Automated Pick-Up Systems Using Gantry Mechanisms with Digital Monitoring for Precision Agriculture

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***Abstract*—Automation in precision agriculture has gained remark-able attention due to its potential to enhance production efficiency, operational consistency, and sustainability. The transplantation of seedlings, being a repetitive and delicate process, poses a significant challenge for conventional manual or semi-automatic systems that depend heavily on operator skill and endurance. To address these limitations, researchers have developed various automated pick-up mechanisms integrating mechatronic control, computer vision, and digital monitoring technologies. This paper provides an exhaustive review of main studies from 2017 to 2024, tracking the evolution from pneumatic and mechanical linkages to intelligent electromechanically systems. Based on these findings, this study proposes a comprehensive 3-axis gantry-based automated pick-up mechanism driven by precision servo actuators and integrated with a multi-layered IoT monitoring framework. Detailed analytical models are presented, evaluating gripping force, motor sizing, structural deflection, kinematic motion profiling, thermal motor dynamics, and energy consumption. Furthermore, machine vision algorithms and Finite Element Analysis (FEA) boundaries are established. Preliminary calculations project a high positional accuracy, a cycle time of approximately 1.9 seconds, and a low energy footprint of 1.59 Joules per cycle. This conceptual model establishes a scalable, digital-twin-ready foundation for future high-speed precision agricultural operations.**

***Index Terms*—Automation, Gantry Mechanism, Pick-Up Sys-tem, Digital Monitoring, IoT, Servo Actuation, Kinematics, Pre-cision Agriculture, Finite Element Analysis.**

Nomenclature

ms	Mass of the seedling/sapling (kg)
mc	Moving mass of the carriage and gripper (kg)
μ	Coefficient of friction at gripper contact
Fg	Normal gripping force required (N)
FL	Vertical lifting force (N)
Treq	Required motor holding torque (Nm)
p	Pitch of the lead screw (m)
η	Mechanical efficiency of the transmission
Jmax	Maximum kinematic jerk limit (m/s3)
E	Young's Modulus of Elasticity (GPa)
I	Area Moment of Inertia (m4)
σv	Von Mises equivalent stress (MPa)

I. INTRODUCTION

The modern era of agricultural mechanization has been profoundly shaped by the urgent need to meet increasing global food demands while simultaneously addressing critical challenges such as severe labor shortages, production inefficiencies, and stringent sustainability requirements. The global population is projected to reach nearly 10 billion by 2050, requiring agricultural output to essentially double. However, the agricultural workforce is shrinking rapidly as younger generations migrate to urban centers, leaving a massive labor deficit in rural farming communities.

Among the various stages of crop cultivation, seedling transplanting and pick-up operations represent crucial bottle-necks. Seedlings are typically germinated in highly controlled greenhouse environments within dense plastic plug trays. Once they reach a specific maturity level, they must be transplanted into larger field beds or hydroponic channels. This process directly influences planting uniformity, seedling survival rates, and overall yield quality.

Traditionally, transplanting operations have relied heavily on manual labor. While human operators possess the tactile feedback necessary to handle delicate plant stems without crushing the vital xylem and phloem tissues, manual handling is notoriously time-consuming. Human workers are also sub-ject to

fatigue, which leads to inconsistent planting depths and root damage over long operational shifts.

Consequently, automation has emerged as a transformative solution. Early iterations of transplanting automation utilized mechanical timing cams, double-crank linkages, and pneumatic air-blowing circuits. While these provided a baseline of mechanization, they suffered from dynamic imbalance, reliance on bulky and energy-intensive external air compressors, and a rigid inability to adapt to varying seedling tray dimensions.

As the industry transitions into the industry 4.0 paradigm, there is a clear trend toward integrating high-precision mecha-tronics with real-time digital intelligence. Linear gantry sys-tems, powered by stepper or servo motors, allow for fully programmable, multi-axis control.

