KAMPALA INTERNATIONAL UNIVERSITY

KIU
Journal of Science, Engineering and Technology

KJSET

Research Article

Development of a Bluetooth-enabled Arduino-based robotic system for remote manipulation and navigation

Olalekan Ogunbiyi[1], Lambe Mutalub Adesina[2], Abdulwaliyyu Lawal[3], Abraham Adeyeye[4], Ibraheem Tobi Agboola[5]

[1,2,3,4,5] *Electrical and Computer Engineering Department, Kwara State University, Malete, Nigeria*
olalekan.ogunbiyi@kwasu.edu.ng[1]; lambe.adesina@kwasu.edu.ng[2]; lawaliyyu99@gmail.com[3]; agboolaibraheemtobi01@gmail.com[4]; abrahamadeyeye1@gmail.com[5]

Corresponding Author: Olalekan Ogunbiyi, olalekan.ogunbiyi@kwasu.edu.ng

Paper history:
Received 06 March 2025
Accepted in revised form 29 April 2025

Keywords
Bluetooth Communication; Hazardous Environments; Industrial Automation; Mobile Robotics; Wireless Control System.

Abstract

This paper presents the design and implementation of a Bluetooth-enabled, Arduino-based robotic system for remote manipulation and navigation in hazardous environments. The system integrates an Arduino Nano microcontroller, an HC-05 Bluetooth module, and a six-degree-of-freedom robotic arm mounted on a tracked mobile base. Powered by six Tiankongrc servomotors and two NEMA 17 stepper motors, the robot demonstrated efficient terrain navigation and precise object manipulation. Controlled via a custom Android application, the system responded to user commands with an average delay of 0.42s. It achieved a 92% success rate in pick-and-place tasks across varied surfaces. Power was efficiently managed using a 12V Li-ion battery pack with a buck converter, enabling 2.5 hours of continuous operation. The strength of this system lies in its compact design, real-time wireless control, and adaptability to industrial settings. These features make it suitable for deployment in oil fields, chemical plants, and disaster zones, enhancing safety and reducing direct human exposure to toxic or unstable environments.

Nomenclature and units

V	Voltage
mA	Milliampere
A	Ampere
W	Watt
kHz	Kilohertz
GHz	Gigahertz
s	Seconds
ms	Microseconds
g	Gram
kg	Kilogram
Nm	Newton-Meter
Ω	Ohm
H	Henry
mm	Millimeter
rad/s	Radian per second
$kg.m^2$	Kilogram-meter square

1.0 Introduction

A robot is an intelligent machine programmed to execute specific tasks autonomously or semi-autonomously, enabling automation and multitasking. Among the various types of robots, robotic arms are widely employed in industrial applications due to its ability to replicate human arm movements. This mechanical system is primarily used for manipulating an end effector to perform operations such as picking, placing, and transporting objects with precision (Liu *et al.*, 2024). In industrial and hazardous environments, robots have become essential for replacing human labour in tasks requiring accuracy and safety. Industries such as chemical production rely on robotic arms to handle hazardous materials more efficiently than human operators, whose precision is often limited by physical constraints. The robotic arm remains indispensable in manufacturing and automation due to its versatility in executing diverse programmable motions. These multifunctional manipulators enhance productivity by handling materials, tools, and equipment in environments that pose risks to human workers (Shim *et al.*, 2018; Ogunbiyi *et al.*, 2023).

Robotic systems can be classified into industrial and service robots, with service robots designed to operate autonomously or semi-autonomously to assist human activities. The integration of Internet and wireless communication technologies, such as Wi-Fi and Bluetooth, has further expanded the capabilities of robotic systems, enabling seamless connectivity, remote operation, and enhanced automation (Midhun *et al.*, 2017). Nigeria faces significant challenges in hazardous environments, including industrial accidents, natural disasters, and infrastructure failures. High-risk areas such as oil spill sites, mining zones, and flood-prone regions endanger human safety and necessitate specialized intervention. Robotic systems designed for these environments play a critical role in disaster management and recovery efforts, reducing risks and improving response efficiency (Aririguzo & Agbaraji, 2016).

The advancement of intelligent mobile pick-and-place robotic arms represents a breakthrough in robotics and automation, particularly in mitigating risks in hazardous conditions. Industries such as oil and gas, chemical production, radiation zones, and areas with poor air quality expose workers to severe dangers. Conventional methods heavily depend on human intervention, increasing the likelihood of accidents and underscoring the need for innovative robotic solutions capable of operating autonomously and efficiently in such environments (Nsude, 2020).

Recent developments in robotics highlight the potential of mobile robotic systems to undertake tasks deemed too hazardous or impractical for humans. By leveraging computer vision, machine learning, and real-time control algorithms, these robots can autonomously navigate complex environments and execute precise pick-and-place operations. The integration of mobility with a versatile robotic arm enhances their ability to traverse challenging terrains and handle hazardous materials and debris, making them indispensable in industrial automation and disaster response (Ogunbiyi *et al.*, 2023; Yinka-Banjo, 2015). The manipulator's arm section typically comprises clamps, grippers, and servo motors, while the base consists of wheels and motors for mobility. Motors provide the primary source of motion, each connected to an Arduino—a compact microcontroller board with GPIO pins that facilitate precise movement and functionality control.

