Quadruped beetle inspired robot for search and rescue during natural/man-made calamities

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Abstract : This report presents the development of a beetle-inspired quadruped robot designed for search and rescue operations in disaster-affected areas. The initial motivation for this project arose from the tragic Silkyara Bend–Barkot tunnel collapse on 12 November 2023, where 41 workers were trapped for 17 days, highlighting the urgent need for technologies that can safely explore confined and unstable environments. As a child, I had always been fascinated by beetle-bots on television, and this fascination eventually merged with real-world rescue requirements to form the basis of my project.

The upgraded Prototype 2 introduces stronger materials, improved servo systems, and a user-friendly control interface, resulting in greater stability, maneuverability, and real-time data feedback. The robot's compact size, multi-servo legged movement, Wi-Fi-based control with live sensor readings, and night-vision camera enable it to enter collapsed tunnels, navigate through rubble, inspect hazardous areas, and assist rescuers by sending live visual and sensor information before human teams enter the danger zone. These enhancements further make the robot suitable for scouting unstable structures, assessing environmental dangers, detecting survivors, and offering real-time situational awareness to rescue teams.

Introduction: Natural disasters such as earthquakes, floods, wildfires, lightning, and tsunamis pose difficult challenges in search and rescue missions, especially in the early stages when visibility is low and structures are unstable. Human responders often face extreme dangers including heat, smoke, toxic gases, and the risk of collapse. In such situations, there is a critical need for compact robots capable of entering hazardous environments before rescuers.

Beetle-inspired robots are particularly suitable for this purpose because of their natural maneuverability, compact size, and stability in tight or uneven terrain. This project focuses on developing a quadruped beetle-inspired robot that can be remotely controlled to navigate confined spaces, send real-time camera feedback, and support rescue teams by identifying hazards or survivors. The upgraded Prototype 2 introduces improvements such as a metal chassis, stronger servos, better gait calibration, sensor integration, and enhanced night-vision capability, allowing the robot to scout unstable environments far more reliably.

By enabling early assessment of disaster zones, this robot aligns with SDG 3 (Good Health and Well-being) and SDG 13 (Climate Action), helping reduce risks faced by first responders and enabling faster, safer decision-making during emergencies.

Background research : The challenge of entering collapsed or debris-filled environments has led researchers worldwide to explore biologically inspired robots, especially multi-legged systems. Wheeled or tracked robots often struggle in such scenarios because they cannot adapt to uneven surfaces, gaps, or unstable rubble. In contrast, insects such as beetles naturally demonstrate stability, agility, and efficient movement through confined or irregular pathways.

Research efforts, including those at the University of Tartu and the Italian Institute of Technology, have produced beetle-like robots capable of navigating tight spaces, climbing over small obstacles, and maintaining balance in rugged terrain. Many designs draw on mechanisms like Klann linkages or soft-robotic limbs to replicate insect locomotion. These studies show that multi-legged robots offer significantly greater mobility in disaster scenarios.

Building on this foundation, the present project develops a practical, field-ready version of such a system. Prototype 2 uses metal-geared servos, an aluminum chassis, inverse-kinematic gait control, and environmental sensors to enhance performance. While inspired by academic research, this design focuses specifically on low-cost implementation, long-range control, night-vision feedback, and real-world usability in emergency response contexts.

Hypothesis : If a quadruped beetle-inspired robot is equipped with multi-servo locomotion and onboard sensors, then it will be able to navigate confined disaster spaces and gather useful data more safely and efficiently than a human rescuer.

Materials: The following materials were used for the development of the beetle robot.

