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Design and Implementation of Arduino-Based NRF Remote Control Steering System for Hand Tractors to Enhance Agricultural Efficiency

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ABSTRACT

Hand tractors are crucial for small-scale farming in Indonesia, but prolonged manual operation leads to operator fatigue, reduced productivity, and safety risks. This study develops a wireless steering control system for a hand tractor using an Arduino microcontroller and NRF24L01 transceiver. The system features a handheld transmitter with joystick input and a tractor-mounted receiver that controls the throttle via a servo motor and steering/clutch mechanisms through solenoids. The design process included system architecture, hardware and power circuit development, software programming, prototype assembly, and testing. Results show that the system operates optimally within 1–2 meters and remains functional up to 8 meters, though with communication degradation (increased delay, packet loss, and reduced actuator accuracy). Key constraints identified include unstable power supply, NRF24L01 limitations, and inadequate solenoid drivers. Recommendations for improvement include using NRF24L01+ PA/LNA modules, separating power rails, and adopting MOSFET-based drivers to enhance reliability and safety.

KEYWORDS: *Wireless control, NRF24L01, Arduino, hand tractor, Automation.*

NOMENCLATURE

XOR	Exclusive OR
AES	Advanced Encryption Standard

1. INTRODUCTION

Agricultural mechanization in Indonesia still relies heavily on simple equipment such as hand tractors for land cultivation in small- and medium-scale farming. While hand tractors significantly improve work capacity, their prolonged use in challenging terrain or under harsh environmental conditions imposes substantial physical demands on operators. This leads to muscle fatigue, reduced alertness, and a higher likelihood of occupational accidents. Observational and experimental studies have confirmed that walking behind and operating a hand tractor in the field imposes high physical workload and induces significant operator fatigue [1]. Globally, literature reviews and accident reports have consistently identified agricultural machinery, particularly tractors, as one of the leading causes of both fatal and non-fatal accidents in the agricultural sector. Contributing factors include limited operator training, poor ergonomic design, and mechanical or communication failures of control systems. Ergonomic and biomechanical studies further demonstrate that exposure to vibration, long operation times, and repeated maneuvers correlate strongly with operator fatigue and reduced operational precision. Such findings emphasize that ergonomic and safety concerns remain critical challenges in small-scale mechanization [2].

In Indonesia, local surveys have documented the high prevalence of musculoskeletal discomfort and injuries among farmers using manual and semi-mechanized equipment. Case studies in regions such as East Java reported frequent complaints of fatigue and injuries in the back and extremities of hand tractor operators. Moreover, national agricultural statistics show the wide distribution of hand tractors and other small-scale farm machinery, underscoring the urgent need for accessible and affordable automation solutions that address both productivity and operator safety [3].

Although existing research has examined issues related to ergonomics, operator fatigue, and accident risks in agricultural machinery, an important gap remains in the holistic integration of these findings with the design of wireless control systems for hand tractors. Many studies tend to isolate a single dimension—for example, vibration analysis, ergonomic evaluation, or communication reliabilitywithout assessing their combined effects on system performance and operator safety in real-world agricultural contexts. This lack of end-to-end evaluation limits the applicability of previous findings to practical field implementation [4].

Another significant gap lies in the empirical characterization of low-power wireless communication modules such as the NRF24L01 when applied to hand tractor steering systems. While these modules are widely used in robotics and hobbyist applications, systematic studies on their latency, packet loss, and range limitations in agricultural environments remain scarce. Furthermore, the consequences of communication degradation—such as delayed actuator response or inaccurate steering commands—have not been sufficiently documented in existing literature. This leaves uncertainty about their suitability for real-time control of agricultural machinery in field conditions [5].

