Design And Analysis of a Terrain Traversal Rover with Color Sorting Robotic Arm

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***Abstract*—Cost-effective robotic sorting across uneven terrain remains an unsolved challenge in small-scale agriculture and material handling. This work presents a low-cost, modular robotic platform combining a manually operated rocker-bogie rover with a 4-DOF robotic arm. A dual-controller architecture — an ESP32 for mobility and an Arduino for arm operation — decouples navigation from manipulation, while a TCS color sensor enables real-time color- and size-based object classification. Rather than pursuing full autonomy, the platform adopts a constraint-aware design philosophy that prioritizes task-level autonomy at the point of manipulation. Performance is validated through physical sorting trials evaluating classification accuracy and arm reliability, demonstrating that meaningful agricultural automation is achievable through targeted autonomy, modular design, and low-cost hardware integration.**

***Index Terms*—Rocker-Bogie Mechanism, Mobile Rover, Pick-and-Place, Color Sorting, Color-Based Object Classification, Robotic Arm, Mobile Platform**

I. INTRODUCTION

Operations like sorting and material handling in small-scale agricultural settings remain largely manual, inefficient, error-prone, and difficult to automate affordably in unstructured field conditions. While robotic sorting systems have advanced considerably [8], and terrain adaptability remain the primary barriers to small-farm adoption [10, 15]. Existing color and size-based sorting robots demonstrate feasibility but are confined to flat, structured environments [11, 12, 15], leaving field deployment unsolved A key challenge is stability across irregular surfaces, conventional systems struggle with obstacles, whereas the rocker bogie mechanism focuses on this by maintaining continuous wheel ground contact [1, 2, 3]. Yet terrain capable rovers rarely integrate manipulation subsystems [4, 7], and till date there’s no affordable system that combines mobility across terrain, autonomous arm-based manipulation, and real time color-based sorting within a single system.

This paper presents a low-cost modular platform combining a manually operated rocker-bogie rover with a 4-DOF robotic arm [6], governed by a dual-controller architecture, an ESP32 for mobility [13, 14] and an Arduino for manipulation [11, 12]. A TCS color sensor enables real-time color- and size-based classification [9, 10], while decoupling navigation from manipulation avoids the overhead of full autonomy [5, 7]. The key contributions are: (i) a modular dual-controller architecture separating mobility and manipulation; (ii) a low-cost sorting platform validated under real operating conditions; and (iii) empirical evidence that partial autonomy is a viable design philosophy for small-scale agricultural sorting.

The key contributions are:

1. Modular dual-controller architecture
2. Low-cost sorting platform
3. Validation under real operating conditions
4. Demonstration of partial autonomy for agricultural sorting

II. PROBLEM DEFINITION

The system must be capable of performing multiple tasks like movement on uneven terrains, object detection, and pick and place operations. For achieving this, the rover needs a stable mechanism similar to a mars rover which can adapt different surfaces. At the same time, the robotic arm mounted on the rover must be able to handle the objects accurately without breaking the rhythm of the moving vehicle, ensuring overall system stability, accuracy and efficient task execution

III. BACKGROUND AND RELATED WORK

2.1. Terrain Capable Rover Platform

The rocker-bogie mechanism, originally developed for NASA's Mars Exploration Rover, remains the most robust passive suspension architecture for uneven terrain [1, 2]. Its passive differential linkage maintains continuous wheel-ground contact without active control, a principle validated for terrestrial applications including stair-climbing [3] and low-cost IoT-integrated implementations using embedded microcontrollers [4], establishing its feasibility for affordable field-deployable platforms.

2.2. Robotic Arm Manipulation and Kinematics

Mohammed and Sunar [6] established that 4-DOF arm configurations provide sufficient workspace coverage for pick-and-place tasks without the complexity of full six-axis systems. Jotheess et al. [7] identified mechanical decoupling between mobility and manipulation as key to field system reliability, while Sabah et al. [13] and Deshpande et al. [14] validated ESP32 and Arduino-based control as practical low-cost alternatives to industrial controllers.

2.3. Agricultural Sorting and Color-Based Classification

Zhou et al. [8] identified deployment cost and sensing complexity as the primary barriers to agricultural robot adoption. Fadlil et al. [15] demonstrated reliable color- and size-based fruit sorting using robotic arms and color sensors, while Elwakeel et al. [10] validated low-cost RGB sensors as effective alternatives to advanced imaging systems. Sharma et al. [11] and Friars et al. [12] further confirmed TCS-series sensors for real-time classification in embedded environments [9].