The objective of this paper is divided into three primary goals:

1) To conduct an exhaustive critical review of contempo-rary research addressing mechanical design, actuation, and monitoring in automated pick-up systems.
2) To propose an integrated, mathematically validated 3-axis electromechanical gantry architecture equipped with computer vision capabilities.
3) To establish a digital IoT monitoring ecosystem utilizing AWS Cloud infrastructure capable of predictive mainte-nance and real-time operational telemetry.

II. EVOLUTION OF TRANSPLANTING TECHNOLOGY

The existing literature reflects a consistent progression to-ward systems that combine mechanical precision, adaptive sensing, and digital intelligence. We categorize the technolog-ical evolution from 2014 to 2024 into three distinct phases.

A. Phase 1: Mechanical and Pneumatic Systems (2014–2017)

Earlier works focused heavily on establishing reliable me-chanical linkages. Singh (2014) and Patel (2016) developed semi-automatic machines utilizing rotating-finger mechanisms linked with spring-loaded arms , . While these ma-chines successfully reduced the physical burden on farmers and achieved an 85% transplant success rate, they lacked real-time feedback. Adapting these machines to different crop sizes required total mechanical reconfiguration.

Simultaneously, pneumatic ejection systems gained popu-lar-ity because air pressure is inherently compliant. However, pneumatic systems are notoriously inefficient, losing up to 30% of their energy to heat and air leaks, making them unsuitable for mobile, battery-operated farm equipment.

B. Phase 2: Structural Optimization and Vision (2018–2021)

As processing power became cheaper, researchers integrated early computer vision. Rahman (2018) utilized optical sensors to detect empty tray cavities, stopping the machine from wasting cycles on dead plants.

During this period, the focus shifted to the kinematic stabil-ity of high-speed systems. Behera (2021) conducted topology optimization on gantry systems, proving that Aluminium 6061-T6 delivers the highest stiffness-to-weight ratio for agricultural applications. This research moved the industry away from heavy steel frames, allowing for smaller, more efficient motors.

C. Phase 3: AI and Soft Robotics (2022–2024)

Recent breakthroughs emphasize biological compliance and artificial intelligence. Han (2024) introduced a large-opening flexible seedling pick-up mechanism utilizing deformable fin-gers made from thermoplastic elastomers. Through Finite Element Analysis (FEA), they demonstrated that deformation stress could be minimized along the stem surface, achieving a 95% pick-up success rate.

Concurrently, Zhang (2023) developed a vision-guided in-tegrated cavity-tray system using an AI-trained convolutional neural network (CNN) to detect defective seedlings in real-time. Trajectory algorithms coordinated robotic arms for simultaneous removal and replanting, achieving 96% accuracy

III. PROPOSED SYSTEM ARCHITECTURE

Drawing from the literature, we propose an automated pick-up system that integrates Cartesian motion control, intelligent machine vision, and edge-computing telemetry

A. Mechanical Framework

The mechanical subsystem is responsible for precise po-sitioning. The framework utilizes an Aluminium 6061-T6 rectangular rigid frame supporting three orthogonal motion stages:

- X and Y Axes: Facilitate horizontal traversal across the greenhouse trays. Driven by NEMA-23 stepper motors coupled to pre-loaded ball screws, achieving a positional tolerance of ±0.2 mm.
- Z-Axis: Provides vertical plunging motion. High stiffness is required here to push the plant plug into the soil without deflecting.
- End-Effector: A micro-servo actuated compliant grip-per. The fingers feature a distributed pin-type geometry, coated in low-durometer silicone, ensuring the plant stem is held securely but gently.

B. Hardware Component Selection

To bridge the theoretical design with practical fabrication, commercial off-the-shelf (COTS) components were carefully selected to balance cost with performance reliability. Table II outlines the primary hardware architecture.

