www.ijarp.com ISSN 2456-9992 Page: 01-13

International Journal Advanced Research Publications

Research Article

Volume: 02
Issue: 06

BLUETOOTH-CONTROLLED ROBOTIC ARM FOR HAZARDOUS WASTE HANDLING IN NUCLEAR AND BIOMEDICAL ENVIRONMENTS

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Article Received: 18 May 2026, Article Revised: 6 June 2026, Published on: 26 June 2026

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Doi: https://doi-doi.org/101555/ijarp.6017

ABSTRACT

Hazardous waste management in nuclear, biomedical, and chemical environments presents serious safety risks because human workers may be exposed to radioactive materials, toxic chemicals, infectious substances, sharp biomedical waste, and unsafe surroundings. This paper presents the design and development of a Bluetooth-controlled robotic arm vehicle for remote hazardous waste inspection and material handling. The proposed system integrates an Arduino UNO controller, HC-05 Bluetooth module, L298N motor drivers, PMDC gear motors, a four-wheel mobile chassis, a night vision camera, and articulated robotic arms with a gripper. The system enables an operator to control vehicle motion, monitor the work area, and perform gripping operations from a safe distance. Mechanical design validation includes motor torque analysis, shaft bending stress, welded joint strength, square pipe bending stress, and battery performance. Calculated values such as 9.54 N-m wheel motor torque, 58.96 N/mm² shaft bending stress, 21 N/mm² welded joint stress, 15.79 N/mm² square pipe stress, 3.5 h charging time, and 2.1 h operating time show that the prototype is structurally safe and functionally suitable for controlled hazardous material handling. The developed system is low-cost, modular, and scalable for future integration of radiation, gas, temperature, and autonomous navigation sensors.

KEYWORDS: Robotic arm, hazardous waste management, Bluetooth control, Arduino UNO, HC-05, night vision camera, gripper, PMDC gear motor, biomedical waste, nuclear waste.

1. INTRODUCTION

Hazardous waste produced in hospitals, nuclear facilities, laboratories, chemical industries, and disaster-affected areas requires careful handling because it may contain infectious, radioactive, toxic, corrosive, or sharp materials. Conventional handling practices often depend on manual collection, inspection, segregation, and transport, which can expose workers to health hazards. The World Health Organization identifies health-care waste as a major public health concern because a portion of it can be infectious, toxic, or radioactive [2]. In India, the Bio-Medical Waste Management Rules, 2016 govern the generation, collection, storage, transport, treatment, and disposal of biomedical waste [3].

Robotic systems are useful in such situations because they can enter unsafe zones, observe the environment through a camera, and perform handling tasks while the operator remains at a safer distance. In nuclear decommissioning, remotely operated and autonomous robots are increasingly used for inspection, mapping, radiation monitoring, waste sorting, and manipulation [4]-[8]. This project applies the same safety concept at a low-cost prototype level by combining remote control, mobile movement, night vision monitoring, and gripper-based material handling.

The robotic arm vehicle described in the uploaded project report is designed around a four-wheel mobile base, Arduino control, HC-05 Bluetooth communication, a night vision camera, motor driver units, PMDC gear motors, three articulated arm motions, and a gripper mechanism [1]. The aim of this paper is to convert that project into a structured research paper with improved literature support, technical explanation, diagrams, and IEEE-style references.

2. Literature Review

Robotic development for hazardous environments has received increasing attention due to the need for safe inspection and manipulation in locations where direct human access is risky. Smith et al. reviewed the development process required for robots used in nuclear environments and explained that such robots must address mobility, radiation tolerance, sensing, reliability, and deployment constraints [5]. Vitanov et al. presented a suite of robotic solutions for nuclear waste decommissioning, showing that remotely controlled robots can perform perception, grasping, cutting, sorting, and disposal tasks in radioactive environments [6].