2.4. Partial Autonomy and Modular Control

Estlin et al. [5] highlighted the substantial computational overhead of full rover autonomy, while Jotheess et al. [7] noted that full navigation autonomy introduces tightly coupled failure modes. Sabah et al. [13] and Deshpande et al. [14] demonstrated that distributing control across dedicated microcontrollers improves modularity and fault isolation, a principle directly adopted in this work by keeping navigation operator controlled while arm operates autonomously

IV. DESIGN AND METHODOLOGY

Rover System Design

The mobility platform consists of a six-wheeled terrain adaptive rover designed for uneven environments. Six 60 RPM DC motors independently drive each wheel for uniform torque distribution. A rocker suspension mechanism improves stability and maintains continuous ground contact on irregular surfaces. The chassis is constructed using lightweight wooden material. A 12V battery powers the system, while an ESP32 microcontroller controls locomotion and communication

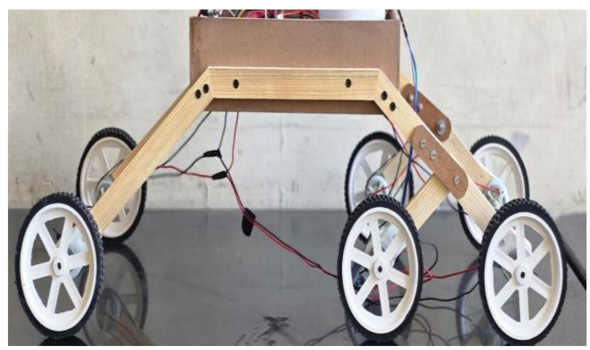

Figure 1. Rover

Robotic Arm and Intelligent Control System

The manipulation unit consists of 4 degree of freedom (DOF) robotic arm mounted on the front side of the rover for pick and place operations. The arm includes base rotation, shoulder, elbow and gripper joints providing flexibility for object handling. The actuation is achieved using 5 servo motors. These servos are driven using PCA9685 16 channel driver which enables stable and simultaneous control of multiple actuators while reducing processing load on controller. The driver communicates with ESP32 microcontroller via the I2C protocol, ensuring efficient and reliable signal transmission. For perception, an OV6760 camera module is mounted near end effector for object detection, while a TCS3200 color sensor is used for color-based classification and sorting. The arm is integrated with an AI based control framework that enables intuitive operation through natural language commands. The architecture allows system to convert user instructions into structured actions.

The control pipeline includes:
1. Speech to Text (STT) for voice input processing
2. Local LLM based intent recognition for command understanding
3. Agent based action for generating motion sequences
4. Execution module for real time servo control.

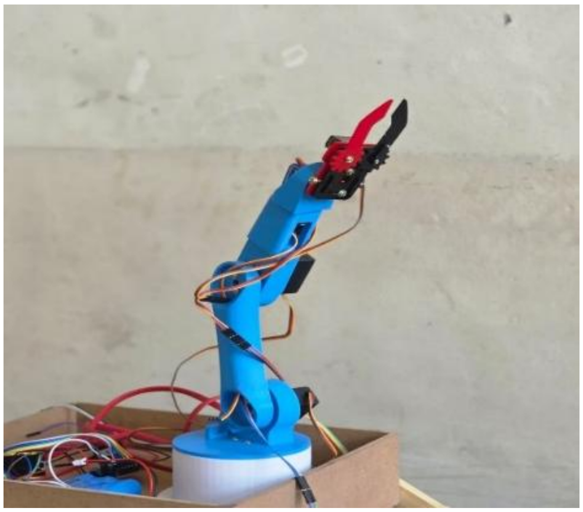

Figure 2. The arm

Integrated System Operation
This operation follows a sequential workflow:
1. The rover moves across uneven surfaces
2. The camera captures object information
3. The AI module identifies the object
4. The robotic arm moves to its assigned position
5. The end effector grasps the object
6. The TCS3200 color sensor detects object color
7. The object is placed in the corresponding color bin