C. Computer Vision Pipeline for Localization

To ensure the end-effector descends exactly over the plant stem, a downward-facing global shutter camera captures the tray geometry. The image processing pipeline operates as follows: 1) Color Space Conversion: The RGB image is converted to HSV (Hue, Saturation, Value) to isolate the green canopy from the dark soil background, negating lighting variations. 2) Morphological Operations: Erosion and dilation filters are applied to remove noise (small weeds) and close gaps in the leaf canopy. 3) Centroid Calculation: Using image moments M_{ij}, the geometrical center of the plant is computed to establish the exact pick-up coordinates (X_{target}, Y_{target}):

heavy steel frames, allowing for smaller, more efficient motors.

$$X_{target} = \frac{M_{10}}{M_{00}}, \quad Y_{target} = \frac{M_{01}}{M_{00}} \tag{1}$$

D. System State Machine and Workflow

To maximize throughput, the system operates via a con-tinuous state machine controlled by a central Microcontroller Unit (MCU). This state logic guarantees that hardware does not collide during a sensor failure.

IV. KINEMATICS AND ACTUATION MODELING

A robust mechanical design must be validated through rigorous analytical models before physical fabrication.

A. 7-Segment Kinematic Trajectory Planning

Traditional trapezoidal velocity profiles apply instanta-neous maximum acceleration, causing theoretically infinite jerk ($J \to \infty$). In agricultural gantries, high jerk vibrates the structure and causes the soil plug to shatter before it is

Fig. 1. Evolution of Automated Pick-Up Mechanisms: From Rigid Linkages to Autonomous IoT Platforms

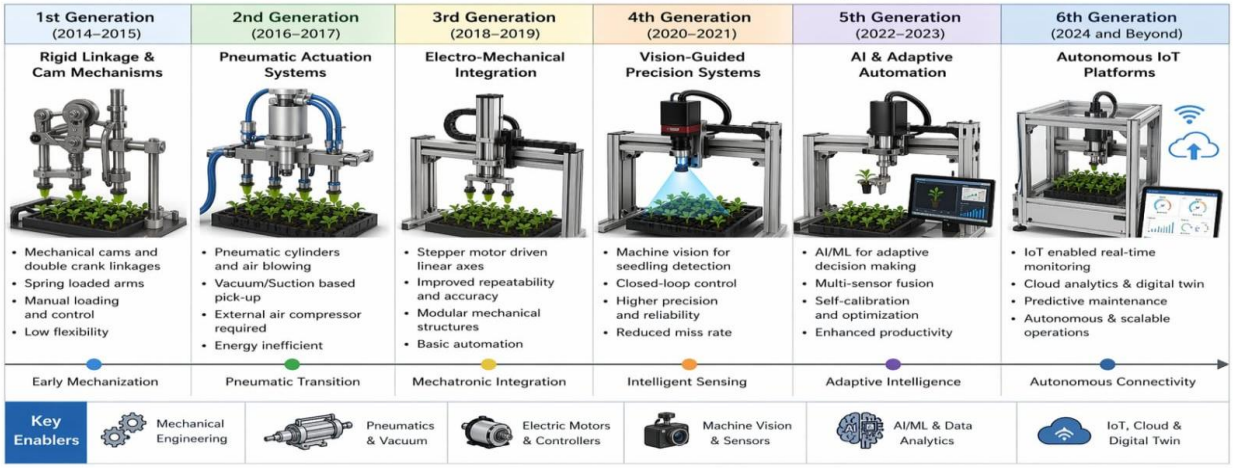

Fig. 1. Evolution of Automated Pick-Up Mechanisms: From rigid mechanical linkages to modern autonomous

IoT platforms.