Finally, prior research rarely provides detailed and practical technical guidelines that can be directly adopted by small-scale farmers or practitioners in rural settings. Studies often stop at conceptual design or prototype demonstration without specifying component-level recommendations, such as solenoid driver selection, MOSFET-based actuation strategies, or power management schemes that ensure system stability. As a result, there is a disconnect between academic research and field-ready solutions that address the realities of smallholder agriculture [6].

This study aims to address these gaps by presenting a comprehensive evaluation of a wireless steering system for a hand tractor, focusing not only on functionality but also on the interdependencies among power supply design, wireless communication parameters, and actuator performance. In doing so, it seeks to provide practical insights and recommendations that are both academically rigorous and technically feasible for small-scale agricultural automation [7].

2. METHODS

The methodology of this study followed an experimental prototyping approach, consisting of system design, hardware development, software implementation, assembly, and functional testing. The system architecture was divided into two primary modules: the handheld transmitter unit and the receiver unit mounted on the hand tractor. The transmitter included an Arduino Uno microcontroller, a dual-axis joystick for directional input, push buttons for auxiliary functions, and an NRF24L01 wireless communication module. The receiver comprised another Arduino board, an NRF24L01 module, a high-torque servo motor for throttle adjustment, two solenoids for clutch and steering actuation, and supporting driver circuitry. Both modules were powered by independent regulated supplies to ensure operational stability.

2.1 System Architecture

The initial step in developing the system involved outlining the general framework of its operation. The block diagram in Figure 1 illustrates the communication and control flow between the transmitter and receiver units. The transmitter module is composed of an Arduino Uno microcontroller, a joystick module that serves as the user input device, and an NRF24L01 wireless transceiver responsible for sending directional control signals. These signals are transmitted over a 2.4 GHz frequency band to the receiver module, which is equipped with a second Arduino Uno, another NRF24L01 module, a servo motor, and two solenoids. The receiver interprets the control signals and actuates the throttle via the servo motor and steers the vehicle left or right by engaging the corresponding solenoid connected to the clutch mechanism [8].

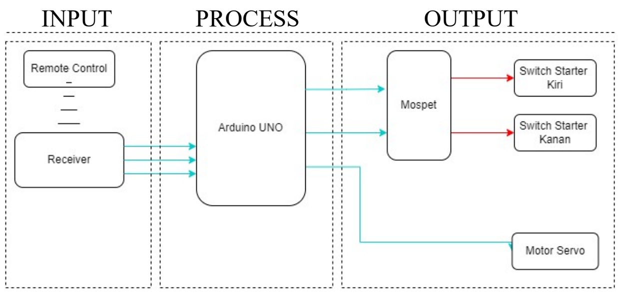

Figure 1: Block diagram of the remote control steering system using Arduino and NRF24L01

2.2 Hardware Design

The hardware design phase focused on the configuration of both the transmitter and receiver circuits, ensuring compatibility among all modules and stable signal transmission. The transmitter circuit, as depicted in Figure 2, comprises an Arduino Uno connected to a two-axis joystick module and an NRF24L01 transceiver. The joystick outputs analog values based on directional movement, which are processed by the Arduino to generate a digital command. The command is transmitted wirelessly through the NRF24L01 module [9].

The receiver circuit, shown in Figure 3, receives and decodes the signal using an identical NRF24L01 module. The Arduino Uno in the receiver module is programmed to translate the decoded signal into appropriate actuator commands. A servo motor connected to the Arduino regulates the throttle mechanism, while two solenoids are used to engage the left and right clutch systems for turning.

