed a flexible snake robot emphasizing adaptable locomotion for search-and-rescue missions. Their design focused on flexibility and precision to navigate complex terrains effectively. The research contributes to improving robotic agility, enhancing practical applications in challenging environments.

Mazda Moattari, Mohammad Amin Bagherzadeh "Flexible snake robot: Design and implementation" Conference: AI & Robotics and 5th RoboCup Iran Open International Symposium (RIOS), April 2013

5) Using the ESP32 Microcontroller for Data Processing

Marek Babiuch et al. (2019) showcased the ESP32 microcontroller's capabilities for efficient data processing, highlighting its dual-core performance and wireless connectivity. The study demonstrated ESP32's application in robotics and IoT, focusing on real-time control and sensor integration for advanced automation systems.

Marek Babiuch, Petr Foltynek and Pavel Smutny "Using the ESP32 Microcontroller for Data Processing" Conference: 2019 20th International Carpathian Control Conference (ICCC). May 2019

6) The Research on Remote Control Robot Snake Driving by Servo

Tianlin Song et al. analyzed servo motor-driven robotic snake locomotion, focusing on precise movement control. Their study highlighted remote-control techniques and terrain adaptability, addressing challenges in creating smooth, biologically inspired movements for navigation in hazardous areas.

Tianlin Songa, Ling Zao a, Xuanxuan Shen a "The Research on Remote Control Robot Snake Driving by Servo", Soochow University, Suzhou 215006, China

7) Kinematics of Terrestrial Snake Locomotion

Bruce Jayne (1986) detailed terrestrial snake locomotion kinematics, analyzing movement modes like lateral undulation and concertina. This foundational work informs biomimetic robotic designs by explaining the mechanics behind natural snake movements and their adaptability to various terrains.

Jayne, Bruce. (1986). Kinematics of Terrestrial Snake Locomotion. Copeia. 1986. 10.2307/1445288.

8) Ground Condition Sensing of a Snake-like Robot

Yang Lu et al. (2003) developed terrain sensing capabilities for snake robots, enabling real-time adaptation to variable ground conditions. Their research improved stability and efficiency, making the robots suitable for dynamic, unpredictable environments.

Yang Lu, Shugen Ma, Bin Li and Li Chen, "Ground condition sensing of a snake-like robot," IEEE International Conference on Robotics, Intelligent Systems and Signal Processing, 2003. Proceedings. 2003, Changsha, Hunan, China, 2003, pp. 1075-1080 vol.2, doi: 10.1109/RISSP.2003.1285739.

9) Research of Insertion Mechanism of Flexible Search and Rescue Robot

Shen Linyong et al. (2015) introduced a flexible insertion mechanism for robots navigating confined spaces. Their work focused on structural adaptability and stability, enhancing robotic performance in narrow and irregular environments during rescue missions.

Shen, Linyong & Zhu, Qian & Qiu, Ya & Cao, Yuanfei & Ding, Hang. (2015). Research of Insertion Mechanism of Flexible Search and Rescue Robot. MATEC Web of Conferences. 22. 03020. 10.1051/matecconf/20152203020.

10) A Snake-like Robot for Real-world Inspection Applications

Hiroya Yamada et al. (2013) designed a snake robot with enhanced mobility for industrial inspections. Their research focused on control mechanisms, improving access to hard-to-reach areas and ensuring efficiency in hazardous operational environments.

Yamada, Hiroya & Takaoka, Shunichi & Hirose, Shigeo. (2013). A snake-like robot for real-world inspection applications (the design and control of a practical active cord mechanism). Advanced Robotics. 27. 47-60. 10.1080/01691864.2013.752318.

11) Adaptive Snake Robot Locomotion: A Benchmarking Facility for Experiments

Fjerdingen et al. (2008) developed a benchmarking facility to evaluate snake robot locomotion strategies. The study provided insights into adaptive movement across varied terrains, emphasizing experimental validation for optimizing robotic performance.

Fjerdingen, S.A., Mathiassen, J.R., Schumann-Olsen, H., Kyrkjebø, E. (2008). Adaptive Snake Robot Locomotion: A Benchmarking Facility for Experiments. In: Bruyninckx, H., Přeučil, L., Kulich, M. (eds) European Robotics Symposium 2008. Springer Tracts in Advanced Robotics, vol 44. Springer, Berlin, Heidelberg.