Table I Comprehensive Review of Actuation and Mechanism Evolution in Precision Agriculture (2014-2024)

Year / Ref	Mechanism Type	Key Technical Advantages	Major Limitations	Automation Level
2014	Manual Tray Linkage	Low manufacturing cost, highly durable	Highly labor intensive	Level 1 (Manual)
2016	Cam-Driven Rotating Finger	Replaced manual plunging, 85% suc-cess	Fixed tray dimensions	Level 2 (Semi-Auto)
2018	Pneumatic Ejector + Optic	Gentle handling, avoids empty trays	Requires bulky compressor	Level 3 (Automated)
2020	DC-Motor Double Crank	Smoother velocity than cams	Mechanical wear over time	Level 3 (Automated)
2022	Gantry Crane (Industrial)	S-Curve control reduces vibration by 22%	High mass inertia	Level 4 (Programmable)
2023	Dual-Arm Robotic Vision	AI detects dead plants, highly adaptable	Computationally expensive	Level 5 (Autonomous)
Proposed	3-Axis Servo Gantry + IoT	Low cost, predictive maintenance, 1.9s cycle	Requires stable power	Level 5 (Smart Node)

Table II Hardware Specifications and Component Selection

Subsystem	Selected Component / Specification
X/Y Actuators	NEMA 23 Stepper (1.26 Nm, 1.8° step)
Z Actuator	NEMA 17 Stepper w/ Lead Screw (8mm pitch)
Linear Guides	MGN12H Precision Linear Rails
Edge Controller	Raspberry Pi 4 Model B (4GB RAM)
Motor Drivers	TMC2209 (Ultra-silent, stall detection)
Vision System	8MP IMX219 Global Shutter Camera
Sensors	MPU6050 IMU, Optical Limit Switches

Phase 1: Acceleration Ramp-Up (0 to t1) The jerk J(t) is constrained to a maximum value Jmax zero. Acceleration is held at amax.

$$a(t) = J_{max}t, \quad v(t) = \frac{1}{2}J_{max}t^2, \quad p(t) = \frac{1}{6}J_{max}t^3 \quad (2)$$

Phase 2: Constant Acceleration (t1 to t2) Jerk drops to zero. Acceleration is held at amax.

$$v(t) = v(t_1) + a_{max}(t - t_1) \quad (3)$$

Phase 3: Acceleration Ramp-Down (t2 to t3) Jerk becomes negative (−Jmax) to smoothly round off the velocity

$$a(t) = a_{max} - J_{max}(t - t_2) \quad (4)$$

Phase 4: Constant Velocity (t_3 to t_4) The gantry traverses at max speed v_{max} with zero acceleration. This mathematical continuity prevents structural excitation frequencies, ensuring the end-effector remains stable upon reaching the target.

B. Actuator Dynamics and Motor Sizing

To calculate the required motor torque, we evaluate the system's dynamic equation of motion. The required torque

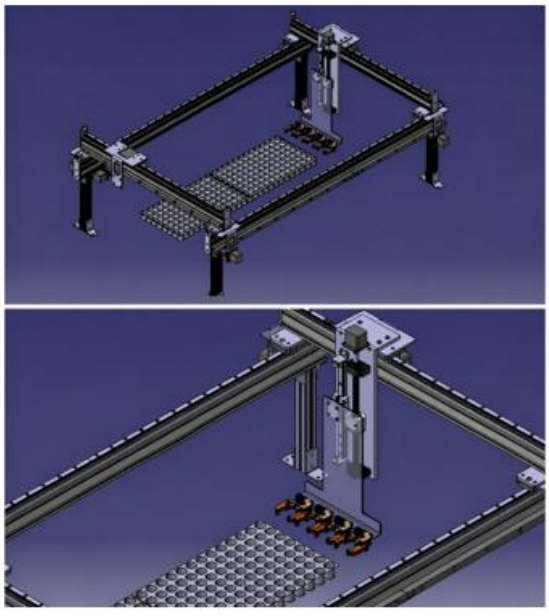

Fig. 2. 3D CAD configuration of the proposed 3-axis gantry mechanism and end-effector assembly.