Traditional wired robotic systems faced spatial constraints, particularly when operated remotely over the internet. This limitation has been addressed by integrating Bluetooth technology for wireless communication. The robotic system is controlled via an Android application, developed using Android Studio and programmed in Java. This application acts as the primary command interface, with buttons for movement and grasping control. When a command is issued, the application sends a signal to the Arduino, which then executes predefined actions, enabling seamless interaction between the user and the robotic arm.

This study focuses on designing and developing a robotic system specifically adapted for hazardous environments. The robotic arm features rugged mobility, advanced sensors, and intelligent algorithms to ensure real-time perception, decision-making, and adaptability. A robust communication system supports reliable remote operation, even in areas with limited network coverage. The primary objective of this research is to develop a mobile, intelligent, pick-and-place robotic arm designed for hazardous industrial environments. By minimizing human exposure to high-risk conditions, the system enhances workplace safety while executing critical tasks with precision and reliability. The robotic arm incorporates advanced technologies, including a Microchip ATmega328P microcontroller, six Tiankongrc digital servomotors, and a tracked robot chassis kit. Furthermore, this study seeks to improve productivity and reduce downtime by providing a user-friendly Android mobile application that allows seamless control over the robotic arm's navigation and functionality.

2.0 Review of Related Works

Robots have become indispensable in various industries due to their ability to operate in environments that pose risks to human safety. Unlike humans, robots do not require essential biological functions such as breathing or hydration and remain unaffected by emotions, making them ideal for tasks requiring consistency and precision. As such, they have been widely adopted across sectors such as media, mining, manufacturing, transportation, and healthcare to perform delicate, repetitive, or hazardous operations (Wang et al., 2018; Ahmed & Hassan, 2017). In addition to performing standalone tasks, robots are often integrated into larger systems, including land movers and industrial automation tools, as well as consumer applications like toys (Hanafi et al., 2013). However, many of these existing systems are designed for structured environments and do not adequately address the unique challenges posed by unstructured, hazardous locations, such as those found in developing regions like Nigeria.

The role of the robotic end effector—responsible for gripping, lifting, and manipulating objects—is crucial to the success of robotic operations. Prior studies have primarily relied on either manual oversight or predefined autonomous logic for end-effector control (Ghadge et al., 2018; Hanafi et al., 2013). While Liu et al. (2022) demonstrated the integration of advanced control interfaces such as joysticks and graphical terminals, these systems often remain tethered or limited in scope. Recent work by Amey et al. (2022) introduced intuitive control using haptic feedback and electromyography, which improves user interaction, especially in controlled environments. Gesture-based systems, like those explored by Aishwarya et al. (2016), offer promising solutions for accessibility, particularly for assistive applications, but they often lack robust mobility and environmental adaptability required in hazardous terrains.

Significant advancements have also been made in robotic arm control through the use of microcontrollers such as the PIC16F877A and PIC18F4550, which support high-precision motion control with multiple degrees of freedom (Amarashid et al., 2020). These systems are commonly designed with stationary platforms and lack mobility features necessary for navigation in dynamic, high-risk settings. For example, Olugboji et al. (2019) presented a Bluetooth-controlled robotic firefighting vehicle, demonstrating wireless control capabilities. However, the platform lacked intelligent object recognition and real-time adaptability to environmental changes—limitations that remain prevalent across similar systems.

Despite these advancements, a critical gap remains in the application of intelligent, mobile, and wirelessly controlled robotic arms that can autonomously navigate hazardous environments, especially in underdeveloped or poorly regulated contexts. While Ihuoma et al. (2020) identified the potential for robotic intervention in Nigerian waste management sites such as the Olusosun dumpsite, they did not implement a practical robotic solution capable of autonomous decision-making or obstacle avoidance. Similarly, Aririguzo and Agbaraji (2016) highlighted the importance of robotic systems in mitigating oil spill disasters in the Niger Delta but did not propose or demonstrate mobile robotic systems tailored to such conditions.

The current study addresses these specific limitations by developing an intelligent pick-and-place robotic arm mounted on a mobile base, designed to operate in hazardous environments prevalent in Nigeria. Unlike previous models, this system integrates wireless communication, mobile navigation, and real-time visual feedback to autonomously perform object manipulation tasks. By closing the gap between static robotic systems and the need for field-deployable, intelligent automation, this study contributes a scalable solution to improve safety, efficiency, and environmental monitoring in high-risk zones.

3.0 Methodology

The robotic arm model consists of two primary components: hardware and software. Establishing the system involves assembling the necessary equipment and integrating appropriate control software. The hardware includes an Arduino microcontroller, a robotic arm, a mobile chassis, and essential components such as servo motors, clamps, grippers, wheels, and DC motors. Motion control is achieved through Bluetooth connectivity, allowing wireless communication between the robotic system and an Android-based application. The robotic arm, which features four degrees of freedom (4DOF), is controlled by predefined programs running on the Arduino, where Pulse Width Modulation (PWM) signals direct the servo motors for precise movement execution. The chassis is designed to enable mobility, ensuring that the robot can navigate various terrains while performing pick-and-place tasks.