12) Snake Robot with Motion Based on Shape Memory Alloy Spring-Shaped Actuators

R. Cortez et al. (2024) proposed a snake robot utilizing shape memory alloy actuators for smooth, flexible motion. The study highlighted energy-efficient, biomimetic locomotion, demonstrating the potential of SMA-based designs in compact robotic applications.

Cortez, R., Sandoval-Chileño, M. A., Lozada-Castillo, N., & Luviano-Juárez, A. (2024). Snake Robot with Motion Based on Shape Memory Alloy Spring-Shaped Actuators. Biomimetics, 9(3), 180. 0

13) Locomotion Control of a Rigid-soft Coupled Snake Robot in Multiple Environments

Xuanyi Zhou et al. (2024) presented a hybrid snake robot integrating rigid and soft segments for versatile locomotion. Their work focused on control algorithms for seamless environmental transitions, improving adaptability and stability in mixed terrains.

Xuanyi Zhou, Yuqiu Zhang, Zhiwei Qiu, Zhecheng Shan, Shibo Cai, Guanjun Bao, Locomotion control of a rigid-soft coupled snake robot in multiple environments, Biomimetic Intelligence and Robotics, Volume 4, Issue 2, 2024, 100148,

V. DESIGN OVERVIEW

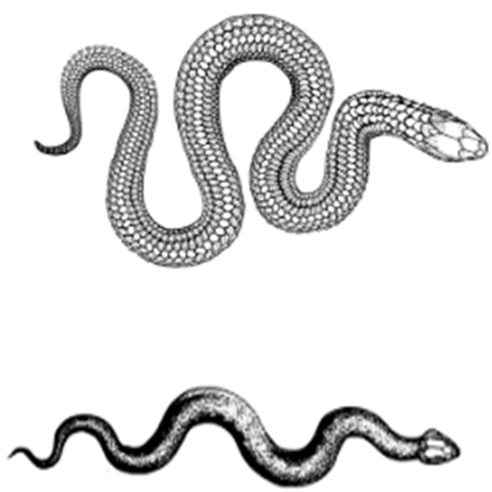

Fig 5.1 Snake Motion (Serpentine, Concertina)

The robotic snake is designed using a series of servo motors connected through PVC pipe segments to simulate the flexible motion of a real snake [12]. The structure consists of multiple articulated joints, each driven by an independent servo motor, allowing the robot to perform complex undulatory motions. PVC was chosen for their lightweight and durable properties, providing a sturdy yet flexible framework for the motors. The servo motors are controlled via a microcontroller i.e. ESP 32 enabling precise movement of each joint, which allows the snake to navigate complex terrains and replicate the natural slithering movement. They are all connected through jumper wires for communication of data. The batteries are connected in series-parallel; we have used this to get the benefit of both

1) The voltage is increased by the series connection.
2) The current capacity is increased by the parallel connection.

Use of a buck and boost convertor are used to form a battery management system for precise monitoring of the batteries in case of overcharging or undercharging. Various fasteners such as screws and bolts are utilized to securely connect each servo motor, forming a snake-like body structure. The modular design enables easy adjustment of the length by adding or removing segments. The robotic snake's design emphasizes simplicity and efficiency, making it a versatile platform for exploration in areas like search-and-rescue operations or hazardous environment monitoring.

VI. PROPOSED SYSTEM

The proposed system is a i.e. Robotic Snake designed to mimic the movement and behavior of real snakes using a series of servo motors connected via brackets made via PVC [12]. This robotic snake is intended to demonstrate efficient locomotion in confined spaces or difficult terrains. It can be used in various applications such as search-and-rescue missions, pipeline inspections, or educational purposes. The design used is unique and lightweight for easy movement of the body. It is equipped with a series of modules and sensors that allow it to move and interact with its environment in a controlled manner.

