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Snake Vision Robot for Hazardous Chemical Environment

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Abstract - The "Design and Development of Snake Vision Robot" project aims to create an innovative robotic system inspired by the movement of snakes. This robot is engineered for efficient navigation and environmental interaction. The project integrates advanced sensors for vision and obstacle detection, enabling real-time processing and adaptive moving in complex environments. The design emphasizes agility and stealth, allowing for applications in marine research, and environmental monitoring. Through a combination of bio-inspired engineering and cutting-edge technology, this robotic system promises to enhance our understanding of environment while minimizing human impact. Project aims to design the robotic snake which describes the design, integration, reliability analysis, plan and prototype testing plan of a low cost, orthogonally articulated snake robot. The snake robot will be programmed to scale various environments with the aid of servo motors integrated within each module via C-brackets. Navigational capabilities include sidewinding and other motion types controlled via Arduino Uno with an infrared remote-control system. The components and manufacturing processes have been selected with respect to reliability and structural analysis of mechanical and electronic parts, as well as cost, availability, environmental and safety factors.

I. INTRODUCTION

The evolution of robotics has been significantly influenced by the study of biological systems. Among various bio-inspired robotic forms, snake robots have garnered increasing attention due to their unique ability to traverse through narrow, uneven, and complex terrains where traditional robots struggle. Unlike wheeled or legged robots, snake robots imitate the locomotion of real snakes, enabling them to move smoothly through pipelines, rubble, and other confined environments. This makes them especially valuable in critical applications such as search and rescue, pipeline inspection, surveillance, and military reconnaissance. The fundamental inspiration behind snake robots lies in the natural design and movement of serpents, which can adapt their motion to various environments using a combination of lateral undulation, sidewinding, concertina, and rectilinear movement. These mechanisms allow real snakes to move efficiently through tight and cluttered spaces, climb trees, swim in water, and navigate across sand or gravel. By mimicking these locomotion patterns, snake robots are designed to replicate such adaptability in artificial system. Recent advancements in mechatronics, miniaturized sensors, actuators, and embedded systems have enabled the development of modular robotic platforms with increased mobility, flexibility, and autonomy. Integrating vision systems into these robots further enhances their capabilities. A camera module placed at the head or multiple segments of the snake robot provides real-time visual feedback, allowing it to navigate intelligently, detect obstacles, and relay crucial environmental information to the operator. This is particularly vital in disasterprone or inaccessible regions where human intervention may be dangerous or impossible.

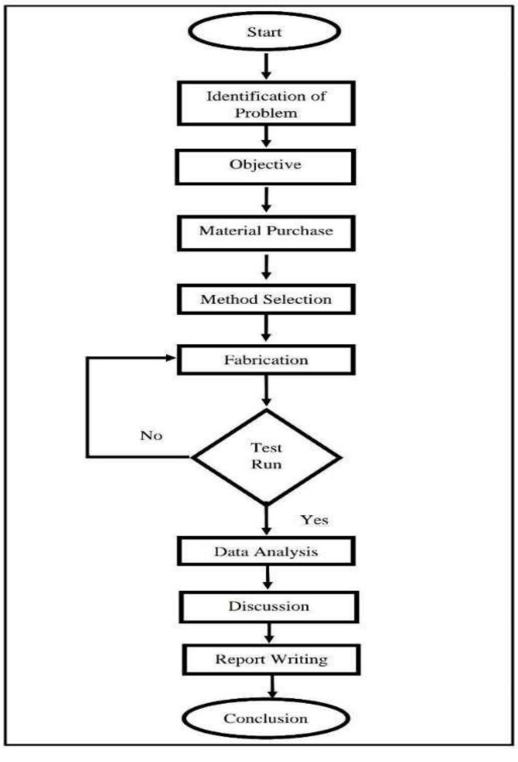
The Snake Vision Robot, as conceptualized in this project, combines both mobility and perception to function effectively in specialized tasks. The camera acts as the “eyes” of the robot, enabling it to “see” and analyse its surroundings, thereby improving the accuracy and effectiveness of its operations. With the aid of vision processing techniques—such as object detection, motion tracking, and edge detection—the robot can identify paths, avoid obstacles, and transmit live video feed to a remote-control station. Moreover, the modular design of snake robots allows for easy scalability and adaptability to different missions. Each segment of the robot can be powered by servo or DC motors, controlled through microcontrollers like Arduino or Raspberry Pi, and enhanced with sensors such as IR, ultrasonic, or IMU (Inertial Measurement Unit). The real-time data collected from these sensors, along with visual input, helps the robot make decisions autonomously or semi autonomously. In fields like underground pipeline inspection, these robots can replace the need for dismantling entire pipeline systems, thereby saving time, cost, and effort.

