COMPUTER VISION & ROBOTICS SOLUTION FOR NPEC

Automated Root Phenotyping & Inoculation System

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The Scientific Goal

- **Goal:** Find disease-resistant genotypes.
- **The Method**: High-Throughput Phenotyping.
- **Requirement:** Precise Root System Architecture (RSA) metrics.

The Operational Gap

- **Capabilities:** 7 state-of-the-art growth modules.
- **Bottleneck:** Manual analysis lags behind growth speed.
- **Result:** Valuable genetic data is lost.

Problem Definition Insights

Project Goal: Automating the Pipeline

Manual

- **Labor Intensive:** High cost, slow throughput.
- **Subjective:** Human error causes data noise.
- **Physical Limit:** Manual inoculation is tedious and error-prone.

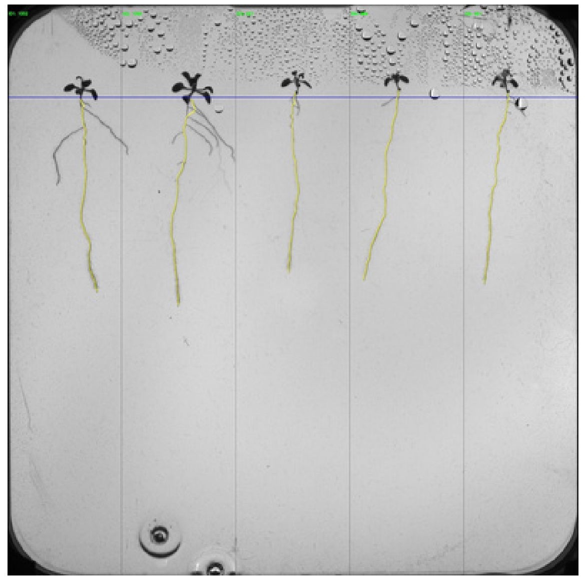
My solution

- **Consistent:** 0.18mm accuracy removes variance.
- **Complex Actions:** Enables precise, repeatable micro-inoculation.

Solution Overview

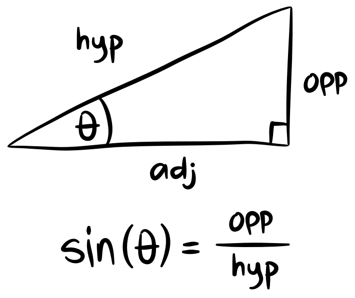
Acquisition

- Raw Hades Images



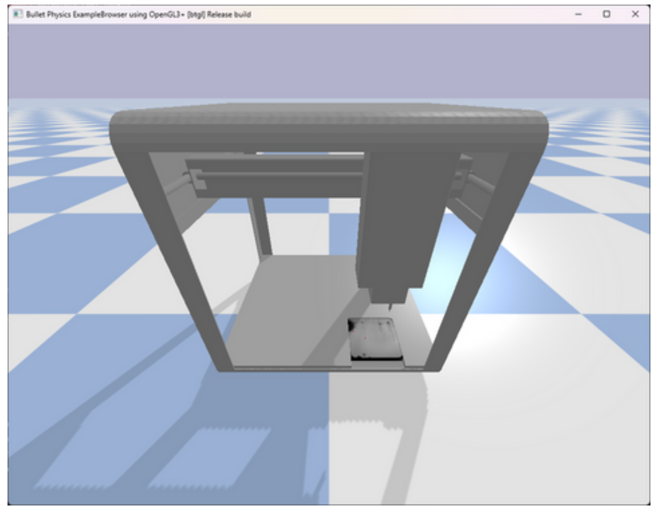
Perception (CV)

- ROI Extraction
- SegFormer Model
- Gathering Measurements
- **Root Tip Detection**