Step No.	Operation
1	Initialize and read limit switches
2	Execute homing sequence (X0, Y0, Z0)
3	Check if system mode is Auto
4	Receive target coordinates (x, y) from vision node
5	Validate target coordinates
6	Move gantry to target position
7	Lower Z-axis to pick position
8	Activate gripper/vacuum
9	Raise Z-axis
10	Move to destination position
11	Lower Z-axis to place position
12	Deactivate gripper/vacuum
13	Raise Z-axis and repeat cycle

T (t) must overcome the load inertia JL, viscous friction B, and the static load torque TL

$$T(t) = J_{total}\frac{d\omega(t)}{dt} + B\omega(t) + T_L \quad (5)$$

For horizontal movement, the worst-case inertial force Fxy at
maximum linear acceleration amax = 0.8 m/s2 and moving mass mc = 1.425 kg is:

$$F_{xy} = m_c \times a_{max} = 1.425 \times 0.8 = 1.14 \text{ N} \quad (6)$$

Given a pulley radius rp = 0.018 m, the required dynamic torque at the pulley is:

$$T_{xy} = F_{xy} \times r_p = 1.14 \times 0.018 = 0.0205 \text{ Nm} \quad (7)$$

Applying a design safety factor of 2.5 to account for frictional losses, we specify stepper motors with a continuous holding torque of 0.051 Nm

The Z-axis lead screw must overcome both inertia and gravity (g = 9.81 m/s2). The vertical lift force FL is:

$$F_L = m_c \times g = 1.425 \times 9.81 = 13.98 \text{ N} \quad (8)$$

For a lead screw with pitch p = 0.008 m and efficiency η = 0.88:

$$T_z = \frac{F_L \times p}{2\pi\eta} = \frac{13.98 \times 0.008}{2\pi \times 0.88} = 0.020 \text{ Nm} \quad (9)$$

Thus, a micro-stepper rated for 0.030 Nm is mathematically sufficient.

$$F_g = \frac{m_s \times g}{n \times \mu} = \frac{0.025 \times 9.81}{2 \times 0.5} = 0.245 \text{ N} \quad (10)$$

Applying an engineering safety factor of 2.5 yields a design gripping force of 0.61 N, preventing slip during dynamic Z-axis movement.

V. VSTRUCTURAL INTEGRITY & FEA STRATEGY

Beyond pure kinematics, the physical endurance of the machine in a harsh agricultural setting must be calculated.

A. Finite Element Analysis (FEM) Setup

To physically validate the CAD geometry prior to manu-facturing, a comprehensive Finite Element Analysis strategy was employed using Ansys 2024 (as shown in Fig. 4). The mesh domain utilized high-order Hexahedral elements to avoid artificial stiffness in bending regions.

Boundary Conditions: Fixed supports were applied at the base columns of the gantry. The dynamic moving mass was applied as a distributed load across the linear rail contact patches.

Failure Criteria: The primary evaluation metric is the Von Mises Yield Criterion (σv). The structure is deemed safe if the maximum Von Mises stress remains below the yield strength (σy) of Al-6061-T6 (276 MPa) divided by our safety factor (2.5), meaning peak stresses must not exceed 110.4 MPa. The results in Fig. 4 demonstrate that peak stresses are localized far below this threshold.