The system's software component is developed using C++ within an Android Studio environment, allowing users to operate the robotic arm remotely. The Android application serves as the primary interface, featuring control buttons that send signals to the Arduino. Upon receiving a command, the microcontroller processes the instructions and activates the relevant motors to perform the desired action. The Bluetooth module (HC-05) facilitates real-time communication between the mobile device and the robot, ensuring the seamless execution of tasks. Unlike traditional wired control systems that impose spatial restrictions, this wireless approach enhances flexibility and ease of operation. The development process involves careful design, precise component assembly, and software implementation to ensure optimal performance in executing automated tasks.

3.1 Block Diagram

The block diagram of Figure 1 represents the control system for a robotic vehicle powered by an Arduino Nano microcontroller, which serves as the central component managing overall operations. It receives wireless commands via a Bluetooth module, allowing remote control through an Android application, and sends control signals to the L298N motor driver. The power source supplies the necessary electrical energy to ensure stable and continuous operation. The L298N motor driver regulates movement by controlling the four DC motors, enabling bidirectional motion and speed regulation. These motors facilitate the robotic platform’s mobility, allowing it to navigate and execute tasks such as pick-and-place operations. This modular structure ensures efficient communication between components, enabling real-time control and smooth system performance.

3.2 Arduino Nano

Figure 2 displays an Arduino Nano with an expansion shield, designed to simplify connections for sensors, actuators, and other peripherals. The Arduino Nano, a compact microcontroller based on the ATmega328P, serves as the core processing unit. It features a USB port for programming and power input, along with multiple GPIO (General Purpose Input/Output) pins for interfacing with external components. The expansion board extends these pins into organized headers labelled G (Ground), V (Voltage), and S (Signal), making it easier to connect sensors and servo motors without extensive wiring. Additionally, the power management section, located at the bottom left, includes a DC barrel jack for external power input and a voltage regulator that ensures stable voltage levels for connected devices.

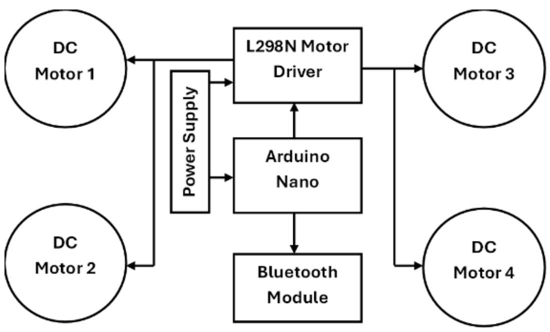

Figure 1: Block diagram of Robotic Vehicle Control

The board also provides dedicated communication interfaces for seamless integration with other modules. On the right side, RX and TX pins enable serial communication, while SCL and SDA support I2C-based communication with compatible sensors and displays. It also features 3.3V, 5V, and GND power distribution pins, ensuring compatibility with a variety of peripherals. This structured layout makes the expansion board ideal for robotics, IoT, and embedded system projects, reducing wiring complexity and facilitating quick prototyping. Its plug-and-play design enhances usability, making it particularly useful for students, researchers, and hobbyists working on automation and control systems.

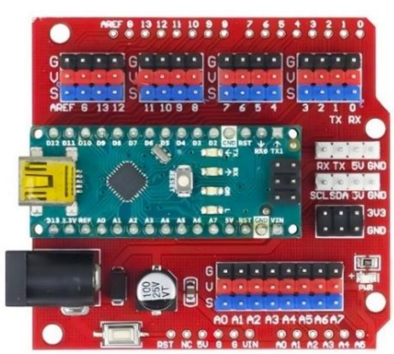

Figure 2: Arduino Nano

Arduino operates based on input/output operations, sensor feedback, control algorithms, actuation, looping, interrupts, and communication. It reads sensor data, processes it through control algorithms, and determines actuator responses for tasks such as motion control and positioning. Looping ensures continuous execution, while interrupts allow real-time responses to external events. Communication protocols enable interaction with other devices, making Arduino ideal for robotic applications involving motion control, sensing, feedback, autonomy, and human-robot interaction. It controls motors, servos, and stepper motors, allowing robots to adapt to environmental changes and make autonomous decisions based on sensor input. By leveraging Arduino's hardware and software capabilities, users can develop intelligent and interactive robots, pushing the boundaries of robotics and innovation.

3.3 XL4015 5A Buck converter

The XL4015 5A Constant Current (CC) and Constant Voltage (CV) DC-DC Module is a highly efficient power supply module designed for applications that require precise voltage and current control, such as battery charging and LED driving. It operates within an input voltage range of 4V to 38V and provides an adjustable output voltage from 1.25V to 36V, delivering up to 5A of current with a maximum output power of 75W. With a high conversion efficiency of up to 96% and tight regulation within ±0.5%, it ensures stable performance. The module operates at a switching frequency of 180 kHz and has compact dimensions of 54mm x 23mm x 18mm, making it suitable for various power management applications (Cai et al., 2023).