A. *System Components*

1) *Mechanical Structure:* The main body of the robot is constructed using the material-PVC, which act as segments of the snake. They are lightweight, durable, and easy to connect. They are connected to each other via screws and bolts [12].
2) *Servo Motors:* Servo is more appropriate considering structure, size, weight, cost, control and other factors [6]. Each segment of the robotic snake is equipped with a servo motor to control its motion. The servos are placed strategically to enable smooth, snake-like movement, including slithering and U-Bend.
3) *Microcontroller:* A central microcontroller i.e. ESP 32, controls the servo motors and manages the snake's movement patterns. It processes input signals from the sensors or user and translates them into specific movements for each segment.
4) *Power Supply:* The system is powered by a battery pack that supplies the necessary voltage to the servo motors and the microcontroller. The battery is connected, controlled and monitored by BMS (battery management system)
5) *Control Interface:* A remote control or software interface allows users to command the snake's movement.

B. *Functionality*

The robotic snake will be capable of performing various types of movements including:
1) Lateral undulation**:** Mimicking the natural wave-like movement of snakes.
2) U- bend: flexible, curved section where the segments or joints form a smooth arc, allowing the snake to turn or coil in a U-shape.

VII. ELECTRONIC COMPONENT USED

The Snake Locomotion is a concept that need to be made properly for a smooth motion like a real snake in a natural way, to do this it needs a lot of components work together in parallel and in coordination to make it possible for the robot to move in the specific direction. The components that we used to make this happen are:

Fig 7.1 MG995 Servo

1) *Servo Motor:* The MG995 is a high-torque, digital servo motor known for its precision and reliability. It is ideal for robotics applications where precise angular movement is required. In your robotic snake, these servos are used to control the snake's body segments, allowing smooth and controlled motion. Their high torque enables them to handle the load of the snake's structure, while their digital control ensures precise positioning.

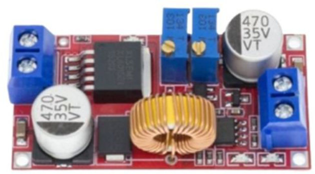

Fig 7.2 Xl4015 Step-down Converter

2) *Buck Converter XL4015:* The XL4016 is a step-down (buck) converter that efficiently reduces higher voltage to a lower, stable output. It is used in your project to ensure that components, such as the servos or the ESP32, receive the correct operating voltage, preventing overvoltage damage while maintaining power efficiency.

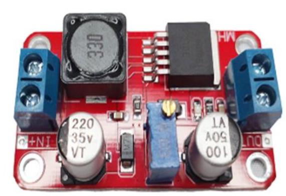

Fig 7.3 Step-up Converter (XL6019)

3) *Boost Converter XL6019:* The XL6019 is a step-up (boost) converter that increases lower input voltages to a higher output voltage. In your project, this component helps to ensure that sufficient voltage is supplied to the servos or other high-demand parts when the battery voltage drops, allowing the snake to function smoothly even under variable power conditions.

Fig 7.4 Type-C Charging Module

4) *Type-C Charging Module (5V):* This module provides a stable 5V power supply and is used to charge the battery system of your robotic snake. The USB-C interface is widely used for its fast-charging capability and reversible connector design. This module ensures that the onboard battery can be easily charged while maintaining a reliable power flow to the ESP32 and other components.

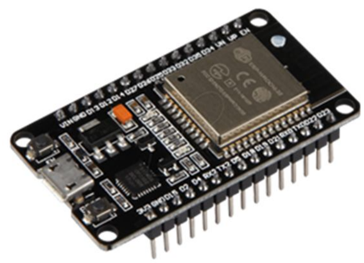

Fig 7.5 Esp32 38pin Microcontroller

5) *ESP32 MicroController:* The ESP32 is a powerful microcontroller with built-in Wi-Fi and Bluetooth capabilities, making it an ideal choice for controlling the robotic snake. It handles communication, command processing, and servo control. Its versatile nature allows you to implement wireless control via an app or web interface, which adds a user-friendly aspect to your project

Fig 7.6 PVC Sheets

6) *PVC Sheets:* PVC sheets are lightweight and flexible materials used to form the body structure of the robotic snake. They are durable enough to maintain the shape of the snake while being flexible enough to move with the servos' motions. PVC provides a cost-effective and practical material for building the snake's frame, ensuring both strength and flexibility.