In conclusion, the background of the Snake Vision Robot project stems from the need for a robotic solution that is flexible, adaptable, intelligent, and capable of functioning in environments where traditional robots fail.

II. OBJECTIVES.

- To integrate a vision system for real-time video streaming and obstacle detection.
- To enable remote control and autonomous navigation capabilities.
- To enable gas detection and environmental monitoring, integrating a metal oxide sensor for real-time sensing of hazardous gases during operation.

III. METHODOLOGY



The project begins with the Identification of the Problem, focusing on the challenges of inspecting long, confined industrial pipes where human access is limited and unsafe. Following this, the Objective is defined to create a snake-like robot capable of detecting cracks, voids, distances, and hazardous gases using sensors and a camera.Next, the Material Purchase phase includes acquiring servo motors, ESP32-CAM, ultrasonic and metal oxide sensors, brackets, and hardware components. Method Selection involves choosing appropriate communication protocols (Wi-Fi), programming platforms (Arduino ESP), and structural design using lightweight metal parts. The Fabrication stage integrates hardware assembly and coding. The robot is constructed in modular segments with sensor wiring and motor connections. A Test Run is then performed to verify mechanical movement, sensor readings, and wireless camera streaming. If errors are found, adjustments are made. On successful testing, Data Analysis is conducted based on air quality (in ppm) and object distance (in cm). The findings are evaluated in the Discussion phase. Finally, detailed documentation is carried out in Report Writing, followed by deriving the Conclusion highlighting project outcomes and future scope.

IV. SYSTEM OVERVIEW

➢ System Architecture

The system architecture of the Snake Vision Robot is built on the concept of modular, serially connected segments, each driven by a servo motor. These segments are controlled via a central microcontroller that also handles sensor inputs and camera output.

- Mechanical Structure: Composed of multiple segments connected with joints. Each joint is actuated by a servo motor allowing lateral movement.
- Control Unit: An Arduino for basic control functions as the brain of the system, executing movement logic, controlling actuators, and processing sensor data.
- Vision System: A Pi Cam is interfaced with the Arduino to capture and stream realtime video. Image processing (object tracking, motion detection) is performed using OpenCV.
- Sensors: Ultrasonic sensors provide data for collision avoidance and basic environment mapping.
- Communication Interface: A Wi-Fi or Bluetooth module facilitates wireless control from a mobile app or laptop.
- Power Management: The system is powered by a rechargeable battery pack with sufficient capacity to run motors and electronics.

➢ Working Principals

The Snake Vision Robot moves using serpentine locomotion, achieved by sequential activation of servo motors across its body segments. These motors create wave-like lateral motions that propel the robot forward. The angle and frequency of each servo motor are controlled via programmed logic to simulate real snake movement.

As the robot moves, the onboard camera captures real-time video, which is streamed to a remote device using Wi-Fi or Bluetooth. The operator can view the live feed and issue directional commands using a graphical interface or console.