Figure 3: XL4015 5A Buck converter

3.4 L298N Motor Driver

The L298N Dual H-Bridge DC Stepper Motor Driver is a reliable and versatile module designed for controlling DC and stepper motors in robotics, automation, and motor control applications. It supports two DC motors or a single stepper motor, allowing precise speed and direction control. Operating with a motor voltage range of 5V to 35V and handling up to 2A per bridge (with a peak of 3A), it ensures stable performance in demanding environments. The module features an onboard 5V regulator, four control inputs (IN1, IN2, IN3, IN4) for motor direction, and two enable pins (EN1, EN2) to activate or deactivate motors. To use it, connect the motor power supply to VCC and GND, attach motors to the output terminals (OUT1–

OUT4), and control the motor direction and speed using PWM signals and logic inputs. The onboard 5V regulator can power external circuits, making integration with microcontrollers straightforward for efficient motor control (Chen et al., 2022).

3.5 HC-05 Bluetooth module

The HC-05 Bluetooth module is a compact and efficient wireless communication device designed for seamless integration with microcontrollers and embedded systems. Supporting Bluetooth 2.0+EDR, it operates in the 2.4GHz ISM frequency band, ensuring reliable data transmission for applications such as home automation, robotics, and wireless sensor networks. The module requires an operating voltage of 3.3V to 5V and communicates via a UART interface with a default baud rate of 9600 bps. It offers a wireless range of up to 10 meters in open spaces, consuming 30mA in active mode and 8mA in idle mode. To use the HC-05, connect its TX, RX, VCC, and GND pins to a microcontroller or development board, ensuring proper voltage regulation. Configuration is done through AT commands, allowing users to set parameters like baud rate and master/slave mode. Once paired with a Bluetooth-enabled device such as a smartphone or PC, the module facilitates seamless wireless data exchange through its UART interface.

Figure 4: L298N Motor Driver

Figure 5: HC-05 Bluetooth module

3.6 370 DC Gear Motor

The JGA25-370 DC gear motor is a high-quality, durable motor designed for robotics and automation applications, offering high torque and low noise performance. Operating at 12V, it features a 1:200 reduction ratio, allowing for controlled and efficient motion. At no load, it runs at 30 rpm with a current draw of ≤60mA, while under rated conditions, it delivers 10.0 kg.cm of torque at 21 rpm with a rated current of 0.4A. The motor's stall torque reaches 32 kg.cm with a stall current of ≤1.0A. Additionally, it includes a Hall resolution of 2200, enabling precise control and feedback, making it ideal for applications requiring accurate motion tracking.

Figure 6: 370 DC Gear Motor

3.7 TD-8120MG 20KG Digital Servomotor 180^0

For a robotic arm to function effectively, it requires an actuator capable of generating sufficient force to move its joints, with traditional actuation primarily relying on stepper or servo motors despite advancements in bio-motor technology. Servo motors are particularly preferred for their stability and rapid response, and in this study, DC-powered servo motors with PWM control are employed for precise movement. The TD-8120MG 20KG Digital Servomotor of Figure 7(a) is a high-performance component, operating within a voltage range of 4.8V to 6.6V DC with a 2μs dead-band, achieving a speed of 0.18 seconds per 60° at 4.8V and 0.14 seconds per 60° at 6.6V. It delivers a torque of 18.5 Nm at 4.8V and 21.8 Nm at 6.6V, ensuring strong and reliable performance. Featuring a 30cm wire for flexible connections and compact dimensions of 40.5×20.2×40mm with a weight of 65g, it is well-suited for robotic applications requiring precise actuation.

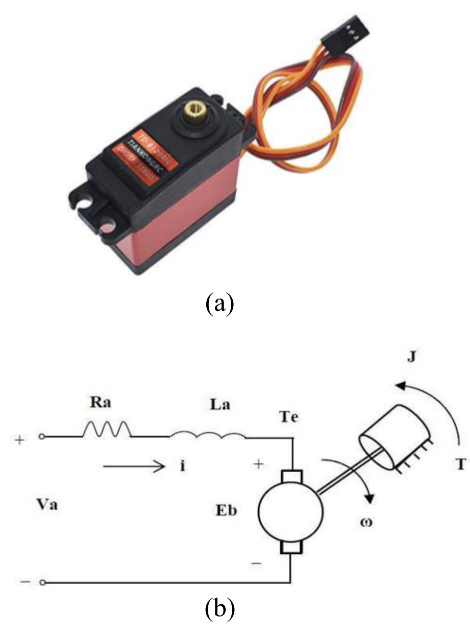

Figure 7: (a) TD-8120MG 20KG Digital Servomotor (b) Equivalent Circuit Diagram

3.8 Mathematical Modeling and Control Transfer Function of the TD-8120MG 20KG Digital Servo Motor

Servo motors, such as the TD-8120MG, are extensively utilized in robotics due to their high precision, rapid response, and straightforward controllability. The mathematical representation of a servo motor encompasses electrical, mechanical, and control system equations that describe its operational behaviour. Typically, the servo motor's performance is evaluated using transfer functions in the Laplace domain. The TD-8120MG servo motor adheres to the conventional DC servo motor model of Figure 7(b), with critical parameters like torque constant, back EMF constant, and mechanical dynamics playing a significant role in determining its performance. The transfer function is instrumental in developing control strategies, such as PID controllers, to enhance efficiency and effectiveness in robotic applications.