Integration

- Coordinate Transform



Actuation

- **Precise Inoculation**

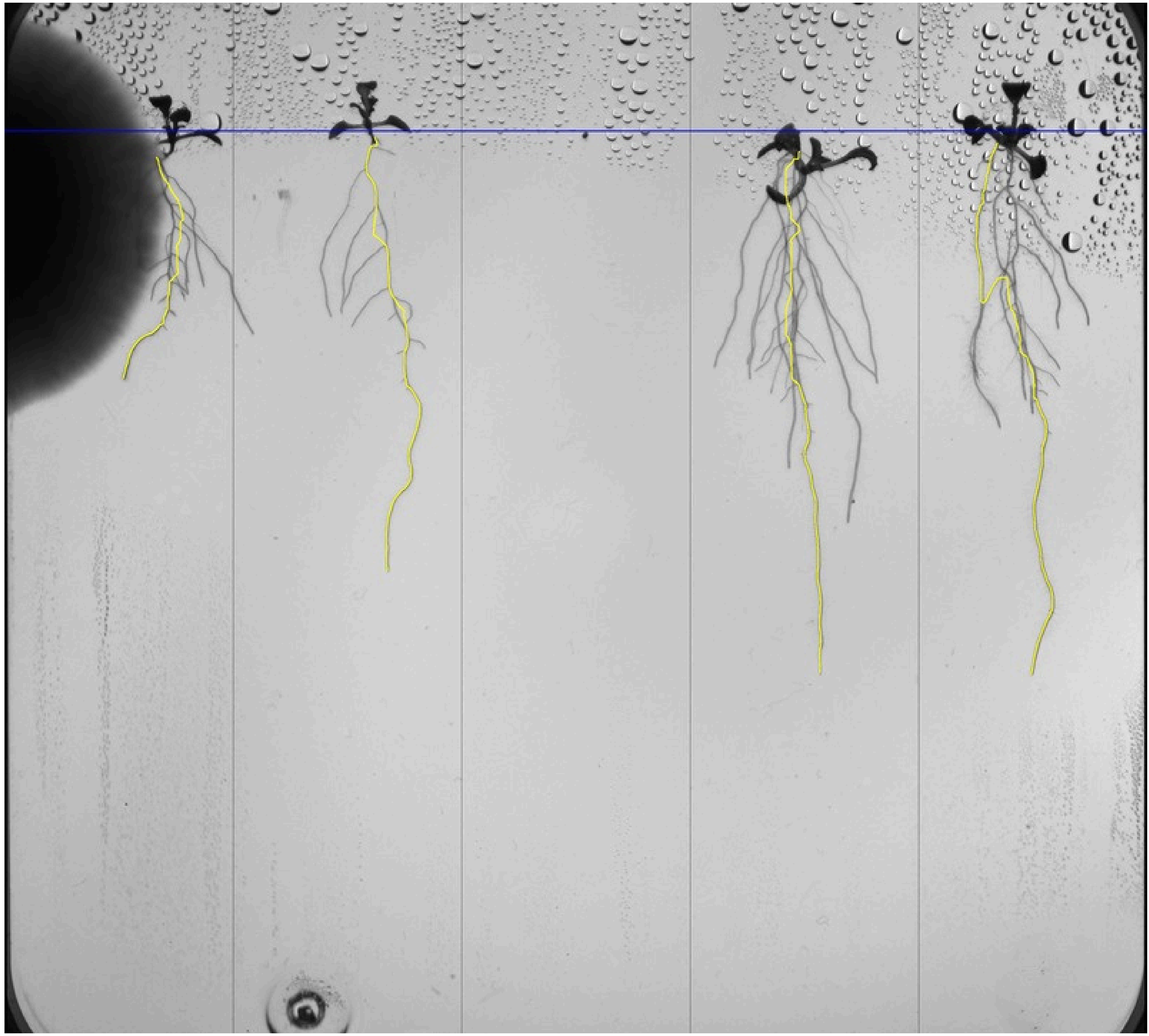
Computer Vision Results

CV Architecture Details

- Model: SegFromer B3
- Input: 128px Patches
- Technique: Skeletonization + MCP

The most important metrics

- Validation F1 Score: 0.83
- Final sMAPE: 11.2%



Error Analysis - Iteration 1 Insights (Baseline)