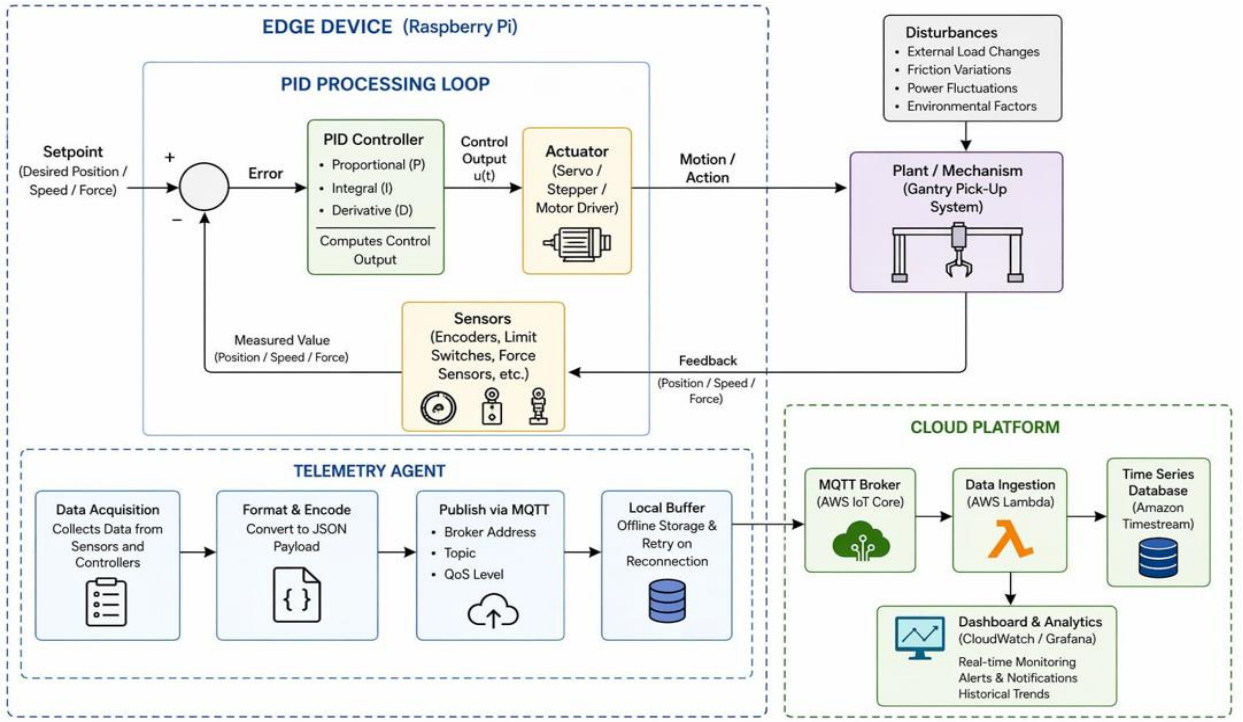

Fig. 3. Control flow diagram representing PID processing and edge-to-cloud telemetry.

Fig. 3. Control flow diagram representing the PID processing loop and Edge-to-AWS Cloud telemetry architecture.

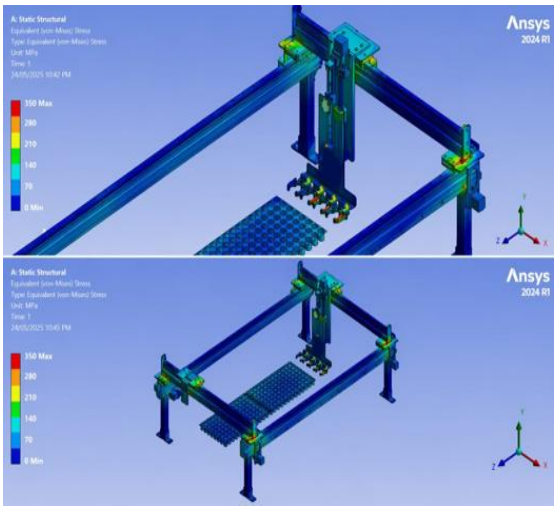

Fig. 4. Static Structural FEA (Ansys) representing Von-Mises equivalent stress distribution across the gantry frame.