Mascarich et al. discussed robotic support for nuclear site decommissioning and emphasized radiation detection, mapping, navigation in degraded visual conditions, and field verification [7]. Lee and Park introduced a dual-arm telerobotic platform for nuclear waste disposition, demonstrating the importance of teleoperation stations, dexterous manipulators, and real-time operator control [9]. Chiou et al. examined robot-assisted nuclear disaster response and highlighted the need for reliable human-robot interaction during field operations [10].

For biomedical waste, safe handling and segregation are essential because untreated or improperly handled waste can spread infection and environmental contamination. Studies on health-care waste show that reliable segregation, collection, and treatment are important for reducing risk [2], [11]. In such applications, a low-cost robotic arm can reduce direct manual contact during collection and handling. On the embedded control side, Arduino UNO provides a practical prototyping platform based on the ATmega328P microcontroller [12], while the L298 dual H-bridge driver is commonly used for driving DC motors and stepper motors from TTL logic inputs [13]. The HC-05 Bluetooth module enables serial wireless communication and is suitable for short-range robotic control [14].

The literature indicates that advanced industrial robots are effective but costly, while simple educational robots often lack integrated mobility, monitoring, and manipulation. The proposed work bridges this gap by presenting a compact prototype that combines wireless operation, mobile locomotion, camera feedback, and mechanical handling.

3. Research Gap

- Existing industrial hazardous-environment robots are costly and difficult to implement in academic and small-scale environments.
- Many mobile robots provide locomotion but lack a useful arm and gripper for physical waste manipulation.
- Many robotic arms are fixed-base systems and cannot travel across a hazardous site.
- Low-cost Bluetooth robots often do not include night vision monitoring, mechanical design validation, or systematic performance analysis.
- There is a need for a modular prototype that can be upgraded later with gas sensors, radiation detectors, object recognition, and autonomous navigation.

4. Problem Statement

The management of hazardous waste in nuclear, biomedical, and chemical sectors exposes workers to dangerous materials and unsafe operating conditions. Traditional handling methods can be slow, risky, and dependent on direct human intervention. Existing low-cost robotic solutions may lack sufficient mobility, precise manipulation, real-time monitoring, or validated mechanical design. Therefore, a remotely operated robotic system is required that can move in hazardous zones, provide visual feedback, handle lightweight waste objects, and reduce human exposure.

5. Objectives

1. To design and develop a Bluetooth-controlled robotic arm vehicle for hazardous waste inspection and handling.
2. To implement Arduino-based control using HC-05 Bluetooth communication and L298N motor drivers.
3. To provide four-wheel mobility for controlled navigation in hazardous work areas.
4. To integrate a night vision camera for real-time monitoring in low-light environments.
5. To design articulated arm and gripper motions for collecting, holding, and releasing lightweight objects.
6. To validate mechanical safety using torque, stress, weld, pipe, and battery calculations.

6. Existing System and Limitations

Existing hazardous waste handling methods can be classified into three main groups: manual handling, semi-automatic handling, and industrial remote robotics. Manual handling uses protective equipment but cannot fully eliminate exposure risk. Semi-automatic systems such as trolleys, fixed grippers, and collection bins reduce effort but still require human presence. Industrial robots used in nuclear or chemical facilities provide high capability but require high investment, trained operators, and specialized infrastructure.

The major limitations of existing methods are high exposure risk, limited monitoring in dark areas, inadequate object manipulation, high cost, and poor flexibility in small-scale environments. These limitations create the need for a compact and low-cost robotic arm vehicle that provides both movement and manipulation.

7. Proposed System

The proposed system is a Bluetooth-controlled robotic arm vehicle for hazardous waste handling. It includes a four-wheel drive base, Arduino UNO controller, HC-05 Bluetooth communication, L298N motor driver circuits, PMDC gear motors, a night vision camera, articulated arm links, and a gripper. The operator sends movement and manipulation commands wirelessly. The robot executes the command and provides camera-based visual feedback for remote inspection.