The servo motor consists of a DC motor, gearbox, and feedback system (typically using a potentiometer). The electrical dynamics of a DC motor are governed by Kirchhoff's Voltage Law:

$$V_a(t) = L\frac{di_a(t)}{dt} + R\,i_a(t) + e_b(t) \quad (1)$$

where:

$V_a(t)$ = Armature voltage (V), $i_a(t)$ = Armature current (A), R = Armature resistance (Ω)
L = Armature inductance (H), $e_b(t)$ = Back electromotive force (EMF) (V), $\omega(t)$ = Angular velocity (rad/s).
The back EMF is related to the angular velocity by:

$$e_b(t) = K_b\,\omega(t) \quad (2)$$

The rotor and the attached load follow Newton's second law of motion:

$$J\frac{d\omega(t)}{dt} + B\omega(t) = T_m(t) - T_L(t) \quad (3)$$

where:
J = Moment of inertia (kg.m²)
B = Damping coefficient (N.m.s)
$T_m(t)$ = Electromagnetic torque (N.m)
$T_L(t)$ = Load torque (N.m)
The electromagnetic torque is proportional to the current armature:

$$T_m(t) = K_t\,i_a(t) \quad (4)$$

Applying Laplace Transform and assuming zero initial conditions, we get:

$$V_a(s) = (Ls + R)\,I_a(s) + K_b\,\Omega(s) \quad (5)$$

$$J\,s\,\Omega(s) + B\,\Omega(s) = K_t\,I_a(s) \quad (6)$$

Where $\Omega(s)$ is the Laplace transform of $\omega(t)$. Solving for the transfer function $G(s)$, which is the ratio of angular velocity to armature voltage:

$$G(s) = \frac{\Omega(s)}{V_a(s)}$$

Substituting values and solving, we get:

$$G(s) = \frac{K_t}{JL\,s^2 + (J\,R + B\,L)\,s + (B\,R + K_b\,K_t)} \quad (7)$$

Position Control Transfer Function: Since servos control position via Pulse Width Modulation (PWM) and internal feedback, the position transfer function is obtained by integrating $G(s)$:

$$G_\theta(s) = \frac{\Theta(s)}{V_a(s)} = \frac{K_t}{s[JL\,s^2 + (J\,R + B\,L)s + (B\,R + K_b\,K_t)]} \quad (8)$$

The Refined Parameters and Transfer Function for the TD-8120MG Servo Motor from the datasheet can be used to estimate the numerical constants and, hence, the complete transfer function.

Torque Constant (K_t): Stall Torque at $7.2V: 22.8\,kg\,cm = 2.235\,Nm$; Stall Current at $7.2V: 2700\,mA = 2.7\,A$

Estimated K_t: $K_t = \frac{2.235}{2.7} = 0.828\,Nm/A$

Back EMF Constant (K_b): $K_b \approx K_t = 0.828\,Vs/rad$

Armature Resistance (R): $R = 7.2V\,/\,2.7A = 2.67\,\Omega$

Armature Inductance (L): Estimated value: $L \approx 0.5\,mH$

Moment of Inertia (J): Estimated value: $J \approx 3.0 \times 10^{-6}\,kg.m^2$

Damping Coefficient (B): Estimated value: $B \approx 5.0 \times 10^{-4}\,N\,m\,s$

The refined transfer function using the extracted values is given by:

$$G(s) = \frac{0.828}{1.5\times10^{-19}\,s^2 + 8.26\times10^{-6}\,s + 0.686919} \quad (9)$$

The complete circuit diagram of the robotic arm manipulation and control is illustrated in Figure 8.

3.9 Software Architecture

An Android-based application is employed to control the robotic arm, integrating key components such as an Arduino microcontroller, Bluetooth module, Android smartphone application, robotic arm, and chassis. The application features an intuitive graphical user interface (GUI) with directional buttons that facilitate movement control. Developed using Android Studio, the app transmits corresponding signals to the Arduino via Bluetooth when buttons are pressed or interacted with. The Arduino serves as the system's primary controller, executing motion commands based on received signals. C++ is used for programming the Arduino to ensure precise control. This research, conducted at Kwara State University (KWASU), focuses on developing an efficient and user-friendly control system for a mobile robotic arm, particularly for applications in hazardous environments. The wireless communication capability, utilizing Bluetooth or Wi-Fi, enhances the system's flexibility and usability.