Sensors such as ultrasonic modules are used to detect nearby obstacles. When an object is detected within a set threshold, the robot adjusts its path to avoid collision. The microcontroller continuously monitors all sensor inputs and modifies the movement commands accordingly. This integration of mobility, vision, and autonomous sensing allows the robot to navigate complex environments such as pipelines, narrow shafts, or collapsed structures while providing visual feedback to the operator.

➢ Components And Connectivity Models

- ESP32 Microcontroller
- DRV8825 Stepper Moter Driver IC Module
- Servo Motors
- Camera Module
- Ultrasonic Sensor
- Metal Oxide Sensor
- LED Lights
- Battery

Connectivity is a crucial aspect of the Snake Vision Robot, as it enables communication between the robot's internal components and with external devices such as smartphones, computers, or remote controllers. Efficient and reliable connectivity ensures seamless control, real-time data transmission, and responsive performance, especially during navigation, surveillance, or rescue operations.

The robot employs both wired and wireless communication protocols depending on the component's role. Internally, modules such as servo motors, sensors, and the ESP32-CAM are connected using standard digital I/O, PWM, I2C, and UART interfaces. These communication lines are routed through a central microcontroller (ESP32), which acts as the robot's brain, orchestrating movement, vision, and sensing tasks.

For wireless connectivity, the ESP32 and ESP32-CAM come equipped with built-in Wi-Fi and Bluetooth modules. Wi-Fi is primarily used for real-time video streaming, enabling the robot to transmit camera feeds to a remote device via a web interface or dedicated app. This is particularly useful in confined or hazardous environments where direct line-of-sight control is not feasible. Bluetooth, on the other hand, is used for short-range control commands, like adjusting movement modes or triggering actions through a smartphone or joystick module.

Additionally, the robot can support communication with cloud platforms using MQTT or HTTP protocols, allowing for remote monitoring, data logging, or control from anywhere via the internet. This cloud connectivity extends the robot's usability in IoT-based automation or research applications.

The robot's modular wiring ensures organized and secure signal transmission; while shielding and isolation techniques are used to minimize interference and voltage drops. Overall, the robust connectivity design enhances the robot's autonomy, flexibility, and remote operation capability, making it suitable for a wide range of practical applications.

V. DESIGN AND FABRICATION

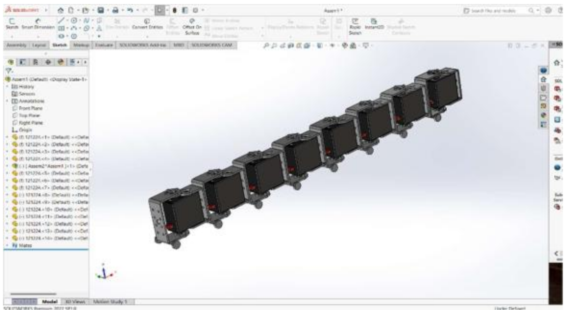


Fig. 3D Assembly using Solid Works software

The design of the Snake Vision Robot is inspired by the biological structure and locomotion of a snake, enabling it to move efficiently through confined spaces and over uneven terrain. The CAD model, as shown in the SolidWorks assembly, consists of a modular arrangement of multiple interconnected segments. Each segment is driven by a high-torque

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RDS3115MG servo motor, housed within a compact casing and supported by aluminium brackets.

The robot is made up of repeating mechanical modules, each containing a servo motor mounted using standard servo clamps. These clamps, made from lightweight anodized aluminium, securely hold the motor in position and allow for rotational motion between connected segments. The design maintains rotational freedom at specific joints, enabling the entire body to mimic serpentine movement patterns.