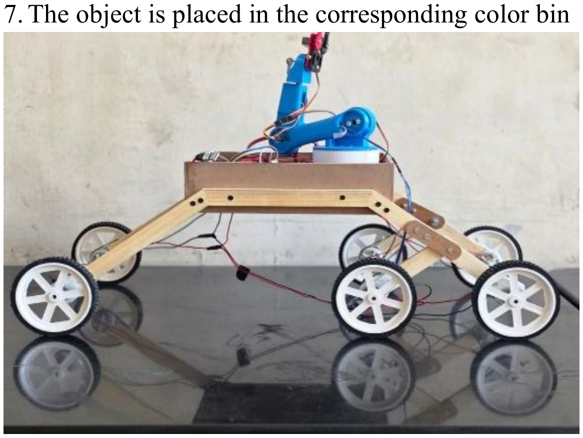

Figure 3. An integration of robotic arm and rover

V. CALCULATIONS

1. Rover Calculations:
System Parameters

Parameters	Value
Length(L)	61 cm
Breadth (B)	37 cm
Height (H)	24 cm
Mass (m)	2.65 kg
Wheel Radius (r)	0.05 m
Number of Wheels	6
Obstacle Height (h)	0.05 m

Centre of Gravity (COG)
Geometric COG
COG = $(\frac{L}{2}, \frac{B}{2}, \frac{H}{2})$ = (30.5, 18.5, 12) cm

Practical COG
$$[COG_z = \frac{\sum(m_i\, h_i) \sum m_i}{\sum m_i} = 7.94cm]$$

Final COG
COG = (30.5, 18.5, 7.94) cm

Torque Calculation
Weight
W = m · g = 2.65 · 9.81 = 26.0 N

Base Torque
T = W · r = 26.0 · 0.05 = 1.30 N·m

Terrain Corrected Torque
T = W · r $(1 + \frac{h}{r})$ = 2.6 N·m

Torque Per Motor
T = $\frac{2.6}{6}$ = 0.43 N·m

With Factor of Safety (2.5)
T = 1.0 N·m per motor

2. Arm Calculations
Forward and inverse kinematics of a 4-DOF robotic arm using Denavit-Hartenberg (DH) parameters. The model includes a rotating base and three planar joints.

DH Parameters:

Link(i)	ai(mm)	αi (deg)	di (mm)	θi
1	0	90	83	θ1
2	119	0	0	θ2
3	89	0	0	θ3
4	105	0	0	θ4

Forward Kinematics:

The homogeneous transformation matrix based on DH parameters is given by:

$$T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The overall transformation matrix is obtained as

$T = T1 \times T2 \times T3 \times T4$

The position of the end-effector is extracted as:

$X = \cos\theta 1 \ (119\cos\theta 2 + 89\cos(\theta 2+\theta 3) + 105\cos(\theta 2+\theta 3+\theta 4))$

$Y = \sin\theta 1 \ (119\cos\theta 2 + 89\cos(\theta 2+\theta 3) + 105\cos(\theta 2+\theta 3+\theta 4))$

$Z = 83 + 119\sin\theta 2 + 89\sin(\theta 2+\theta 3) + 105\sin(\theta 2+\theta 3+\theta 4)$

Inverse Kinematics:

$\theta 1 = \tan^{-1} (Y / X)$

$r = \sqrt{(X^2 + Y^2)}, z = Z - 83$

Let φ denote the desired end-effector orientation.

$r' = r - 105 \cos\varphi, z' = z - 105 \sin\varphi$

$D = (r'^2 + z'^2 - 119^2 - 89^2) / (2 \times 119 \times 89)$

$\theta 3 = \cos^{-1}(D)$

$\theta 2 = \tan^{-1} (z' / r') - \tan^{-1} (89 \sin\theta 3 / (119 + 89 \cos\theta 3))$

$\theta 4 = \varphi - (\theta 2 + \theta 3)$

VI. RESULT

The developed Terrain adaptable rover for object detection and color sorting was experimentally evaluated for terrain and obstacle adaptability, wheel slip characteristics, and robotic arm workspace performance. The rover was tested under three different conditions: flat surface, uneven surface, and loose soil terrain.

A. Terrain Traversal Performance

The rover successfully adapted all three terrain conditions while maintaining its stability. On flat surface, the rover moved with very little wheel slip because all wheels maintained equal balance on surface. On uneven terrain, the rocker bogie suspension balanced the load across the wheel which improved grip. In loose soil conditions, some slipping was noticed, but the rover was able to move forward smoothly without getting stuck.