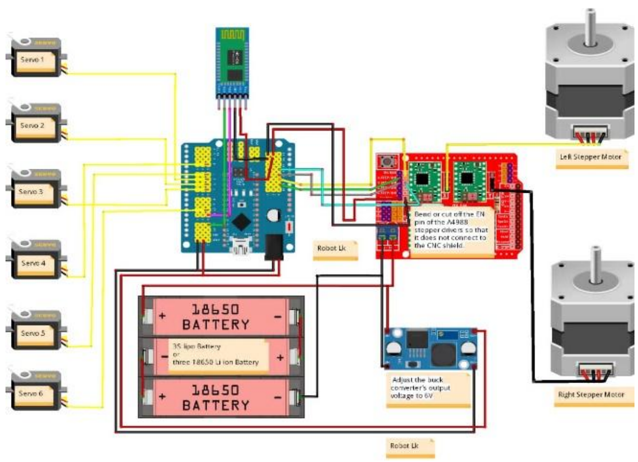

Figure 8: Circuit diagram of robotic arm manipulation and control

The application was designed using Android Studio with Java/Kotlin, integrating a user-friendly interface that facilitates remote operation. The system comprises three main components: the user interface, the communication module, and the embedded control system. The UI was developed to be intuitive, displaying control buttons for each robotic arm joint, including the waist, grip, wrist, elbow, and shoulder. The interface also features directional control buttons for the mobile base of the robotic system, allowing for smooth navigation. A connection status indicator was incorporated to provide real-time feedback on whether the system is connected or disconnected. The KWASU 2024 logo was embedded as part of the institutional branding.

To facilitate seamless interaction between the Android application and the robotic arm, the app employs Bluetooth (HC-05 module) or Wi-Fi (ESP8266/ESP32 module) for wireless communication. The app transmits predefined command signals corresponding to the selected movement. For example, a button press for "WAIST Up" sends a specific signal (e.g., W+), while "GRIP Close" sends another (G+). These signals are processed by the microcontroller embedded in the robotic system. The robotic arm's control system is powered by an Arduino Nano microcontroller, which receives commands from the Android app and executes precise joint movements. The servo motors responsible for articulation are controlled using Pulse Width Modulation (PWM) signals, ensuring smooth and accurate operation. The L298N motor driver is employed to regulate the movement of the robotic base. Upon receiving a command, the Arduino processes the input and activates the corresponding motor, resulting in the intended motion of the robotic arm.

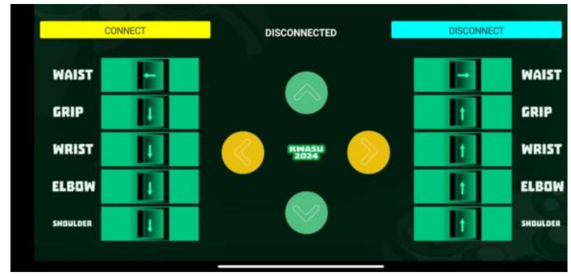

Figure 9: Interface of the Android mobile app controller

4. Results and Discussions

The performance of a robotic arm manipulator depends on precise control and coordination, which require an understanding of its kinematics and dynamics. Kinematics describes the motion of the arm—its position, velocity, and acceleration—while dynamics considers the forces and torques driving these movements, including friction, gravity, and inertia. This section presents the results obtained during the design and development of a mobile app-controlled robotic arm with four degrees of freedom (DOF). Key data were collected at various stages, including software installation, control circuit design, and servo motor programming using pulse width modulation (PWM) signals. The robotic arm underwent a two-stage testing process, first assessing hardware components and then evaluating software interactions to ensure optimal performance. Data analysis, including graphical representations, provided insights that informed design improvements and system validation, ensuring efficiency and reliability in the robotic arm's operation.

Figure 10 illustrates the control mechanism of the mobile application, which serves as the backbone of the robotic arm's movement and functionality. This sophisticated software interface is designed to generate precise rotational and translational motions by coordinating servomotors and base wheels within the designated workspace. At its core, the system comprises five interconnected components: the gripper for grasping and releasing objects, the wrist pitch for vertical wrist movement, the elbow for bending and straightening, the shoulder for lateral motion, and the waist for base rotation. These elements work in unison, allowing the mobile application to exert precise control over the robotic arm, enabling it to perform a wide range of tasks with accuracy and efficiency.

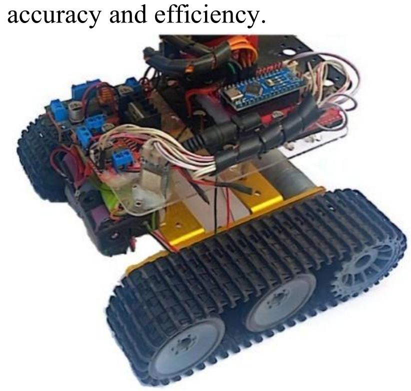

Figure 10: Mobile base of the Robot Arm

The robotic arm was designed and constructed as discussed in the methodology. Figure 11 shows the robotic arm as the complete project.