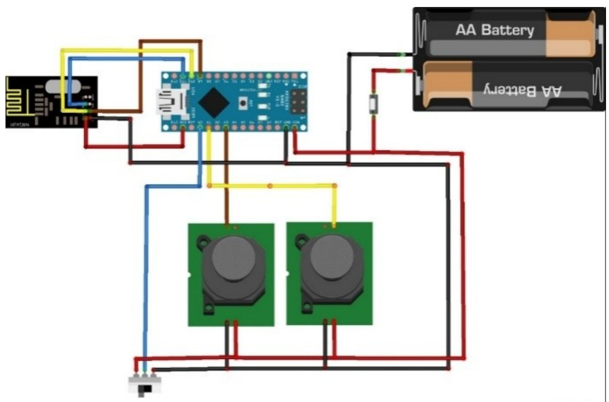

Figure 2: Transmitter circuit schematic illustrating the connection between the joystick, Arduino Uno, and NRF24L01 module

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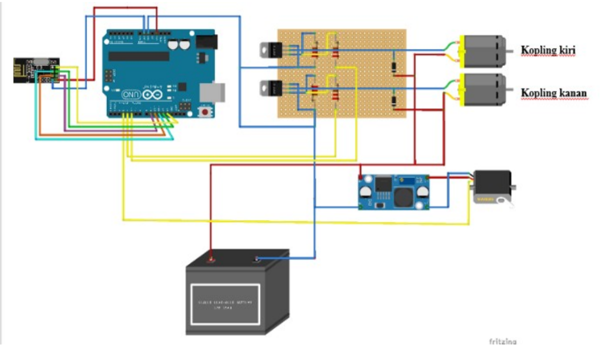

Figure 3: Receiver circuit schematic featuring the Arduino Uno, NRF24L01 module, servo motor, solenoids, motor driver, and power supply

These solenoids are driven using an L298N motor driver. A buck converter (LM2596) is included to supply 3.3V power to the NRF24L01, ensuring its stable operation. The entire system is powered by a 12V DC battery [10]. Special attention was given to the voltage requirements of each component to avoid power drops or signal interference. All wiring was arranged to minimize electrical noise and ensure secure connectivity.

2.3 Software Design

The software development process involved writing control programs for both the transmitter and receiver modules using the Arduino IDE. The transmitter code reads analog input values from the joystick on the X and Y axes and maps them into control commands. These commands are serialized and transmitted using the RF24 library, which supports the NRF24L01 communication protocol [11].

Upon reception of the signal, the receiver interprets the command structure and performs specific actions. For instance, a forward command rotates the servo motor to open the throttle, while left or right joystick movements activate the corresponding solenoid to engage the tractor's clutch mechanism.The operational logic of the transmitter is illustrated in Figure 4, which outlines the process starting from system initialization, reading joystick input, transmitting data, and continuously looping for real-time control [12].

On the receiver side, illustrated in Figure 5, the Arduino Uno receives the transmitted signal via another NRF24L01 module. It then translates the command into specific actuator actions. Servo motor rotates according to the joystick input to control engine throttle, solenoids are engaged to operate tractor's clutch system through a switch starter mechanism.

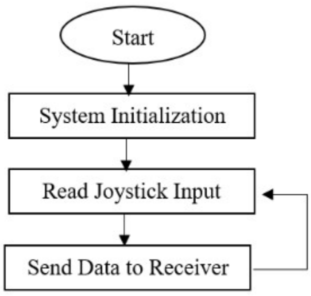

Figure 4: Schematic of the transmitter circuit

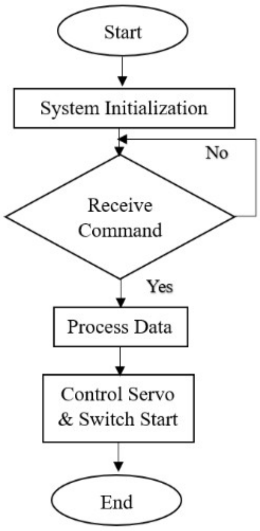

Figure 5: Schematic of the receiver circuit

A motor driver (L298N) is used to control the solenoids, and a step-down converter (LM2596) ensures stable voltage for the wireless module [13]. This modular approach allows real-time bidirectional control and flexible hardware expansion in future system iterations.