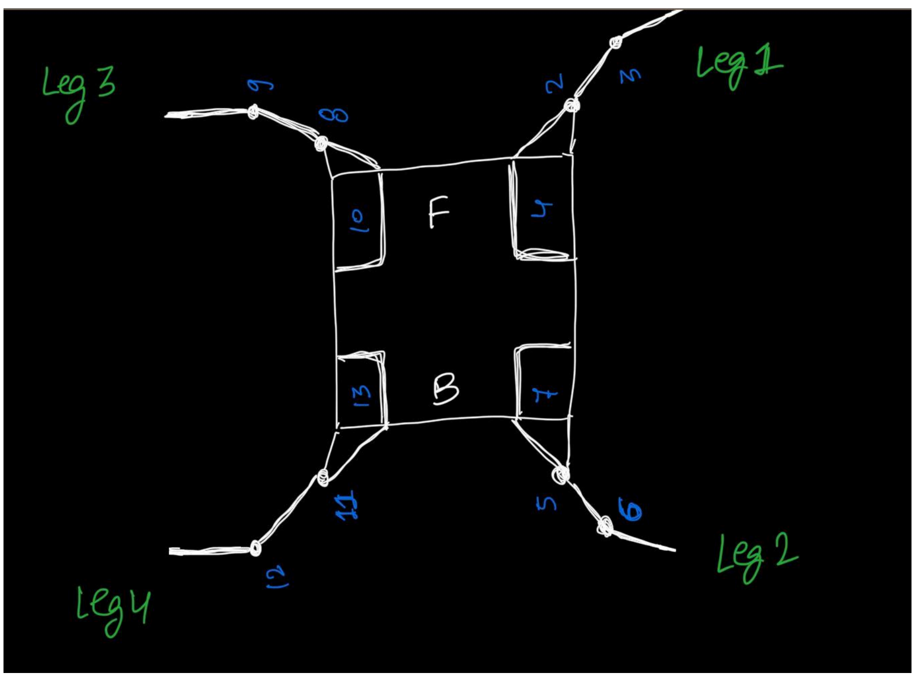
- 3D printed chassis- 3D model from thingiverse
- Aluminum metal chassis- SunFounder PiCrawler kit
- Arduino Nano- Open-source breadboard-friendly microcontroller board based on the Microchip ATmega328P microcontroller (MCU)
- Nano 328P Expansion Adapter Breakout Board IO Shield- Arduino Nano slotted into this which allows for each servo and component to be easily connected
- 9g Plastic geared Servo motors X 12- 180° rotation
- ADS-1115 Module
- ESP-32 for WiFi communication
- MQ2, MQ3 Gas sensors
- Ultrasonic Sensor
- DHT11 Sensor

- 9g Metal geared Servo motors X 12- 180° rotation
- Servo Horn, screws, plastic supports
- Voltage Regulator circuit- Breaks up the voltage from batteries into 5V and 3.3V pins for easier use.
- 3A Switch Mode UBEC 5V 6V
- PTZ camera- Wi-Fi Camera with 720p video, audio recording and night vision
- 18650 lithium batteries X 2
- On-Off rocker switch
- Wire organizer
- Foam double sided tape and Acrylic pieces

Methodology : The development of the robot was carried out in two phases: the initial Prototype 1 construction using a 3D-printed chassis, followed by the upgraded Prototype 2 integrating a metal chassis, stronger servos, and sensor modules. The methodology below describes the complete engineering process.

Step 1 : All electronic and mechanical components, including servos, the Arduino Nano, the 3D-printed chassis, and wiring supplies, were first collected

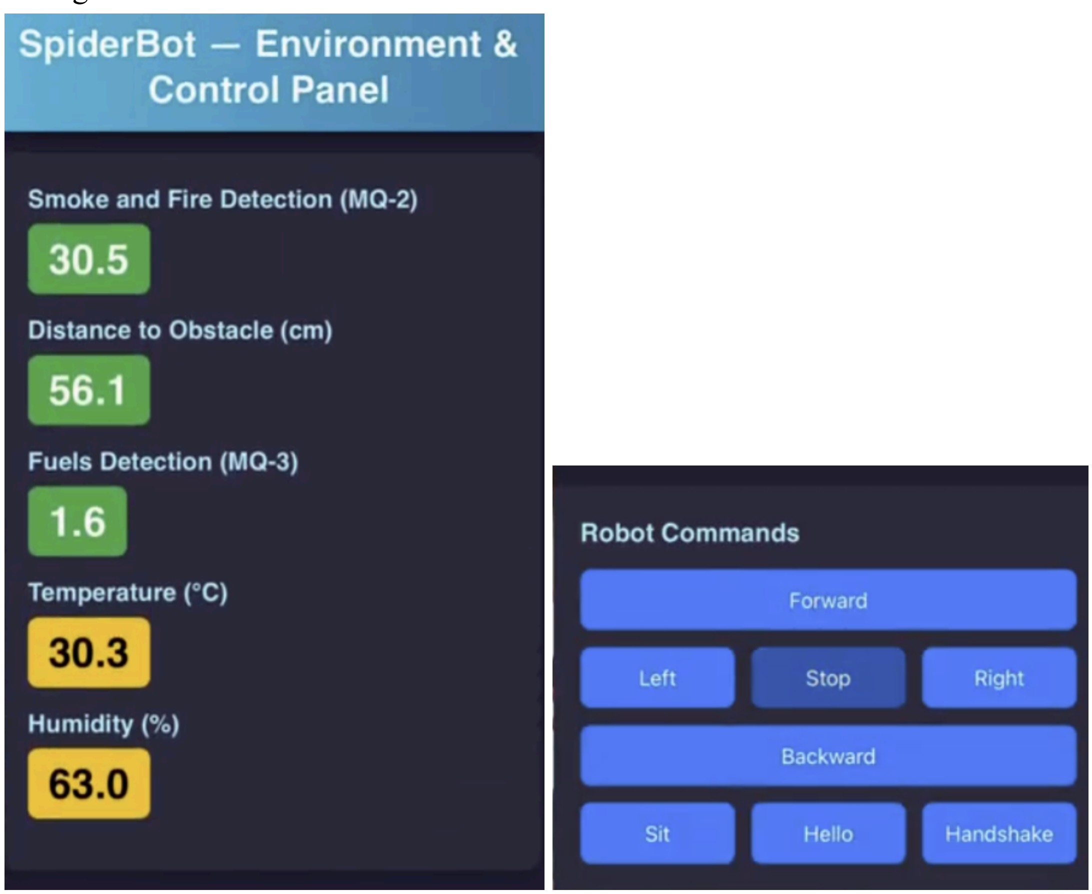
Step 2 : All servos were calibrated to their 90° neutral position to ensure symmetrical movement using the Arduino Nano through the Nano Expansion I/O shield following the pin configuration diagram. Power was supplied through a UBEC voltage regulator delivering 5 V at 3A.



