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Design of a Snake-Inspired Robot for Disaster Response

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Abstract: In response to the urgent need for rescue operations in complex post-disaster environments, this paper presents the design and implementation of a snake-like rescue robot characterized by high mobility, strong environmental adaptability, and intelligent capabilities. Beginning with an overview of the background, the paper highlights the critical role of rescue robots in improving operational efficiency and reducing risks to human personnel. It provides an in-depth analysis of key technologies including joint structure design, control systems, communication functions, motion control, and spatial data management. The proposed robot adopts a modular architecture, integrating multiple sensors and intelligent algorithms to enable agile navigation, real-time perception, autonomous decision-making, and remote collaboration. Capable of performing detection and rescue tasks efficiently in narrow and hazardous areas, this robot offers a viable technological solution for disaster emergency response. The research lays a solid theoretical and practical foundation for advancements in the field of intelligent search and rescue robotics.

Keywords: Snake-like Robot; Search and Rescue; Disaster Response; Modular Design.

1. Introduction

R Rescue robots have emerged as indispensable tools in disaster relief and emergency response, revolutionizing the ability to save lives in critical situations. These advanced systems are designed to swiftly penetrate disaster zones during the pivotal "golden hour"—the critical window immediately following a disaster when prompt action can maximize survival rates. Unlike human rescuers, rescue robots can safely access hazardous environments, including areas with extreme temperatures, toxic substances, or high radiation levels, significantly reducing risks to human personnel. Their flexible, snake-like structures enable them to navigate complex and unstable terrains, such as rubble, debris, or narrow crevices, reaching locations that are otherwise inaccessible by conventional rescue methods or larger equipment.

Recent advancements in artificial intelligence (AI) have further elevated the capabilities of rescue robots, endowing them with greater autonomy and intelligence. AI-driven algorithms enable these robots to perform complex tasks, such as autonomous navigation, obstacle avoidance, and survivor detection, with minimal human intervention. This increased autonomy not only accelerates response times but also reduces the cognitive and operational burden on rescue teams, allowing them to focus on strategic planning and execution. Moreover, the integration of AI fosters continuous learning and adaptation, enabling robots to refine their performance in dynamic and unpredictable environments. [1]

The development of rescue robots is driving innovation across multiple fields, including robotics, sensing technologies, and advanced materials. For instance, lightweight yet durable materials enhance the robots' mobility and resilience, while cutting-edge sensors improve their perception capabilities. These technological advancements are strengthening global disaster response systems, making them more robust and adaptable to a wide range of emergency scenarios. Beyond their practical applications, rescue robots embody the humanitarian value of technology, demonstrating how innovation can serve society by protecting lives and alleviating suffering in times of crisis. By bridging the gap between cutting-edge engineering and real-world impact, these robots are redefining the future of disaster relief and reinforcing the critical role of technology in safeguarding humanity.

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2. Research Background

The development and application of rescue robots stem from the urgent need to improve rescue efficiency and ensure human safety in the face of frequent natural and man-made disasters. Events such as earthquakes, floods, fires, tsunamis, mine accidents, and nuclear leaks often create hazardous environments—including collapsed structures, confined spaces, toxic gases, extreme heat, and radiation—that pose significant challenges to traditional manual rescue efforts.

In such scenarios, rescue personnel must act quickly within the "golden hour" to locate and save trapped individuals, but are often hindered by dangerous and inaccessible terrain. These limitations have highlighted the need for robotic assistance in search and rescue missions. [2]

With rapid advances in robotics, artificial intelligence, sensor technology, control systems, and materials science, the development of rescue robots has become increasingly feasible. Various types of robots—such as tracked robots for rubble navigation, drones for aerial monitoring, and snake-like robots for exploring narrow gaps—have demonstrated strong mobility, perception, and adaptability in complex environments. These capabilities enable them to perform critical tasks like survivor detection, environmental sensing, and data collection in high-risk zones unreachable by human teams.