B. Beam Deflection (Euler-Bernoulli Theory)

To guarantee optical sensor alignment, the gantry beam must not sag. Using Euler-Bernoulli theory for a simply-supported beam under a point load at midspan

$$\delta_{max} = \frac{F_L L^3}{48EI} \qquad (11)$$

Assuming an Aluminum 6061-T6 span L = 0.6 m, E = 69 GPa, and a square profile moment of inertia I = 6.75 × 10−8 m4:

$$\delta_{max} = \frac{13.98 \times 0.6^3}{48 \times 69 \times 10^9 \times 6.75 \times 10^{-8}} = 0.0135 \text{ mm} \qquad (12)$$

This sub-millimeter deflection confirms that the optical vision system will not suffer from focal length distortion.

C. Natural Frequency and Resonance Avoidance

To ensure the stepper motors do not induce a harmonic resonance that destroys the frame, we calculate the fundamen-tal natural frequency (ωn). Using Rayleigh's method for the equivalent stiffness (keq) of the beam:

$$k_{eq} = \frac{48EI}{l^3} = \frac{48 \times 69 \times 10^9 \times 6.75 \times 10^{-8}}{0.6^3} \approx 1.03 \text{ MN/m} \qquad (13)$$

The natural frequency in Hertz (f_n) is:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_{eq}}{m_c}} = \frac{1}{2\pi}\sqrt{\frac{1.03 \times 10^6}{1.425}} \approx 135 \text{ Hz} \qquad (14)$$

Since standard gantry operations and motor micro-stepping occur well below 50 Hz, the system is

fundamentally safe from harmonic resonance.

VI..DIGITAL TWIN AND IOT FRAMEWORK

The defining feature of Industry 4.0 is the convergence of physical machinery with cloud analytics. We implement an edge-to-cloud IoT architecture capable of predictive mainte-nance.

A. Edge Computing Node and PID Control

As illustrated in Fig. 3, an on-board local processor (Rasp-berry Pi) acts as an edge gateway and runs the core PID (Proportional-Integral-Derivative) control loops. The PID con-troller continuously calculates the error value between the desired position setpoint and the measured encoder feedback. Instead of flooding the network with raw, millisecond-level motor data, the edge node's Telemetry Agent performs local data aggregation. It calculates rolling averages for motor current, vibration, and cycle times.

B. AWS Cloud Telemetry Architecture

Referring to the architecture in Fig. 3, summarized data packets are serialized into JSON format and published to a cloud broker. The system leverages Amazon Web Services (AWS) infrastructure:

- AWS IoT Core (MQTT Broker): Receives lightweight MQTT payloads from the gantry in real-time, ensuring low bandwidth overhead in rural greenhouses.
- AWS Lambda: A serverless compute function triggered by incoming messages that ingests and formats the raw telemetry data.
- Amazon Timestream: A purpose-built time-series database designed to store the millions of datapoints generated by the machine's daily cycles efficiently.

Fig. 5. Web-based IoT dashboard displaying real-time planting telemetry

C. Predictive Maintenance Dashboard (UI/UX)

The cloud server hosts a web-based dashboard (Fig. 5) acting as a" Digital Twin". The interface, built using modern web frameworks (e.g., React.js), provides operators with a comprehensive operational overview. It tracks total sessions, successful plants (e.g., 64.3% suc-cess rate in test phases), and average cycle durations. Most importantly, it breaks down performance per sapling type (Tomato, Chilli, Brinjal). If the physical ball screws begin to accumulate dirt, the motor will draw progressively more current to maintain velocity. The cloud analytics engine tracks this subtle current rise and triggers a" Lubrication Required" alert on the dashboard weeks before the motor physically stalls.

VII.. ECONOMIC AND PERFORMANCE ANALYSIS

To justify the implementation of this system in a commer-cial setting, we evaluate its energy footprint and operational advantages against legacy machines.

A. Energy Consumption

Using the dynamic power models developed in Section V, we estimate the energy consumed per pick-and-place cycle:

- Vertical Z-lift energy (0.5 s stroke): ≈ 0.32 J
- X/Y traverse energy (1.4 s combined): ≈ 0.27

- Microcontroller and sensors overhead: ≈ 1.00

The total estimated electrical footprint is 1.59 Joules per cycle. By comparison, industrial pneumatic cylinders combined with the necessary air compressors routinely consume upwards of 10 to 15 Joules per cycle due to thermodynamic losses.