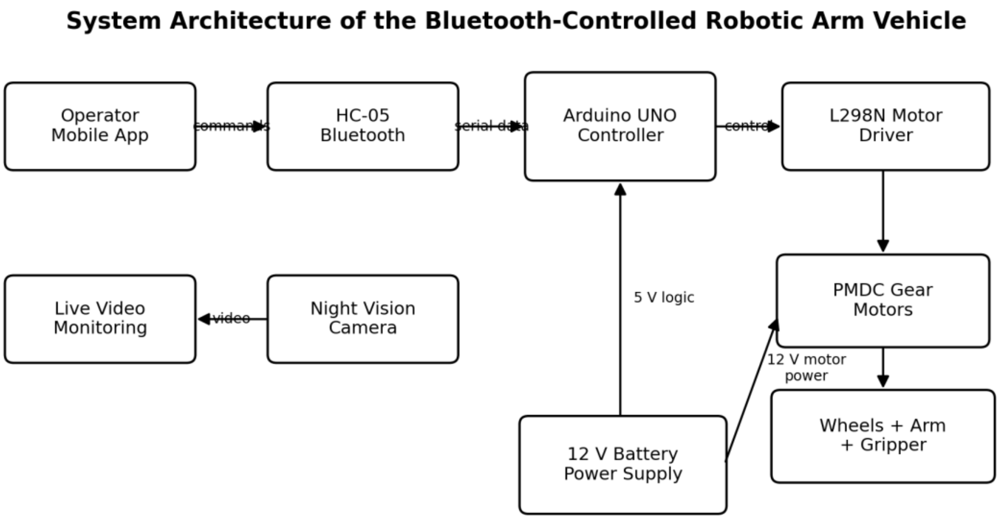

Figure 1. System architecture of the Bluetooth-controlled robotic arm vehicle.

7. System Components

Table 1. Major hardware components used in the proposed system.

Sr. No.	Component	Function
1	Arduino UNO	Main control unit for receiving commands and driving output signals.
2	HC-05 Bluetooth Module	Provides short-range wireless serial communication between operator device and robot.
3	L298N Motor Driver	Dual H-bridge motor driver used to control direction and power of DC motors.
4	PMDC Gear Motors	Used for wheel motion and robotic arm movement because gear reduction provides higher torque.
5	Night Vision Camera	Enables visual inspection and operation in low-light hazardous areas.
6	Four-Wheel Chassis	Provides stability and mobility for movement across the work area.
7	Robotic Arm and Gripper	Provides picking, holding, shifting, and releasing of lightweight hazardous objects.
8	Lead-Acid Battery	Supplies portable power to motors and electronic components.

9. METHODOLOGY

The research methodology follows a practical engineering development sequence. First, the topic and application area were identified. Next, literature related to hazardous waste robotics and remote handling was reviewed. Material and component selection was carried out according to strength, availability, cost, and suitability. CAD modelling and calculations were used to validate the mechanical design. After fabrication, electronics were integrated and Arduino code was tested. Finally, movement, gripping, camera monitoring, and structural performance were evaluated.