The entire model is designed in SolidWorks 2022, where mating constraints and kinematic joints were applied to simulate real-time motion and test articulation accuracy. Each servo is strategically aligned to rotate the module in alternating directions, resulting in a wave-like movement that allows the robot to slither forward, backward, or turn. For fabrication, the structural components such as the brackets and. The assembly process involves inserting servo motors into the brackets, aligning servo horns, and linking segments with screws and fasteners. Electrical wires for power and signal transmission are routed internally or along the exterior using protective sleeves

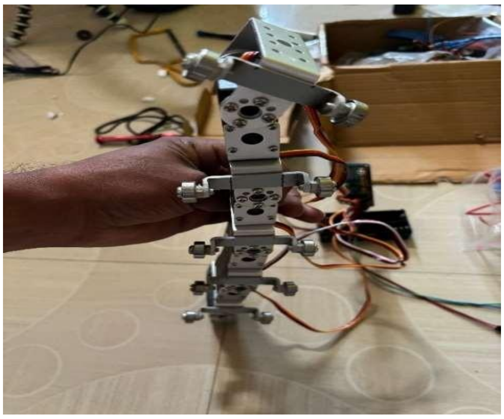

Fig. Assembly

The fabrication of the Snake Vision Robot involves a precise integration of mechanical components such as aluminium brackets, bearings, wheels, nuts, and bolts to create a stable, mobile, and modular platform. As seen in the mechanical image provided, the brackets are used to house the servo motors (RDS3115MG) and serve as the base for connecting adjacent segments.

To enable controlled ground interaction and smooth locomotion over surfaces, miniature wheels are mounted on the lower side of selected segments. These wheels are supported by ball bearings, which significantly reduce friction and allow for smoother rolling motion. The bearings are press-fitted into the bracket holes or mounted using retaining clips, depending on the bracket design. They also enhance durability by minimizing wear and tear during continuous serpentine motion.

Nuts, bolts, and screws play a critical role in securing all mechanical assemblies. The wheels are fixed to the brackets using shoulder bolts or axles, which are passed through the bearings and fastened tightly using locknuts or washers to avoid loosening due to vibration. The brackets themselves are joined to the servo motors using appropriate mounting screws, ensuring firm grip and alignment. The use of standardized mechanical fasteners makes the robot easy to assemble, disassemble, and maintain. Additionally, it allows for modular upgrades or part replacements without specialized tools

Fig. Connection

VI. WORKING AND FABRICATION

➢ Modes of Operations

The Snake Vision Robot is engineered to function in diverse environments through two primary modes of operation: Manual Control Mode and (Optional/Future Scope) Autonomous Mode. These modes offer flexibility in deployment and adaptability to different applications, whether the robot is navigating through debris in a disaster zone or being used in a controlled inspection scenario.

Manual Control Mode - In this mode, the user directly controls the robot using a mobile or web-based interface. The robot establishes a Wi-Fi connection via the ESP32-CAM module, allowing a smartphone or laptop to access the robot's IP address for a live video feed and directional control. A user friendly graphical interface includes buttons, sliders, or a joystick for navigating the robot's movements forward, backward, left, right as well as controlling camera angles if mounted on a servo. This mode is ideal for real-time exploration in environments where human entry is difficult or unsafe. The camera provides the operator with a first-person view (FPV), allowing them to make navigation decisions with high accuracy. The operator can also control LEDs for night vision and monitor battery status or sensor alerts, depending on the implementation.

Autonomous Mode (Future Scope) - Though currently optional, autonomous operation can be enabled through onboard sensors like ultrasonic sensors, IR sensors, or gyroscopes. These components allow the robot to avoid obstacles and make decisions based on its surroundings without manual input.Basic autonomy may involve wall-following, line-following, or stop-and-go behaviour based on sensor thresholds. More advanced autonomy could include visual-based navigation, using the camera to identify objects, track paths, or even use AI to make decisions.In future versions, sensor fusion combining camera input with sonar or LIDAR (light detection and ranging) could be implemented for SLAM (Simultaneous Localization and Mapping), enabling the robot to map unfamiliar terrain while navigating through it autonomously.