Equipped with technologies such as cameras, thermal imagers, gas sensors, and acoustic detectors, rescue robots can transmit real-time data to command centers, supporting more accurate situation assessments and strategic decision-making. This not only enhances the precision and efficiency of rescue operations but also significantly reduces risks to human rescuers. Research on computer information network security technology. [3]

2.1. EJoint Structure Design

The joint structure design is a critical factor in enabling the high mobility and adaptability of snake-like rescue robots. These robots typically consist of multiple joint modules connected in series, allowing them to replicate the undulating motion of biological snakes. This structure grants excellent flexibility and maneuverability in complex environments. To meet the demands of varied rescue scenarios, joint design must balance flexibility, stability, and efficiency.

Each joint module can independently control its angle and direction, driven by actuators such as servo motors, stepper motors, or pneumatic devices. Servo motors are often used for their precision in controlling joint angles, enabling fine-grained movement in challenging terrains. Joints are typically connected via linkages or hinges to form a highly flexible motion system with multiple degrees of freedom, allowing rotation and bending in several directions. Through coordinated movement, the robot can perform various locomotion patterns such as serpentine, inchworm, or rolling motion.

Advanced motion control algorithms—such as inverse kinematics and PID control—are employed to ensure accurate and smooth motion trajectories. In addition to flexibility, the joints must withstand external forces encountered in debris, narrow spaces, or unstable terrain. To ensure durability and robustness, joints are commonly built using high-strength lightweight materials like aluminum alloys or carbon fiber. Flexible elements such as springs or rubber gaskets may also be integrated to absorb shocks and enhance resistance to environmental interference. The structure of the snake-like rescue robot is shown in the Figure1. [4]

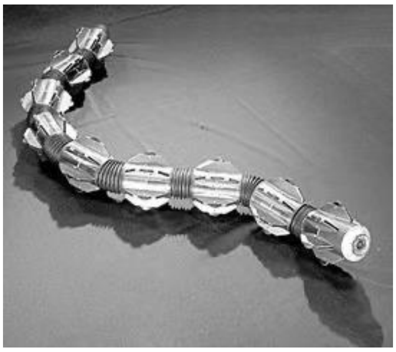

Figure 1. Pareto deconvolution chart

2.2. Control Architecture Design

The control architecture of the snake-like rescue robot integrates distributed control, precise motion coordination, real-time sensor feedback, and intelligent decision-making to ensure efficient operation in complex and dynamic environments. A distributed system is adopted, where the central control unit manages global task scheduling and motion planning, while each joint module contains an independent sub-controller for precise local actuation.

Motion control is achieved through inverse kinematics and waveform-based locomotion strategies, enabling the robot to adopt various movement patterns—such as serpentine and inchworm—based on environmental conditions. Each joint is driven by servo or stepper motors, which work collaboratively to produce multi-degree-of-freedom motion.

To perceive and adapt to the surrounding environment, the robot is equipped with multiple sensors, including angle sensors, force sensors, cameras, and LiDAR. These provide real-time feedback, supporting obstacle avoidance and path adjustment. Adaptive control algorithms allow the robot to modify motion parameters on the fly, ensuring stable performance even in unstructured terrains.

Path planning and obstacle avoidance are handled using algorithms such as A*, RRT, and Dijkstra, enabling the robot to navigate dynamically and avoid entrapment or collisions. To enhance decision-making, AI techniques like reinforcement learning may be integrated, allowing the robot to optimize its task strategies through trial and error.

Power is supplied by onboard batteries, monitored by a Battery Management System (BMS) to ensure operational stability. Additionally, energy recovery mechanisms capture braking energy to improve overall efficiency. Collectively, the control architecture empowers the robot with accurate movement, responsive adaptation, and intelligent autonomy—enabling reliable performance in debris, narrow passages, and other challenging rescue environments. [5]

2.3. Communication Function Implementation

The communication function of the snake-like rescue robot is a critical component that ensures real-time data exchange and coordinated operations between the robot and the external command center, other robots, and internal modules. The communication system typically employs wireless technologies such as Wi-Fi, Bluetooth, Zigbee, or Low Power Wide Area Network (LoRa), enabling adaptability across various operational scenarios.