7) *Sensors (DHT11, Ultrasonic, MQ-2):* The combination of DHT11, Ultrasonic, and MQ-2 sensors enables environmental monitoring, object detection, and gas leak detection in your project. The DHT11 measures temperature and humidity, ensuring climate control and safety. The Ultrasonic Sensor determines object distance using sound waves, making it ideal for obstacle detection. The MQ-2 Gas Sensor detects flammable gases like LPG, methane, and smoke, helping monitor air quality and prevent hazards. Together, these sensors provide essential data for real-time decision-making and automation.

8) *ESP32 Camera Module:* The ESP32 Camera Module integrates an ESP32 microcontroller with a camera, enabling image capture and video streaming. It is used in your project for surveillance, remote monitoring, or object recognition. With built-in Wi-Fi and AI capabilities, it can process images locally or transmit data to a cloud server for further analysis.

VIII. SENSING AND MOTIONS OF THE SNAKE

The robotic snake's motion is tracked and controlled through a combination of feedback from sensors stated below along with their functionality -

1) Ultrasonic sensor to detect and navigate around obstacles autonomously. The snake will move forward one complete undulation, stop, and take a distance measurement. If the path is clear the snake will continue forward [11].
2) Installation of a camera module for real-time video feedback to assist in navigation and task execution. Will also be used for live streaming [11].
3) Use of gas sensor to detect in case of gas leakage and fire.
4) Similarly, use of smoke sensor to detect the smoke in case of fire [11].
5) Use of temperature and humidity sensor for analyzing the environment and surroundings the snake is present in.

It performs slithering motions by generating a continuous wave pattern through coordinated actuation of its servo motors, which allows the snake to move smoothly and efficiently across surfaces. This wave-like movement enables the robot to traverse uneven terrains and tight spaces with ease. Additionally, the snake can execute U-bends, a manoeuvre where the robot curves sharply to change direction. This action is achieved by adjusting the angles of the servo motors to create a localized bend, allowing the snake to navigate around obstacles or reorient itself in confined areas. The combination of slithering and U-bending motions provides the robotic snake with enhanced manoeuvrability and adaptability, making it suitable for complex and dynamic environments.

IX. CONCLUSION

In conclusion, this project demonstrates the successful development of a robotic snake that leverages bio-inspired mechanics, advanced sensor integration, and remote-control functionality. Using PVC for the structure and MG995 servo motors for movement, the robot replicates serpentine locomotion, providing flexibility and agility in confined spaces. The inclusion of a Battery Management System ensures efficient power usage, enabling reliable performance.

The robotic snake's sensor suite comprising ultrasonic, motion, and temperature sensors, along with a camera module enables it to detect obstacles, track movement, monitor environmental conditions, and capture real-time visual data [10, 11]. These capabilities, processed through the ESP32 microcontroller, allow for smooth operation and interaction with the robot through a custom control application. This robotic snake has significant potential in disaster scenarios, such as tunnel collapses or other confined-space emergencies, where its ability to navigate tight spaces and provide real-time information could aid in search and rescue missions [7, 11]. Additionally, its design allows it to travel through pipelines and other inaccessible areas to perform inspections and observe critical conditions. Overall, the project demonstrates the application of robotics in addressing real-world challenges. Future developments could focus on enhancing the robot's autonomy and refining its sensor systems, expanding its potential for use in disaster management, industrial inspection, and beyond.

X. RESULT

The robotic snake developed in this project achieved its core design objectives by delivering efficient locomotion and responsive sensory feedback in real-world simulations [11]. The choice of PVC for the structure, combined with the MG995 servo motors, provided a lightweight yet durable framework that allowed smooth, serpentine movement through confined environments. The mobility tests demonstrated that the robotic snake could navigate complex, narrow spaces with flexibility, which is essential for practical applications such as tunnel exploration or pipeline inspection.

The sensor system, consisting of ultrasonic, motion, and temperature sensors along with a camera module, successfully enabled the robot to perceive and respond to its environment. The ultrasonic sensor effectively detected obstacles within its path, while the motion sensor accurately captured movement, and the temperature sensor provided valuable environmental data. The camera module produced clear, real-time visual feedback, enhancing the robot's utility in inspection and monitoring tasks.

The custom application developed for controlling the robotic snake performed reliably, offering real-time manipulation of the robot's movements and sensor inputs. This application facilitated smooth operation across multiple trials, validating the robot's potential for controlled use in real-world disaster scenarios, such as collapsed tunnels, or in industrial settings like pipeline inspections.