➢ Movement Patterns (Serpentine Locomotion)

The Snake Vision Robot's distinctive capability lies in its serpentine locomotion, a movement pattern inspired by real snakes. This mode of locomotion allows the robot to navigate complex, constrained, or uneven environments where traditional wheeled or legged robots might struggle.

The design replicates the sinuous wave-like motion that snakes use to propel themselves efficiently and silently through various terrains. The robot's body consists of multiple interconnected segments, each controlled by servo motors such as the RDS3115MG. These servos articulate the joints, enabling the robot to bend and twist along its length. By programming the servos to move in coordinated sequences with carefully timed phase shifts, the robot generates lateral undulating waves. These waves push against the ground, propelling the robot forward or backward smoothly The serpentine gait can be mathematically modelled as a sinusoidal wave propagating through the robot's body. Parameters such as wave amplitude, frequency, and phase difference between segments are tuned to optimize speed, stability, and manoeuvrability. By adjusting these parameters, the robot can perform different locomotion styles:

- Forward locomotion: The wave travels from head to tail, pushing the robot forward.
- Backward locomotion: The wave direction is reversed, allowing the robot to move backward.
- Turning: By increasing the wave amplitude on one side or altering phase relationships, the robot can turn left or right.
- Sidewinding: A more advanced technique enabling the robot to move diagonally or sideways, useful for loose or slippery surfaces.

This flexibility makes the robot highly adaptive in confined spaces, rubble-strewn environments, and narrow pipes or ducts. Unlike wheeled robots, the snake robot's ability to compress and elongate its body segments means it can squeeze through gaps smaller than its resting width. Additionally, the modularity of the design allows easy scaling by adding or removing segments, which directly impacts the complexity and length of movement waves.

➢ Control via Remote/Mobile

The Snake Vision Robot is designed for versatile and intuitive control through wireless communication, primarily leveraging Wi-Fi and Bluetooth technologies. This allows operators to remotely manoeuvre the robot, access live video feeds, and adjust operational parameters, all through commonly available mobile devices or computers.

Wireless communication Framework - At the heart of the robot's communication system is the ESP32-CAM module, which integrates a camera and Wi-Fi capabilities into a compact, cost-effective platform. Upon startup, the ESP32-CAM either connects to an existing Wi-Fi network or establishes its own access point, creating a local hotspot. Operators can then connect their smartphone, tablet, or laptop to this network. Once connected, the operator accesses a web interface hosted by the ESP32-CAM. This interface displays the real-time video stream captured by the onboard camera, allowing for visual feedback essential for navigation. Alongside the video feed, the interface offers control elements such as directional buttons, sliders, or a virtual joystick that command the robot's movements—forward, backward, turning left or right, and adjusting the speed of movement.

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Mobile App and Custom Interfaces - Beyond the web interface, custom mobile applications can be developed for Android or iOS platforms, utilizing Bluetooth or Wi-Fi communication. These apps offer enhanced control features, including gesture controls, presets for common movement patterns, and integration with other sensors onboard the robot for comprehensive situational awareness. For areas with no Wi-Fi infrastructure, Bluetooth modules like HC-05 or HC-06 can be integrated, enabling local wireless control over short distances (typically up to 10 meters). This is especially useful in environments where network security or interference is a concern.

Real-Time Feedback and Control Synchronization - Real-time video streaming coupled with low-latency command transmission is critical to responsive and safe operation. The combination of the ESP32-CAM's efficient MJPEG streaming and the lightweight control interface ensures minimal lag, enabling operators to make precise adjustments and avoid obstacles or hazards in real time. Advanced implementations may include additional. feedback loops from sensors monitoring battery life, motor temperature, or obstacle proximity, displayed on the control interface for informed decision-making. Using familiar devices such as smartphones to control the robot eliminates the need for specialized remote controllers, reducing cost and complexity. The wireless nature of the control allows operators to stay safely at a distance from hazardous zones, enhancing safety during operations like disaster assessment, pipeline inspection, or military reconnaissance.