Servo pin configuration diagram

Step 3 : Each leg was assembled using three servos (coxa, femur, tibia). The legs were mounted onto the 3D-printed chassis using servo horns and screws. This established the basic quadruped structure and allowed initial testing of motion.

Step 4 : Basic gaits, forward, backward, left turn, and right turn, were coded using inverse kinematics. The robot was then tested for stability, step accuracy, and responsiveness. During these tests, it was observed that the plastic-geared servos of Prototype 1 lacked the torque required to support the robot's weight reliably.
Step 5 : To improve structural strength, the 3D-printed chassis was replaced with an aluminum frame. All limb servos were upgraded to higher-torque metal-geared variants. This significantly improved load-bearing ability and motion smoothness.
Step 6 : An ESP-32 was installed for Wi-Fi control, allowing for real-time control of the robot's gait speed and direction as well as live sensor readings.
Step 7 : Prototype 2 incorporated multiple sensors including MQ-2, MQ-3, DHT11, and an ultrasonic sensor to measure gas levels, temperature, humidity, and distance to obstacles. A Wi-Fi 720p camera with infrared night vision was mounted on the chassis to capture real-time visuals in dark environments. All of these components were secured using acrylic mounting plates and foam tape.
Step 8 : A simple web interface was programmed to display real-time sensor readings as shown below. Abnormal sensor values were highlighted to alert rescuers to potential hazards such as toxic gases.



Simple Web Interface

Step 9 : All wiring was organized using cable organizers to prevent entanglement during motion. The final prototype was tested indoors and through small gaps to simulate collapsed environments. The robot successfully demonstrated stable movement, obstacle navigation,and reliable control while transmitting live visual and environmental data. This video demonstrates how it works and gives an introduction to the project, and an image of the final project has been attached below:

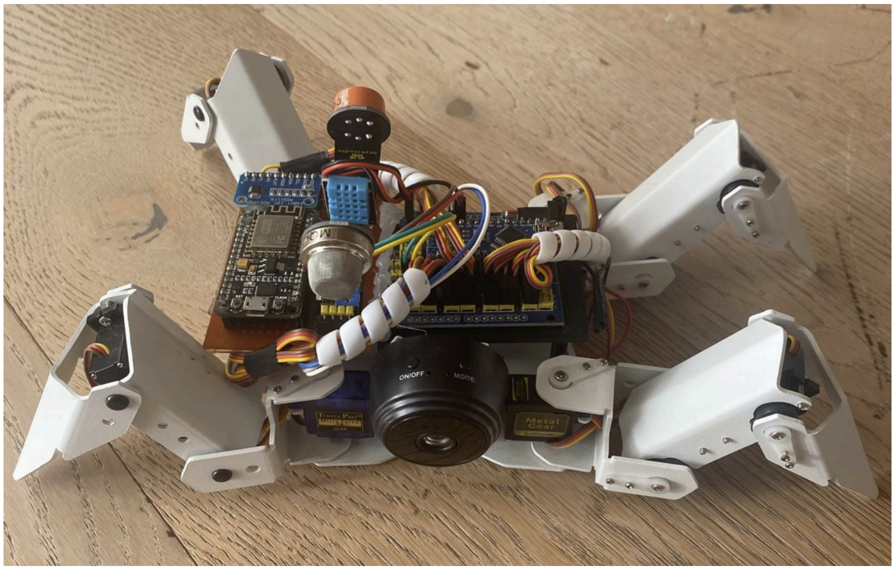


Image of Prototype 2

Results : The upgraded Prototype 2 successfully demonstrates key functionalities required for disaster search and rescue:

- High maneuverability: Multi-servo quadruped gait allows navigating through collapsed structures and debris-filled areas.
- Enhanced stability: Metal-geared servos and aluminum chassis provide strength and smooth locomotion.
- Real-time situational awareness: The 720p Wi-Fi camera with IR night vision offers live visuals in pitch-dark environments.
- Sensor integration: Gas, temperature, humidity, and proximity sensors provide critical environmental data to rescuers.
- User-friendly interface: The custom web dashboard allows simultaneous control and monitoring of sensor outputs with ease.

These capabilities make the robot extremely useful for entering hazardous zones, scanning for survivors, detecting environmental dangers, and helping rescue teams plan safe entry routes.

Limitations : Despite its functionalities, the robot has several limitations:

1. Battery Life: Servos consume significant power, reducing operational time in real disasters.
2. Load Capacity: While the metal servos improve strength, the robot cannot carry heavy payloads such as advanced sensors or communication modules.
3. Terrain Restrictions: Extremely loose rubble or fine dust may hinder foot traction.
4. Signal Issues: Wi-Fi control may experience interference inside deep tunnels or underground structures.
5. Heat Sensitivity: Servos may overheat under continuous load, limiting prolonged operation.
6. Lack of Full Autonomy: The robot currently requires manual control and cannot independently navigate unknown environments.

Addressing these limitations in future versions will significantly enhance the robot's real-world usability.

Future Work : Future iterations of the robot could integrate:

- Autonomous navigation through SLAM
- Thermal imaging camera
- Improved heat-resistant materials
- Bi-directional audio for communication with trapped victims
- 6 or 8-leg variants for enhanced stability
- Integration with fire departments and disaster-response agencies for large-scale deployment

Conclusion : The development of the quadruped beetle-inspired robot demonstrates the viability of using small, maneuverable multi-legged systems for search and rescue applications. The upgraded Prototype 2, equipped with metal-geared servos, an aluminum chassis, sensors, and a night-vision camera, successfully navigates confined spaces and provides real-time data to rescuers. This enhances situational awareness while reducing risks for human responders. Although limitations such as battery life, heat buildup, and signal interference remain, the project establishes a strong foundation for future improvements including autonomous navigation, stronger materials, and thermal imaging. Overall, the robot shows significant potential as a low-cost, practical tool for disaster response aligned with SDG 3 and SDG 13.

Citations:

- https://researchinestonia.eu/2024/05/14/beetle-inspired-robots/
- https://sdgs.un.org/goals/goal3
- https://www.un.org/en/academic-impact/robots-rescue-using-technology-mitigate-effects-natural-disasters
- https://researchinestonia.eu/2024/05/14/beetle-inspired-robots/
- https://www.researchgate.net/profile/Ankamma-Rao-Kandula/publication/362667771_DESIGN_AND_DEVELOPMENT_OF_SIX-LEGGED_ROBOT_FOR_MINE_RESCUE_SYSTEM/links/62f76c2579550d6d1c78f99f/DESIGN-AND-DEVELOPMENT-OF-SIX-LEGGED-ROBOT-FOR-MINE-RESCUE-SYSTEM.pdf
- https://aiforgood.itu.int/disaster-robots-revolutionizing-emergency-response-with-autonomous-robots/
- https://d1wqtxts1xzle7.cloudfront.net/112258172/8f0b19b60a570e0d9824ab953fd7110eca29-libre.pdf?1710006818=&response-content-disposition=inline%3B+filename%3DDesign_of_Six_Legged_spider_Robot_and_Ev.pdf&Expires=1728993083&Signature=HwZEKft9KL3XVNriByxMzWpL8cQtr~8Oqy1eQ1NH30TcFX5q-QOEFr8D5e5GewPgDZJ8-I4UQPB6eq4L~tfLG0OILb6tusdg~8e4v35ZFq~9~lEnGDmckIv-Xc34fXlIxvPcM~uY7fd~waBqQucMVC5TjXTR54IB5j-QY54AeZAQ5naFb8NqMUVboxCBewq2f94Sve-03t1wRjjcAgTkKmWWsR4ez1I1s2Pk6OgDzSZhZUv7ke9il1WC-iCWUufm0YjwmVFUtZJIDRKNQ8Go3Kz4qxCeM172cXyeF8W5i5H2qhU5RtNWmj5yY112iWY1jXyunvgIgw~7LRyDigow-g__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA
- http://jestr.org/downloads/Volume15Issue6/fulltext21562022.pdf