For internal communication, the main control unit communicates with each joint module via efficient local protocols such as CAN bus or RS485, enabling fast transmission of control commands and sensor feedback to support precise and synchronized motion control. [6]

During rescue missions, the robot maintains a wireless link with the external command center to transmit real-time information such as location, environmental data, and task progress. This allows rescue personnel to monitor the robot remotely, adjust operational strategies, and issue commands as needed.

Moreover, multi-robot collaboration relies on stable communication protocols to enable coordinated task execution, improving overall rescue efficiency. The communication system's stability, low latency, and anti-interference capability are essential to ensure that the robot performs reliably in complex and high-risk environments.

3. Motion Control Design

3.1. Acquisition of Relative Joint Pose

The motion control design of snake-like rescue robots is a sophisticated process that hinges on the precise acquisition of relative joint pose, enabling seamless navigation and operation in complex, unstructured environments. This process integrates a suite of advanced technologies, including multi-sensor fusion, kinematic modeling, and robust pose estimation algorithms, to ensure accurate and reliable joint positioning. By leveraging data from sensors such as Inertial Measurement Units (IMUs) and rotary encoders, and combining their outputs with both forward and inverse kinematics models, the robot can meticulously calculate the relative position and orientation between adjacent joints, forming the foundation for precise motion control. [7]

To achieve high accuracy in pose estimation, advanced sensor fusion algorithms, such as the Extended Kalman Filter (EKF) and particle filtering, are employed to integrate data from multiple sources. These algorithms effectively mitigate the effects of sensor noise, measurement errors, and environmental disturbances, delivering refined and dependable pose data critical for real-time control and path planning. By continuously refining sensor inputs, these methods ensure that the robot maintains a clear and accurate understanding of its joint configurations, even in dynamic or unpredictable rescue scenarios.

The resulting pose information is pivotal for enabling closed-loop control systems, which allow the robot to execute flexible and precise movements while optimizing its path through confined or rugged terrains. This capability is particularly vital in rescue missions, where the robot must navigate narrow passages, debris, or other obstacles with agility and reliability. To further enhance system performance, error compensation mechanisms, such as zero-drift calibration and sensor redundancy, are implemented. Zero-drift calibration corrects for gradual deviations in sensor readings, while sensor redundancy ensures that backup data sources are available in case of individual sensor failures, collectively bolstering the stability and accuracy of pose estimation.

These combined measures ensure that snake-like rescue robots can operate with exceptional reliability and precision in critical, high-stakes rescue scenarios. Whether navigating collapsed structures or confined spaces, the robust motion control design, underpinned by accurate joint pose acquisition, empowers the robot to perform complex maneuvers with confidence, overcoming the limitations of traditional robotic systems and significantly enhancing mission success rates in challenging environments.

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3.2. Establishment of Motion Control Functions

The motion control functions of snake-like rescue robots are typically built upon periodic wave functions, integrated with nonlinear dynamic models to simulate various types of locomotion such as peristaltic motion, lateral undulation, and three-dimensional traveling waves. The joint motion control function can be defined as the angular position of each joint over time. [8]

In dynamic control, to describe the forces acting on the joints and the associated energy variations, the Lagrangian formulation is applied to derive the dynamic model. The Lagrangian is defined as the difference between the system's total kinetic energy and potential energy:

$$\mathrm{L} = \mathrm{T} - \mathrm{V}$$

The kinetic energy is primarily the sum of the rotational kinetic energy of each joint:

$$T = \frac{1}{2}\sum_{i=1}^{n} J_i \dot{\theta}_i^2$$

Where: Ji is the moment of inertia of the i joint, θi is the angular velocity. The potential energy include gravitational, elastic, or other external forces, depending on the operating environment. Using the Euler-Lagrange equation:

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\theta}_i}\right) - \frac{\partial \mathcal{L}}{\partial \theta_i} = \tau_i$$

Where: τ_i is the control torque applied to the i joint.

This dynamic model can be combined with the previously defined motion control functions. Through closed-loop feedback control, the system can dynamically adjust the applied torque to achieve high-precision posture control and optimized energy consumption. This ensures the robot's stability and maneuverability in complex terrains, such as debris fields and narrow passages.