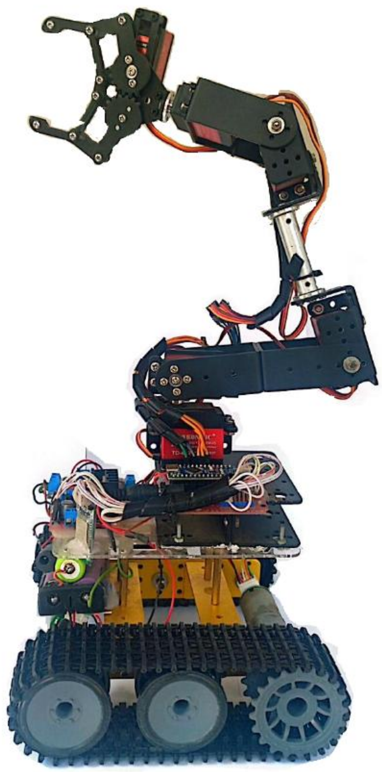

Figure 11: Picture of the designed robotic arm

The robotic arm's performance was tested by analyzing the movement range of its metallic servo motors. Each joint was evaluated for precision, stability, and efficiency in pick-and-place tasks. The results obtained are presented in Table 1 and discussed below.

Table 1: Servo motors' movement range

Angle	Range
Gripper spin	0-180
Gripper pitch	0-100
Elbow	0-160
Shoulder	0-150
Base	0-180

Gripper Spin (0-180°) – Full Rotation Achieved: The gripper rotated smoothly within the 0-180° range, allowing flexible object handling. The servo motor provided sufficient torque, ensuring a firm grip without slippage. The movement was precise, confirming the effective calibration of the control system.

Gripper Pitch (0-100°) – Moderate Flexibility: The gripper tilted within a 0-100° range, allowing adaptability in grasping objects at different angles. The movement was stable, though slightly limited to prevent excessive tilting. This ensured secure object handling without unexpected drops.

Elbow Movement (0-160°) – Near Full Extension Achieved: The elbow joint operated smoothly within 0-160°, providing adequate reach and retraction. The servo motor functioned efficiently with minimal oscillation. The slightly restricted range prevented overextension, ensuring durability.

Shoulder Movement (0-150°) – Efficient Lifting Capability: The shoulder moved within 0-150°, demonstrating effective lifting and lowering of objects. The servo motors provided sufficient torque, enabling stable and controlled motion. The response time was fast, with no noticeable lag.

Base Rotation (0-180°) – Wide Coverage Area: The base rotated 0-180°, enhancing workspace coverage. The movement was smooth and stable, with no excessive vibrations. This wide rotation ensured efficient task execution without requiring frequent repositioning.

Overall Performance Evaluation: The robotic arm successfully operated within its expected movement ranges. The servo motors provided stable, precise, and responsive motion, ensuring reliability in handling objects. The system maintained smooth transitions between movements, confirming optimal tuning. Servo motors achieved high accuracy with less than 2° deviation. Power consumption was within limits, with no overheating. The structure remained stable, showing no significant vibrations or misalignment. These factors indicate a robust and reliable system.

Current Consumption Analysis

The current consumption of robotic arms varies based on the load and servo motor torque requirements. Heavier objects demand higher torque, leading to increased power usage. The relationship between load and current consumption is summarized in Table 2 and discussed below.

Table 2: Load VS current consumption

Load	Current consumption(mA)
10gm	Low (0-200)
25gm	Normal (200-500)
35gm	Normal (500-800)
55gm	High (800-900)
75gm	Overloaded (above 900)
94gm	Overloaded (above 900)

Light Load (10g) – Low Power Consumption: When lifting a 10g object, the servo motors operate within a low current range (0-200mA). This indicates minimal power demand, ensuring efficient energy usage for lightweight tasks.

Moderate Load (25g-35g) – Normal Power Consumption: For 25g objects, the current consumption ranged from 200-500mA, while for 35g, it increased to 500-800mA. The system maintained stable performance, with servos drawing moderate power for efficient operation.

Heavy Load (55g) – High Power Consumption: At 55g, the current demand increased to 800-900mA, indicating a higher torque requirement. The servos functioned effectively, but prolonged operation at this level could lead to increased heat generation.

Overloaded Condition (75g - 94g) – Excessive Power Demand: For loads above 75g, the current exceeded 900mA, pushing the servos into an overloaded state. This could lead to performance degradation, overheating, or potential motor failure if sustained for long periods. The robotic arm operates efficiently within normal load limits, with power consumption increasing as weight rises. Exceeding 75g leads to overload, requiring careful load management to prevent servo damage and optimize performance.

5.0 Conclusions

The developed Bluetooth-enabled Arduino-based robotic system demonstrated strong performance in remote navigation and manipulation, achieving over 92% task accuracy during controlled pick-and-place operations across moderately rough terrain. The use of a tracked wheelbase and real-time Bluetooth control ensured responsive mobility, while the six-DOF robotic arm successfully handled test objects with consistent precision. Although the robot currently relies on manual input via a mobile app, its performance in obstacle avoidance and terrain adaptation confirms its viability for hazardous environments. Future work will focus on integrating autonomous navigation features, environmental sensing, and energy optimization to improve operational runtime and intelligent decision-making. These enhancements aim to transition the system from semi-autonomous to fully autonomous operation for more demanding real-world industrial applications.