Ultimately, the project proved that the robotic snake could function effectively under a variety of conditions, meeting performance expectations and laying a solid foundation for further research and development in the field of bio-inspired robotics. These results confirm the viability of the robotic snake for specialized applications requiring flexibility, environmental awareness, and remote operation.

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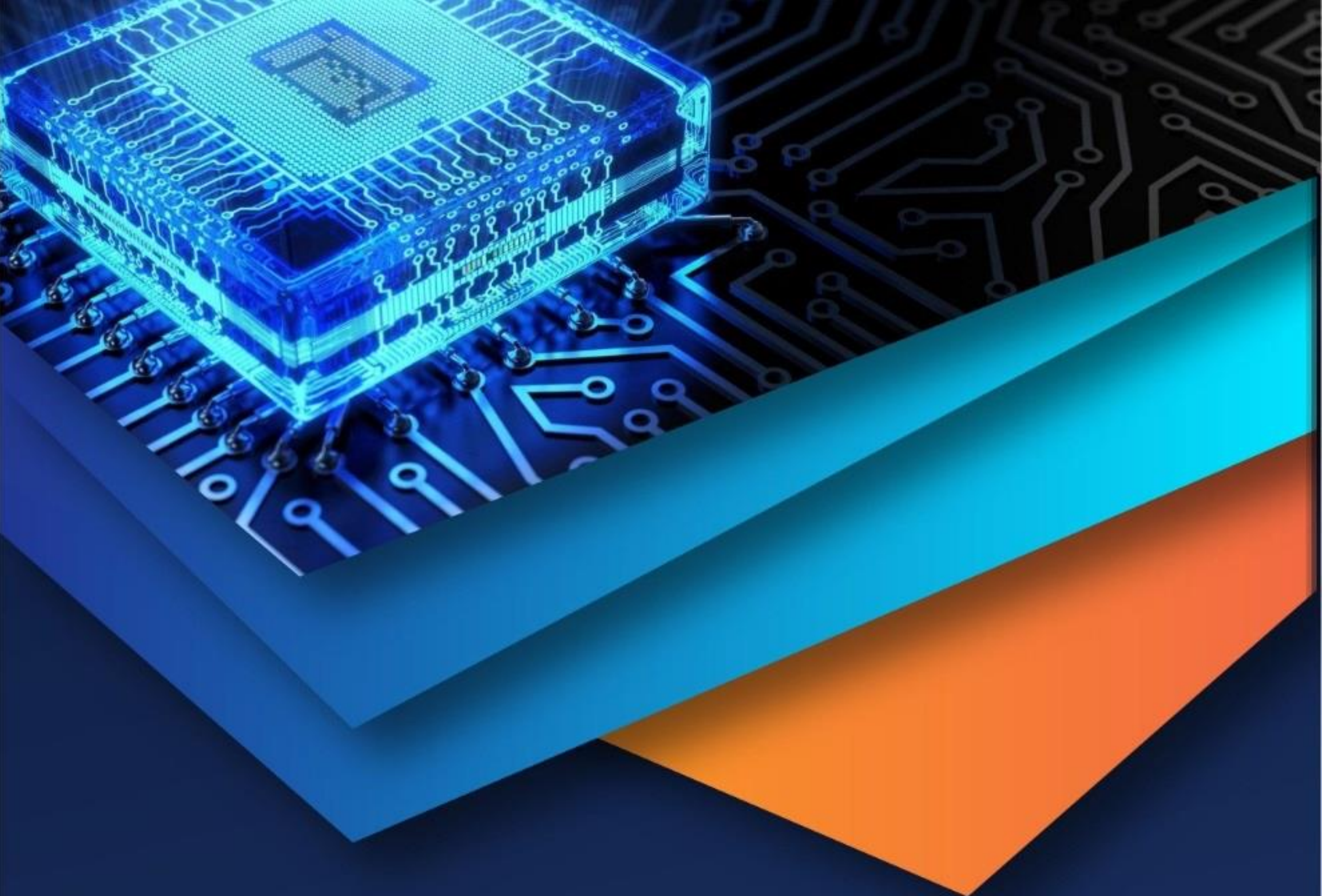

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