Challenge

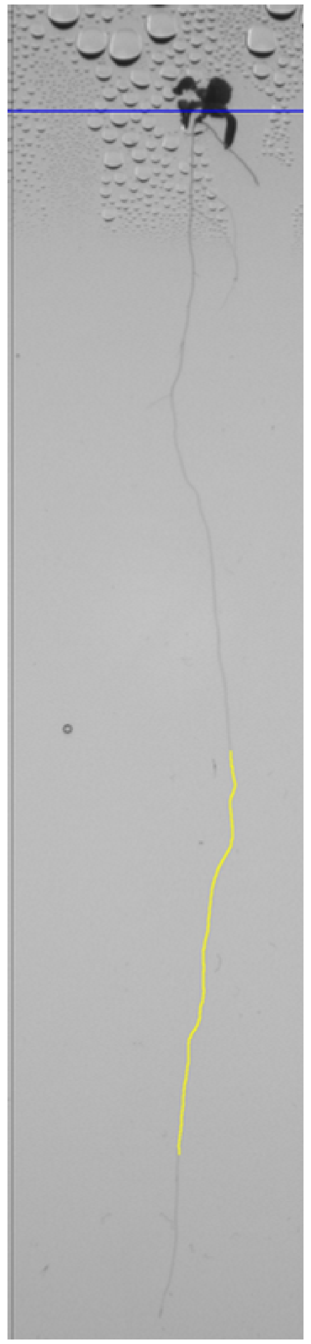
- **Issue:** Relative Left-to-Right sorting
- **Failure:** Missing plant → Index shift (P4 becomes P3).
- **Impact:** Catastrophic sMAPE error.
- **Bonus Challenge:** Ruptured plants are rendered as multiple plants.

Action

- **Logic:** Fixed Spatial Bucketing.
- **Implementation:** Divided dish width into 5 static zones.

Result

- **Outcome:** 100% ID Stability (Empty slots stay empty).
- **Bonus:** Automatically grouped ruptured roots in the same vertical slot.



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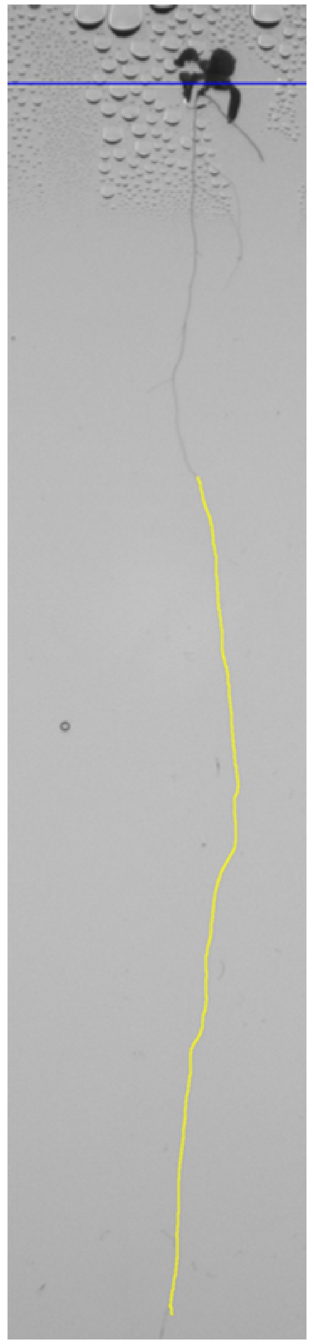


Challenge

- **Issue:** Root ruptures (segmentation gaps).
- **Failure:** Model detected 1 plant as 2 separate objects.

Action

- **Logic Change: Multi-Stage "Bridge" Logic**.
- **Step A:** Targeted vertical closing (25, 5).
- **Step B:** "Orphan Rescue" (Vertical alignment heuristic).

Result

- **Outcome:** Successfully reconnected broken segments.
- **Trade-off:** Conservative approach (avoided over-merging neighbors or debris).

Key Learnings from Iteration 2 (Almost Final CV)

Error Analysis - Iteration 3 (RL accuracy problem)

Challenge

- **Simulation:** 100% Success (0.57mm accuracy).
- **Full Integration:** Accuracy dropped to 1.4mm.
- **Cause:** Momentum overshoot on short distances.