The software is divided into two parts: the transmitter firmware and the receiver firmware. The transmitter reads analog values from the joystick, normalizes them, and encodes them into structured packets. Each packet contains a header, sequence number, command type, data bytes, and a checksum for error detection. The receiver validates the packet and translates it into actuator commands. A watchdog timer and heartbeat mechanism are implemented to ensure fail-safe operation: if no valid command is received within a predefined time window, the system resets the actuators to a safe state [14]. A simplified pseudocode for the transmitter can be seen in Figure 6. And for the receiver is depicted in Figure 7.

```
loop:
  x = analogRead(joystickX);
  y = analogRead(joystickY);
  x_smooth = filter(x);
  y_smooth = filter(y);
  packet = buildPacket(seq, x_smooth, y_smooth);
  radio.write(packet);
  seq++;
  delay(10); // 100 Hz loop
```

Figure 6: Pseudocode for the transmitter

```
loop:
  if (radio.available()):
    packet = radio.read();
    if (valid(packet)):
      applyServo(packet.x);
      applySolenoid(packet.y);
      last_time = millis();
  if (millis() - last_time > timeout):
    emergencyStop();
```

Figure 7: Pseudocode for the receiver

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This control algorithm ensures real-time communication and provides fault tolerance in case of packet loss or interference.

2.4 System Assembly and Integration

In the final stage, all hardware components were mounted and enclosed in suitable protective casings. The transmitter unit was housed within a modified PlayStation controller shell, allowing ergonomic handling and ease of use for the operator. Buttons and joystick placements were adjusted to match natural hand movements, minimizing user fatigue during prolonged operation [15].

The receiver circuit was securely installed on the hand tractor frame using a combination of bolt fastenings and insulating materials to prevent short circuits. The wiring was organized using cable sleeves to protect against moisture, vibration, and temperature fluctuations commonly encountered in agricultural environments. All components underwent basic functional testing before integration, and post-assembly evaluations were conducted to verify signal transmission range, mechanical response time, and system durability under simulated working conditions [16].

3.0 RESULTS AND DISCUSSION

3.1 Individual Component Testing

Comprehensive testing was conducted on each component to ensure functionality prior to system integration. The testing results for individual components are presented in Table 1.

Table 1: Individual component testing results

Component	Testing Objective	Testing Results	Status
Joystick	Provide analog values according to movement	Analog output corresponds to directional movement	Functional
NRF24L01 Module	Wireless communication between transmitter and receiver	Communication established at 1-8 meter range with regulator constraints	Functional
180° Servo Motor	Rotate within 0-180 degree range	Servo motor achieves 0-180 degree rotation	Functional
Arduino UNO	Provide appropriate voltage and signal output	Delivers correct signals and voltage levels	Functional
Arduino Nano	Receive joystick signals and transmit to NRF	Successfully receives and transmits signals as instructed	Functional
Switch Starter (Solenoid)	Retract solenoid rod for clutch operation	Capable of retracting solenoid rod according to program	Functional

3.2 NRF24L01 Communication Testing Results

Communication testing of the NRF24L01 module was performed to determine optimal range and evaluate different communication methodologies. Three distinct communication methods were evaluated, with results summarized in Table 2. The XOR Encryption method was selected as the optimal solution based on performance criteria. Communication range testing results using this method are presented in Table 3.

Table 2: NRF24L01 communication method evaluation

Method	Status	Description
XOR Encryption	Functional	Message encryption with key-based security, prevents interference from external devices
AES	Non-functional	High power consumption, unsuitable for limited power supply applications
Addressing	Non-functional	Excessive interference, data transmission failure

Table 3: NRF24L01 communication range testing

Range	Communication Status	Delay (seconds)
1 meter	Connected	2
2 meters	Connected	10
3 meters	Connected	5
4 meters	Connected	10
5 meters	Connected	10
6 meters	Connected	10
7 meters	Connected	10
8 meters	Connected	10
	Average delay	8.375

The NRF24L01 communication system demonstrated functionality up to 8 meters distance, with optimal performance range between 1-2 meters. Beyond 8 meters, loss of connection occurred, resulting in data transmission failure.