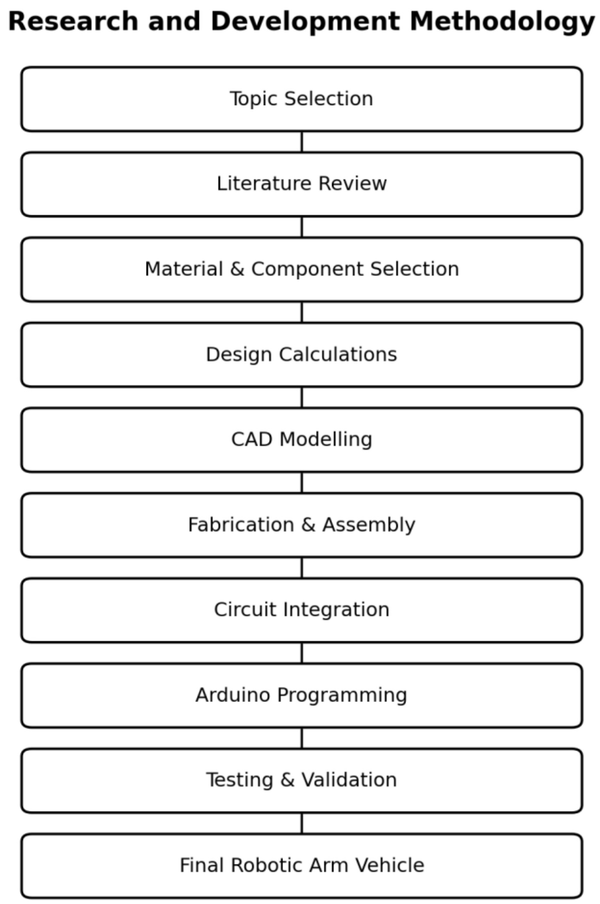

Figure 2. Research and development methodology.

10. Algorithm / Working Flow

The robot operates through a command-based flow. The user pairs the control device with the HC-05 module and sends commands. Arduino reads the command and activates the correct motor driver outputs. Depending on the command, the robot performs vehicle movement, arm movement, or gripper operation. The camera provides continuous visual monitoring. The command cycle continues until the user stops the robot.

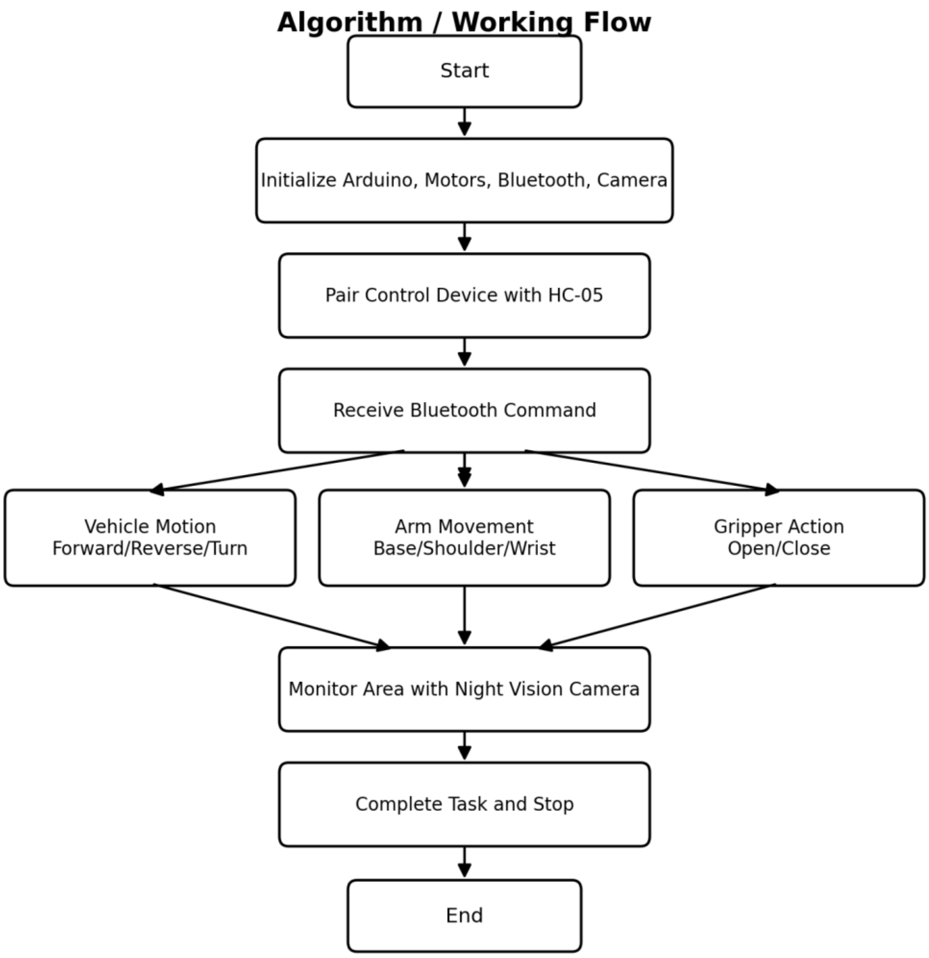

Figure 3. Algorithm and working flowchart of the robotic arm vehicle.