3.3. Spatial Storage Design

The spatial storage design of snake-like rescue robots is a critical factor in enabling their flexible multi-joint movement, reducing structural redundancy, and significantly improving rescue efficiency in demanding environments. This design requires a comprehensive approach that seamlessly integrates the robot's modular physical structure, the compactness of its joint drive components, and sophisticated strategies for managing multi-sensor data. By prioritizing both physical and electronic optimization, the design ensures the robot can operate effectively in complex and constrained spaces, addressing the challenges faced by traditional rescue robots.

Physically, each module of the snake-like robot is engineered with a highly compact layout, incorporating critical components such as joint drive motors, rotary encoders, and inertial measurement units (IMUs) into tightly integrated modular units. This streamlined configuration minimizes space occupancy, reduces the robot's overall weight, and enhances its motion flexibility, allowing it to navigate narrow or irregular terrains with greater agility. The modular design also facilitates maintenance and scalability, ensuring the robot can be adapted for various rescue scenarios while maintaining structural efficiency.

On the electronic data storage level, a multi-layered architecture is employed to handle the vast amounts of data generated by the robot's sensors. Real-time sensor data, such as positional and environmental inputs, is temporarily cached in embedded storage units for immediate processing and quick response. Meanwhile, critical data, including pose information, movement trajectories, and detailed environmental mappings, is transmitted to the robot's central processing unit for long-term storage and comprehensive decision analysis. To optimize storage efficiency, advanced compression algorithms are utilized to reduce data redundancy, ensuring that the system can manage large datasets without compromising performance or speed. [9]

In complex rescue missions, this carefully crafted spatial storage design delivers multiple benefits, enabling the robot to maintain a compact, lightweight, and highly maneuverable form factor. It provides a stable and reliable data foundation that supports real-time environmental perception, precise path planning, and dynamic decision-making. By enhancing the robot's adaptability and integration in confined, unpredictable, or rugged terrains, this design enables precise motion control and overcomes the limitations of traditional rescue robots. As a result, snake-like rescue robots equipped with such advanced spatial storage systems are better equipped to perform effectively in hazardous and constrained environments, ultimately improving mission success rates. Moreover, the system supports remote control, allowing the robot to explore deep into rubble and narrow crevices, significantly improving the accuracy and efficiency of information acquisition during search-and-rescue missions. Furthermore, the robot is equipped with storage and delivery capabilities for emergency supplies, providing initial support to trapped individuals and buying valuable time for subsequent rescue operations.

In summary, this research not only expands the application scenarios of snake-like robots but also offers a feasible pathway and practical foundation for the advancement of intelligent post-disaster rescue technologies. [10]

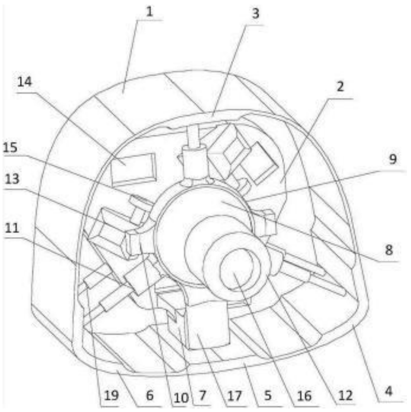

Figure 2. Design of the Storage Module

4. Conclusion

This study focuses on the needs of search and rescue operations in post-disaster rubble environments and presents the design and implementation of a snake-like rescue robot with high mobility and strong environmental adaptability. By effectively integrating the Mecanum wheel motion principle with serpentine gait, the robot achieves precise motion control in rugged and complex terrains, overcoming the mobility limitations of traditional rescue robots in confined spaces. Additionally, the system supports remote operation, enabling the robot to explore narrow gaps within debris, thereby improving the efficiency and accuracy of information acquisition during search and rescue missions. Furthermore, the robot is equipped with storage and delivery capabilities to provide preliminary support to trapped individuals, gaining valuable time for subsequent rescue efforts. In summary, this research not only expands the application scenarios of snake-like robots but also offers a practical pathway and theoretical foundation for the development of intelligent post-disaster rescue technologies.

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