VII. TESTING AND RESULT

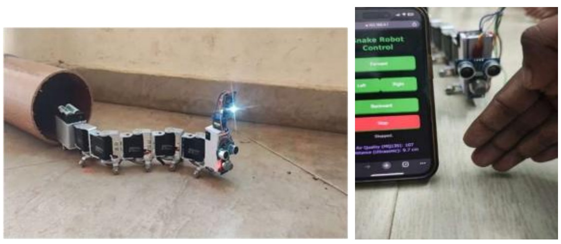

Fig. Final Testing Image

The image illustrates the practical testing of sensor functionality on the Snake Vision Robot, specifically the HC-SR04 ultrasonic sensor and the MQ135 metal oxide gas sensor (MOS), integrated with a real-time mobile control interface. The robot is connected to a smartphone via a local IP address (192.168.4.1), where directional controls and sensor data are displayed through a web-based dashboard. The interface presents both navigation buttons (Forward, Left, Right, Backward, Stop) and live sensor readings, verifying the successful hardware and software integration.

The HC-SR04 ultrasonic sensor is used for measuring the distance between the robot and nearby objects. As shown in the image, a hand is placed in front of the sensor, and the system accurately reports a measured distance of 9.7 cm. This value is in centimetres (cm) as per the International System of Units (SI), confirming the sensor's functionality in detecting obstacles. The HC-SR04 operates by emitting ultrasonic waves at 40 kHz and calculating the time taken for the echo to return, using the formula: Distance (cm) = (Time × Speed of Sound) / 2 where the speed of sound in air is approximately 343 m/s at 20°C. The MQ135 sensor is designed for detecting air quality by measuring gases like ammonia (NH_3), nitrogen oxides (NO_x), benzene, smoke, and carbon dioxide (CO_2). The value displayed, 107, is a Raw Analog-to-Digital Converter (ADC) output, typically without a unit, but it correlates to parts per million (ppm) after calibration. According to standard air quality indices, a lower ppm value indicates better air quality. For meaningful interpretation, this value should ideally be mapped to a calibrated ppm scale as per EPA or WHO standards. This test confirms accurate real-time acquisition and wireless transmission of sensor data, demonstrating the robot's capability to perceive its surroundings for autonomous navigation and environmental assessment.

VIII. APPLICATIONS

- surveillance
- Pipeline Inspection.
- Disaster Management
- Military Use
- Space Applications

IX. FUTURE SCOPE

While the Snake Vision Robot in its current state serves as a capable prototype for exploration, surveillance, and obstacle navigation, there exists significant potential for enhancements that can elevate it to a higher level of autonomy, intelligence, and multi-functionality. The following areas outline the future scope of development across mechanical, electrical, software, and application domains.

Advanced Autonomy and AI Integration- Currently, the robot is controlled manually through a mobile or PC interface. Future iterations can incorporate artificial intelligence (AI) and machine learning (ML) for real-time decisionmaking and environment adaptation. By training the robot using data from different terrains and scenarios, it can learn to autonomously choose optimal paths, avoid obstacles, and even recognize specific objects. Integration of convolutional neural networks (CNNs) can allow the robot to distinguish between humans, objects, and structural hazards, making it invaluable for search-and-rescue and surveillance.

Improved Power Management- Power constraints were a significant limitation in the present design. Future versions can utilize advanced battery management systems (BMS) with higher-capacity Li-Po or Li-ion batteries and energy-efficient motors to prolong operational time. Additionally, incorporating solar panels for outdoor operations or energy harvesting systems from the environment can make the robot more sustainable and suitable for long-duration tasks.

- Enhanced Sensor Array- While the prototype includes basic sensors like ultrasonic and MOS gas sensors, the sensor suite can be expanded with:
- Thermal imaging cameras for heat detection in fire or human search missions.
- LIDAR for precise depth mapping and 3D environment reconstruction.
- Vibration and seismic sensors for structural inspection in buildings or tunnels. This expansion will increase the robot's functionality across industries such as mining, archaeology, and disaster response.