Pseudo-code

Start

Initialize Arduino pins, motor drivers, Bluetooth serial port and camera system

Pair operator device with HC-05 module

While robot power is ON:

Read Bluetooth command

If command = Forward: rotate wheel motors forward

Else if command = Backward: rotate wheel motors backward

Else if command = Left/Right: control wheel direction for turning

Else if command = Arm Up/Down: operate corresponding arm motor

Else if command = Gripper Open/Close: actuate gripper motor

Else if command = Stop: stop all motors

Display/observe live camera feedEnd

11. Mechanical Layout

The mechanical layout consists of a mild steel chassis carrying the battery, motor drivers, Arduino controller, camera, wheels, arm mechanism, and gripper. The design uses mild steel due to its low cost, availability, weldability, machinability, and suitable strength for prototype fabrication. The robot is designed for slow and controlled movement rather than high-speed travel, which is appropriate for hazardous waste handling.

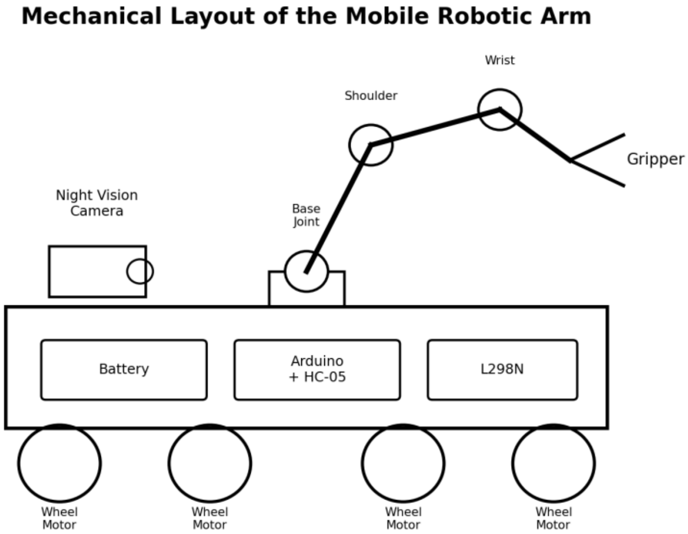

Figure 4. Schematic mechanical layout of the mobile robotic arm.

12. Design Calculations and Equations

Important design calculations were performed to verify that selected motors, shafts, welded joints, and square pipe members are safe for the expected load. The following equations were used in simplified design validation:

- Motor torque: $T = F \times r$
- Wheel force: $F = T / r$
- Bending stress in shaft: $\sigma = M / Z$
- Weld stress: τ = Load / Effective weld area
- Battery charging time ≈ Battery capacity / Charging current
- Battery discharge time ≈ Battery capacity / Load current

These calculations are suitable for prototype-level validation. For industrial deployment, detailed finite element analysis, environmental qualification, radiation testing, and fail-safe certification would be required.

13. RESULTS AND DISCUSSION

The design results from the project report show that the robotic arm vehicle works within safe structural limits. The wheel motor torque of 9.54 N-m provides sufficient force for low-speed movement. The vehicle speed of 0.07 km/hr is slow but suitable for precision hazardous waste handling. The shaft bending stress is 58.96 N/mm², which is lower than the allowable stress value, indicating safe shaft design. The welded joint stress and square pipe stress are also within permissible limits. Battery calculations show 3.5 h charging time and approximately 2.1 h operating time, which is suitable for intermittent prototype testing and demonstration.