B. Slip Ratio Analysis on Different Terrains

Slip ratio was analyzed to evaluate wheel traction performance under varying conditions. The slip ratio is calculated using the formula:

$$S = \frac{Vt - Va}{Vt} * 100$$

where:

- S = Slip Ratio (%)
- V_t = Theoretical wheel velocity
- V_a = Actual rover velocity

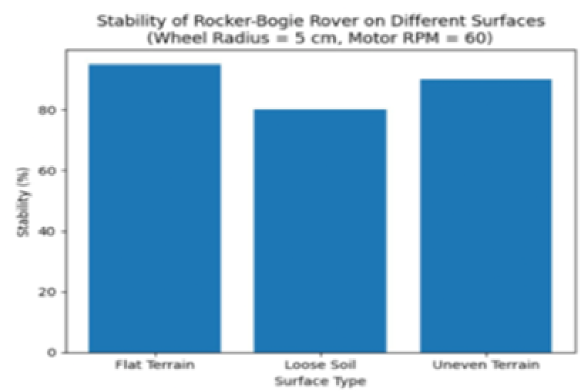

Figure 4. Stability

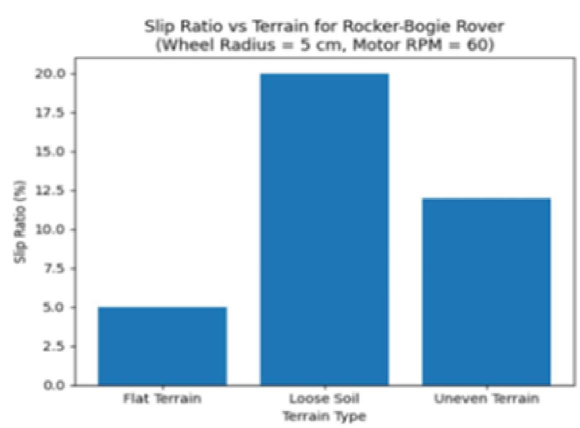

Figure 5. Slip ratio

The results display that the wheel slipping has increased on uneven and softer surfaces. Despite of these challenges, the rover continued to move in all conditions, proving that the rocker bogie suspension helps rover adapt and travel smoothly on different types of terrain

C. Obstacle Traversal Capability

The rover was tested to check its obstacle climbing ability using a obstacle of 5cm height, whereas the wheel radius is 10 cm. During the experiments, the rover successfully tackled the flat surface, uneven terrain and loose soil conditions

The obstacle climbing capability satisfies the condition:

$h \leq r$

where:

- h= Obstacle height
- r= Wheel radius

Since the obstacle height was equal to 50% of the wheel radius, the rocker bogie suspension equivalently distributed the load and successful contact of wheels during climbing. The rover maintained its mobility and did not experience problems.

D. Workspace Analysis of the 4-DOF Robotic Arm

Workspace analysis was performed to evaluate that how far the robotic arm mounted on the rover can move.

The maximum reach of the arm can be obtained by:

$R_{max} = L_2 + L_3 + L_4$

Using the link dimensions:

- L_2 = 119 mm
- L_3 = 89 mm
- L_4= 105 mm

The maximum reachable distance is:

R_{max} = 119 + 89 +105 = 313 mm

The robotic arm successfully performed pick and place operations and color sorting within the workspace while focusing on the stability of the rover platform. The mounted camera and TCS3200 color sensor enabled object identification and sorting without significant positioning error.

VII. RESULT TABLE

1. Slip Ratio on Different Terrains

Terrain Type	Average Slip Ratio (%)	Observation
Flat Surface	3–5	Smooth motion with good mobility
Uneven Terrain	7–11	Moderate wheel slip due to irregular contact
Loose Soil	14–19	Higher wheel slip due to soft soil deformation

2. Obstacle Climbing Performance

Obstacle Height (cm)	Wheel Radius (cm)	Traversal Result	Stability
2	10	Successful	Stable
3	10	Successful	Stable
5	10	Successful	Stable
6	10	Partial Difficulty	Moderate

3. Robotic Arm Workspace and Pick and Place Performance

Parameters	Values
Degrees Of Freedom	4
Maximum Reach	250 mm
Average Pick and Place time	30 – 50 seconds
Color Sorting Accuracy	80%
Payload Capacity	500 g

4. Color Detection and Sorting Accuraacy

Object Color	Detection Status	Sorting Accuracy (%)
Red	Successful	79
Green	Successful	85
Blue	Successful	75

VIII. CONCLUSION

This work presented a low-cost terrain traversal rover integrated with a 4-DOF robotic arm for object detection and color-based sorting. The rocker-bogie mechanism provided stable movement on uneven terrain and obstacles, while the robotic arm successfully performed pick-and-place and sorting operations. Experimental results demonstrated that the proposed system can achieve terrain adaptability and intelligent sorting using affordable hardware, making it suitable for small-scale agriculural and material handling applications.

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