Miniaturization and Soft Robotics- To enhance manoeuvrability, especially in the medical field, future designs can explore miniaturization of components. Using soft robotics technology, the robot can adopt flexible and stretchable materials to reduce rigidity and risk of damage. This would make it suitable for internal Body inspections or minimally invasive surgeries, drawing inspiration from real-life endoscopy robots.

Swarm Robotics- Developing a system where multiple snake robots can operate collaboratively opens up possibilities for large-scale search-and-rescue operations or terrain mapping. Using swarm intelligence, these robots could share data, avoid collisions, and cover more area efficiently. This would be especially valuable in military or post-disaster environments where time and efficiency are critical.

Weatherproofing and Outdoor Capabilities- The current prototype is suited primarily for indoor or dry environments. To broaden its deployment, future versions can incorporate waterproof and dustproof enclosures, ruggedized motors, and corrosion-resistant materials, making it resilient to harsh outdoor conditions. This would allow for operations in rain, snow, or chemical spill zones, thereby expanding its applicability.

High-Definition Video and Edge Computing- Replacing the ESP32-CAM with more powerful platforms such as Jetson Nano or Raspberry Pi 4 with camera modules can enhance processing capabilities, allowing onboard image processing instead of relying on remote servers. This upgrade would improve responsiveness and reduce latency in control. High-definition cameras with night vision and zoom functions could further support security, inspection, and Replications.

Modular Tool Attachments- Future versions can include swappable tool heads or modular attachments such as grippers, cutters, or sample collectors. These would enable the robot to perform not just passive surveillance but also active intervention like retrieving objects, opening valves, or delivering first-aid kits.

Integration with IoT and Cloud Services- Enabling the Snake Vision Robot to connect with IoT platforms and cloud-based dashboards can provide real-time data analysis, long-term storage, and AI-based diagnostics. Such integration will be particularly useful for industrial inspection, predictive maintenance, and environmental monitoring.

Educational and Research Tool- Lastly, as a low-cost and customizable platform, the Snake Vision Robot can be developed further into an educational kit for engineering students, promoting hands-on learning in robotics, AI, and embedded systems. With documentation and open-source access, it could foster innovation and experimentation in academic and research communities.Together, these improvements promise to transform the Snake Vision Robot from a capable prototype into a next-generation robotic platform, bridging the gap between biological inspiration and technological innovation. Its flexibility, combined with smart vision and advanced control, ensures its relevance in a future increasingly dependent on intelligent, mobile robotic systems.

X. CONCLUSION

The development of the Snake Vision Robot successfully demonstrates an efficient and costeffective solution for inspecting hazardous or inaccessible industrial environments, particularly long hollow pipelines. By mimicking the serpentine motion of a snake, the robot can navigate narrow and confined spaces with agility, offering a distinct advantage over conventional wheeled or tracked robots.The integration of key sensors such as the ultrasonic sensor for obstacle detection and distance measurement (in centimetres), and the metal oxide sensor (MQ135) for detecting toxic gases (in ppm), ensures the robot can collect valuable environmental data. Additionally, the ESP32CAM module provides real-time video streaming over Wi-Fi, allowing operators to visually inspect internal conditions remotely.

Through wireless control and modular mechanical design, the robot achieves flexibility, precision, and ease of maintenance. The project also highlights successful implementation of embedded system programming, sensor calibration, and IoT-based monitoring.This prototype can be extended further with features like autonomous navigation, cloud-based data logging, and additional sensor integration. Overall, the project meets its objective and proves to be highly applicable in industrial sectors such as oil & gas, chemical plants, and disaster-prone environments where human inspection is dangerous or impractical.

Fig. Final Image of Snake Vision Robot

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