3.3 Servo Motor Testing Results

Servo motor testing was conducted across various distances to evaluate response accuracy to joystick input commands. Comprehensive testing data is presented in Table 4.

Table 4: Servo motor range and rotation testing results

Distance	Joystick Command Value	Servo Motor Rotation
1 meter	1023	180°
	1002	45°
	974	180°
	1023	20°
	1023	180°
	958	45°
	1023	180°
	1023	0°
	1023	180°
	1023	180°

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Distance	Joystick Command Value	Servo Motor Rotation
2 Meters	1023	0°
	1023	0°
	563	20°
	1023	45°
	1023	180°
	513	0°
	513	0°
	513	0°
	513	0°
3 meters	1023	45°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
4 meters	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
6 meters	1023	20°
	1023	0°
	1023	20°
	1023	0°
	1023	20°
	1023	0°
	1023	20°
	1023	0°
	1023	20°
	1023	0°
7 meters	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
	1023	20°
8 meters	1023	20°
	1023	0°
	1023	20°
	1023	20°
	1023	0°
	1023	20°
	1023	20°
	1023	0°
	1023	20°
	1023	20°

At 1-2 meter distances, the servo motor demonstrated satisfactory response to varying joystick inputs. At 3-8 meter ranges, servo rotation remained consistently at 20° despite maximum joystick input (1023), indicating communication degradation.

3.4 Switch Starter (Solenoid) Testing Results

Solenoid testing was performed to evaluate the retraction capability for tractor clutch operation. Testing results at 1-meter distance are shown in Table 5.

Table 5: Switch starter (solenoid) testing results at 1 meter

Joystick Input Values		Solenoid Output	
Left	Right	S1	S2
573	574	Engaged	Engaged
582	582	Engaged	Engaged
517	519	Disengaged	Disengaged
531	531	Disengaged	Disengaged
544	545	Disengaged	Disengaged
549	549	Disengaged	Disengaged
559	562	Disengaged	Disengaged
612	612	Disengaged	Disengaged
635	635	Disengaged	Disengaged
647	647	Disengaged	Disengaged

The solenoid system experienced operational constraints after the second trial due to connection loss and MOSFET inability to sustain continuous commands. A minimum threshold value of 573 was required for solenoid activation. Logic testing of the solenoid system demonstrated improved stability, as shown in Table 6.

Table 6: Solenoid logic testing results

S1 Input Value	S2 Input Value	S1 Status	S2 Status
573	574	Engaged	Engaged
582	582	Engaged	Engaged
612	612	Engaged	Engaged
635	635	Engaged	Engaged
647	647	Engaged	Engaged
650	650	Engaged	Engaged
631	631	Engaged	Engaged
658	657	Engaged	Engaged
651	654	Engaged	Engaged
881	881	Engaged	Engaged

4.0 CONCLUSION

This research successfully developed a functional remote control steering system for hand tractors using NRF24L01 wireless communication technology. The system demonstrates effective control of throttle operations through servo motor integration and steering mechanisms via solenoid-operated clutch systems. Key findings indicate that the system operates optimally within a 1-2 meter range, with communication capability extending up to 8 meters under favorable conditions. The XOR Encryption method with channel 100 configuration, 1 Mbps data rate, and retransmit functionality provides the most reliable communication performance among tested methods. The system successfully addresses the primary objective of enabling remote tractor

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operation, improving operator safety and reducing physical strain during agricultural activities. However, operational constraints include limited communication range, power consumption requirements, and component reliability issues, particularly with continuous solenoid operation. Future development should focus on enhancing communication stability, extending operational range, and improving component durability for sustained field operations. The developed system provides a foundation for advanced agricultural automation and demonstrates significant potential for small-scale farming applications.

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