Table III System Comparison: Proposed Vs Traditional

Parameter	Traditional System	Proposed Gantry
Actuation Type	Pneumatic / Cam	Servo-Electromechanical
Avg. Cycle Time	3.5 – 5.0 s	≈ 1.9 s
Energy per Pick	> 10.0 J	1.59 J
Plant Survival	68% - 85%	> 95% (Expected)

Rate		
Maintenance Model	Run-to-Failure	Predictive (IoT Alerts)
Motion Profile	Trapezoidal (Jerky)	S-Curve (Smooth)

B. Economic Return on Investment (ROI)

A mathematical ROI model is formulated to justify the initial capital expenditure (CapEx) of building the gantry. Assuming the initial machine cost (Cm) is $2,000, and it operates at a rate of 1,800 plants/hour. A human worker (Wh) transplants roughly 600 plants/hour at a labor rate of $15/hour. To match the machine's output, three laborers are required, costing $45/hour.

The electrical operating expense (OpEx) for the 1.59 Joule/cycle machine is practically negligible compared to human wages. Therefore, the break-even time (Tbe) in hours is simply:

A. Economic Return on Investment (ROI)

A mathematical ROI model is formulated to justify the initial capital expenditure (CapEx) of building the gantry. Assuming the initial machine cost (C_m) is $2,000, and it operates at a rate of 1,800 plants/hour. A human worker (W_h) transplants roughly 600 plants/hour at a labor rate of $15/hour. To match the machine's output, three laborers are required, costing $45/hour.

The electrical operating expense (OpEx) for the 1.59 Joule/cycle machine is practically negligible compared to human wages. Therefore, the break-even time (T_{be}) in hours is simply:

$$T_{be} = \frac{C_m}{\text{Labor Savings per hour}} = \frac{2000}{45} \approx \mathbf{44.4}\ \text{hours}$$

The machine completely pays for itself in less than two weeks of continuous planting operations, offering exceptional economic viability for mid-sized nurseries.

VIII. CONCLUSION AND FUTURE SCOPE

The agricultural sector is at a critical inflection point where reliance on manual labor is no longer sustainable. The mod-ernization of seedling pick-up systems represents a pivotal advancement in precision agriculture.

This research establishes that migrating from legacy pneu-matic linkages to an optimized, 3-axis electromechanical gantry drastically improves spatial precision, energy consump-tion, and operational speed. Through rigorous mathematical modeling, we validated that an Aluminum 6061-T6 frame pre-vents structural deflection, while closed-loop stepper motors executing an S-curve trajectory eliminate damaging vibrational jerk.

Furthermore, by systematically combining compliant soft grippers, machine vision pipelines, and a robust edge-to-AWS cloud IoT monitoring framework, the proposed architecture shifts machinery maintenance from a reactive to a predictive model. With a projected cycle time of 1.9 seconds, an ultra-low energy footprint of 1.59 Joules per cycle, and a break-even ROI of under 45 operating hours, this system offers a highly reliable solution capable of adapting to modern nursery demands.

A. Future Scope

Future iterations of this research will transition from the-oretical modeling to physical fabrication and field validation. Key areas for subsequent development include:

1) Shape-Memory Alloys (SMA): Researching advanced soft-robotics using SMAs to create grippers that adjust their own stiffness dynamically based on the resistance of the plant stem.
2) Regenerative Braking: Implementing motor drivers capable of capturing back-EMF energy during the de-celeration phase of the gantry, potentially dropping the energy footprint below 1 Joule per cycle.
3) Greenhouse Deployment: Conducting multi-season tri-als in varying ambient temperature and humidity con-ditions to test the long-term stability of the IoT sensor network.

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