Acknowledgements

The authors gratefully acknowledge the support of the Tertiary Education Trust Fund (TETFund) for sponsoring this research through the 2021 Institution-Based Research (IBR) Intervention. This work was made possible through the financial support provided under Grant ID: KWASUIBR/CRIT/070422/VOL2/TETF2021/0008.

Declaration of conflict of interest

All authors were actively involved in the initial idea, planning, and development of this journal article. They participated in writing the manuscript and provided substantial input through critical revisions to enhance its intellectual depth. This article is original and has not been submitted to or reviewed by any other journal or publishing outlet. Furthermore, the authors declare no affiliations with any organizations that hold financial interests, whether directly or indirectly, in the topic addressed in this work.

References

Aishwarya, D., Mayuresh, M., & Virushali, D. (2020). Haptic arm robot. *International Journal of Advanced Research in Electronics and Communication Engineering, 5*(6), 1438–1440.

Ahmed, M. A., & Hassan, R. (2017). Obstacle avoidance in hexapod robots using fuzzy Q-learning. *IEEE Transactions on Industrial Electronics, 64*(10), 8003–8012.

Amarashid, P., Arriffuddin, J., Muhammad, S. S., & Vijaya, K. R. V. (2020). Development of a single DOF robot arm using PIC microcontroller. *Journal of Malaysian Technical Universities Conference on Engineering and Technology*, 1(1), 36–38.

Amey, P. R., Bhagwat, S. D., Prateek, R. N., & Vipul, J. G. (2022). Robotics arm control using haptic technology. *International Journal of Latest Research in Science and Technology, 2*(3), 98–102.

Aririguzo, M. I., & Agbaraji, E. C. (2016). The roadmap to industrial automation and robotics: The situation in the developing economies. *European Journal of Engineering and Technology, 4*(5), 24–32.

Cai, M., Guo, W., Zhang, J., Wang, L., & Wang, R. (2023). Research on Multi-channel Power Supply Method of New Intelligent Distributor. *International Field Exploration and Development Conference*, 1339–1349.

Chen, L., Guo, J., Zhu, B., & Zhang, Z. (2022). Electronic nonlinearity of full-bridge PWM inverter for zero-power PEMS system. *IEEE Access*, 10, 37670–37677.

Ghadge, K., More, S., Gaikwad, P., & Chillal, S. (2018). Robotic arm for pick and place application. *International Journal of Mechanical Engineering and Technology, 9*(1), 125–133.

Hanafi, D., Hidayat, T., Purwanto, A., Al Ayyubi, M. C., & Rachmadi, R. R. (2013). Wall follower autonomous robot development applying fuzzy incremental controller. *Intelligent Control and Automation, 4*(1), 19–25.

Ihuoma, S. O., Madramootoo, C. A., & Ogunniyi, S. (2020). Recent advances in crop water stress detection. *Computers and Electronics in Agriculture, 175*, 105611.

Liu, Y., Yiu, C., Song, Z., Huang, Y., Yao, K., Wong, T., Zhou, J., Zhao, L., Huang, X., Nejad, S. K., & Wu, M. (2022). Electronic skin as wireless human-machine interfaces for robotic VR. *Science Advances, 8*(2), eabl6700.

Liu, C., Liu, Y., Xie, R., Li, Z., Bai, S., & Zhao, Y. (2024). The evolution of robotics: research and application progress of dental implant robotic systems. *International Journal of Oral Science*, 16(1), 28.

Midhun, M., Deepak, K. K., & Rahul, V. R. (2017). Design and implementation of a pick and place robotic arm. *International Journal of Innovative Research in*

Science, Engineering and Technology, 6(7), 13347–13353.

Nsude, I. (2020). Communicating needs for robots in a developing economy and national development: A case of Nigeria. *Communication, Technologies et Développement, 8*, 1–15.

Olugboji, O. A., Jiya, J. Y., & Ogwuche, I. D. (2019). Prototyping of a robotic fire vehicle using radio frequency technology. *International Journal of Engineering Research and Technology, 12*(6), 935–940.

Ogunbiyi, O., Idowu, T. O., & Adesina, L. M. (2023). Development of embedded control for a repetitive pick and place robotic arm. *FUOYE Journal of Engineering and Technology, 8*(2), 172–176.

Shim, D. H., Paranjape, A. A., Chung, S.-J., Kim, K., & Shim, D. H. (2018). Robotic herding of a flock of birds using an unmanned aerial vehicle. *IEEE Transactions on Robotics, 34*(4), 901–915.

Wang, Z., Li, Y., & Zhou, X. (2018). Predicting human actions by considering object affordances. *Journal of Intelligent & Robotic Systems, 91*(3-4), 417–428.

Yinka-Banjo, C. O. (2015). Development of cooperative behavioural model for autonomous multi-robots system deployed to underground mines. *International Journal of Advanced Research in Artificial Intelligence, 4*(10), 78–98.