Table 2. Summary of design calculation results.

Sr. No.	Parameter	Calculated Value	Discussion
1	Wheel motor torque	9.54 N-m	Sufficient for low-speed vehicle movement
2	Wheel force	272.8 N ≈ 27.8 kg	Adequate support capacity per wheel
3	Motor shaft bending stress	58.96 N/mm²	Safe below 270 N/mm² allowable limit
4	Vehicle speed	0.07 km/hr	Suitable for controlled hazardous-area tasks
5	Second arm motor lifting force	≈ 4.8 kg	Suitable for lightweight object handling
6	Third arm motor lifting force	≈ 2.8 kg	Suitable for gripper-end load
7	Transverse fillet weld stress	21 N/mm²	Safe for designed load
8	Battery charging time	3.5 h	Acceptable for prototype operation
9	Battery operating time	2.1 h	Suitable for intermittent usage
10	Square pipe bending stress	15.79 N/mm²	Safe below 90 N/mm² limit

The results confirm that the chosen materials and components are appropriate for a low-cost prototype. The system is not intended for heavy industrial payloads in its present form, but it can safely demonstrate remote hazardous object handling, inspection, and surveillance.

14. Advantages

- Reduces direct human exposure to hazardous substances.

- Enables wireless operation through Bluetooth communication.
- Provides camera-based monitoring in dark or low-light areas.
- Combines mobility and manipulation in one prototype.
- Uses low-cost and easily available components.
- Provides modular design for future sensor and software upgrades.
- Suitable for academic demonstration, training, and prototype development.

15. Limitations

- Bluetooth communication range is limited compared with Wi-Fi, LoRa, RF, or 5G communication.
- The current prototype is suitable only for lightweight objects.
- The robot is manually controlled and does not yet include autonomous navigation.
- Radiation, gas, temperature, and chemical sensors are proposed but not included in the current prototype.
- Battery runtime may not be sufficient for long industrial operations.
- The current structure requires additional sealing and ruggedization for real hazardous environments.

16. Applications

- Biomedical waste collection and handling in hospitals and laboratories.
- Nuclear waste inspection and remote observation.
- Chemical spill inspection and sample handling.
- Low-light surveillance in restricted zones.
- Disaster response and unsafe area assessment.
- Training and academic robotics demonstration.
- Industrial safety prototyping and remote material handling research.

17. Future Scope

- Add gas sensors, radiation detectors, temperature sensors, and humidity sensors for real-time hazardous environment monitoring.
- Replace Bluetooth with Wi-Fi, LoRa, ZigBee, RF, or 5G communication for long-range control.
- Develop a dedicated Android application with live camera display and joystick-style controls.

- Add ultrasonic/LiDAR sensors for obstacle detection and collision avoidance.
- Implement autonomous navigation using SLAM, path planning, or line-following algorithms.
- Use stronger lightweight materials and improved actuators for increased payload capacity.
- Integrate AI-based object detection for automatic waste classification and safe picking.
- Improve power system by using lithium-ion batteries and battery management circuitry.
- Add fail-safe stop, overload protection, and emergency return functions for safer deployment.

18. CONCLUSION

This research paper presented a Bluetooth-controlled robotic arm vehicle for hazardous waste handling in nuclear, biomedical, and chemical environments. The system integrates Arduino UNO, HC-05 Bluetooth communication, L298N motor drivers, PMDC gear motors, a night vision camera, a four-wheel mobile base, articulated arm movement, and a gripper. The robot allows an operator to inspect and manipulate lightweight hazardous objects from a safe distance.

Mechanical validation shows that the selected motors, shaft, welded joints, and square pipe structure are safe for the designed prototype conditions. The calculated values for motor torque, shaft stress, welded joint stress, battery charging time, battery operating time, and square pipe bending stress support the reliability of the prototype. The proposed system improves safety by reducing direct human intervention and offers a practical platform for future development in remote hazardous waste management robotics.

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