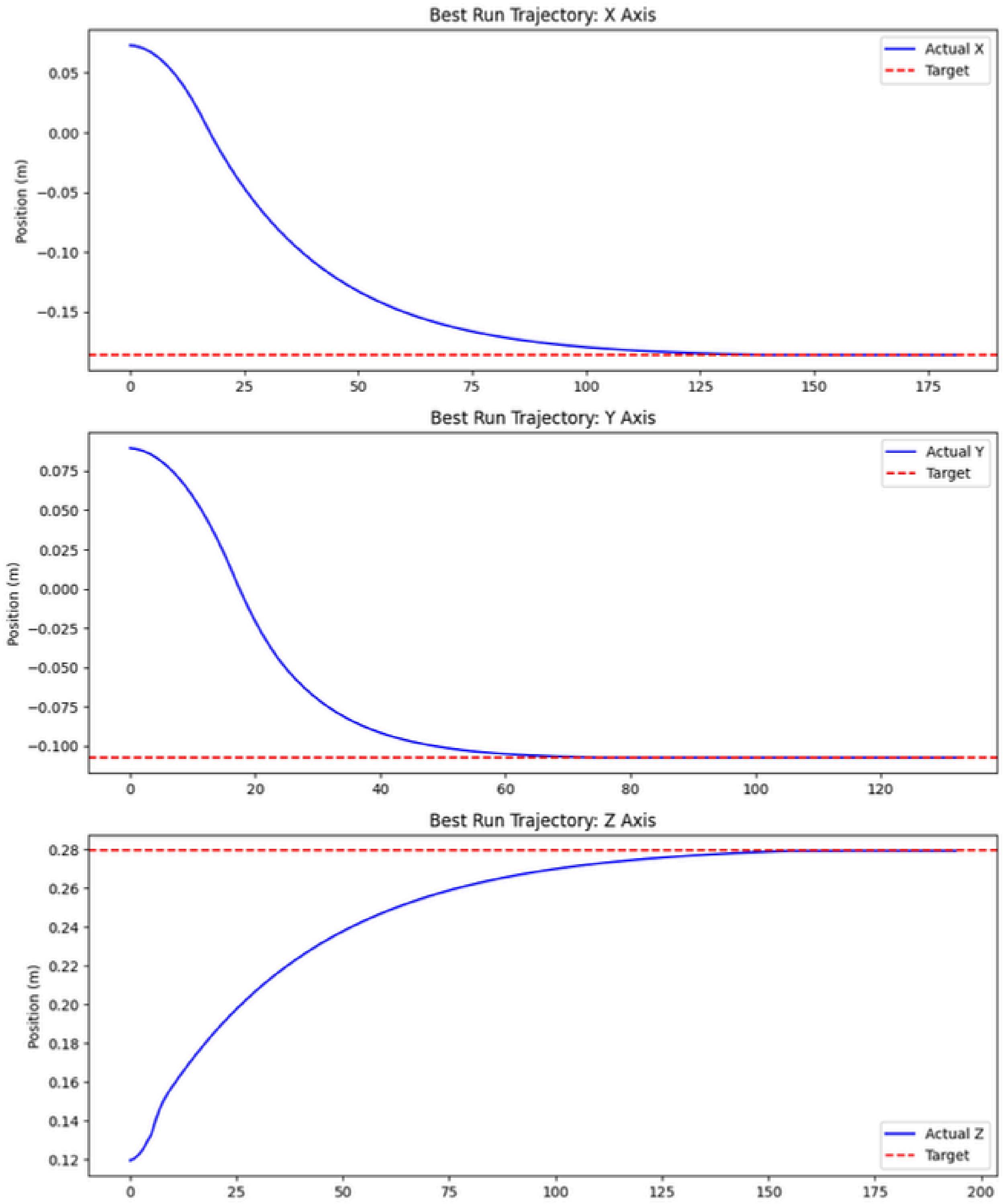
Action

- **Fix A:** Velocity Clamped to 50%.
- **Fix B:** Added 10-step settling window.

Result

- **Outcome:** Precision restored to 0.18mm.
- **Efficiency:** Maintained rapid 1.2s cycle time.

Robotics Controller: PID



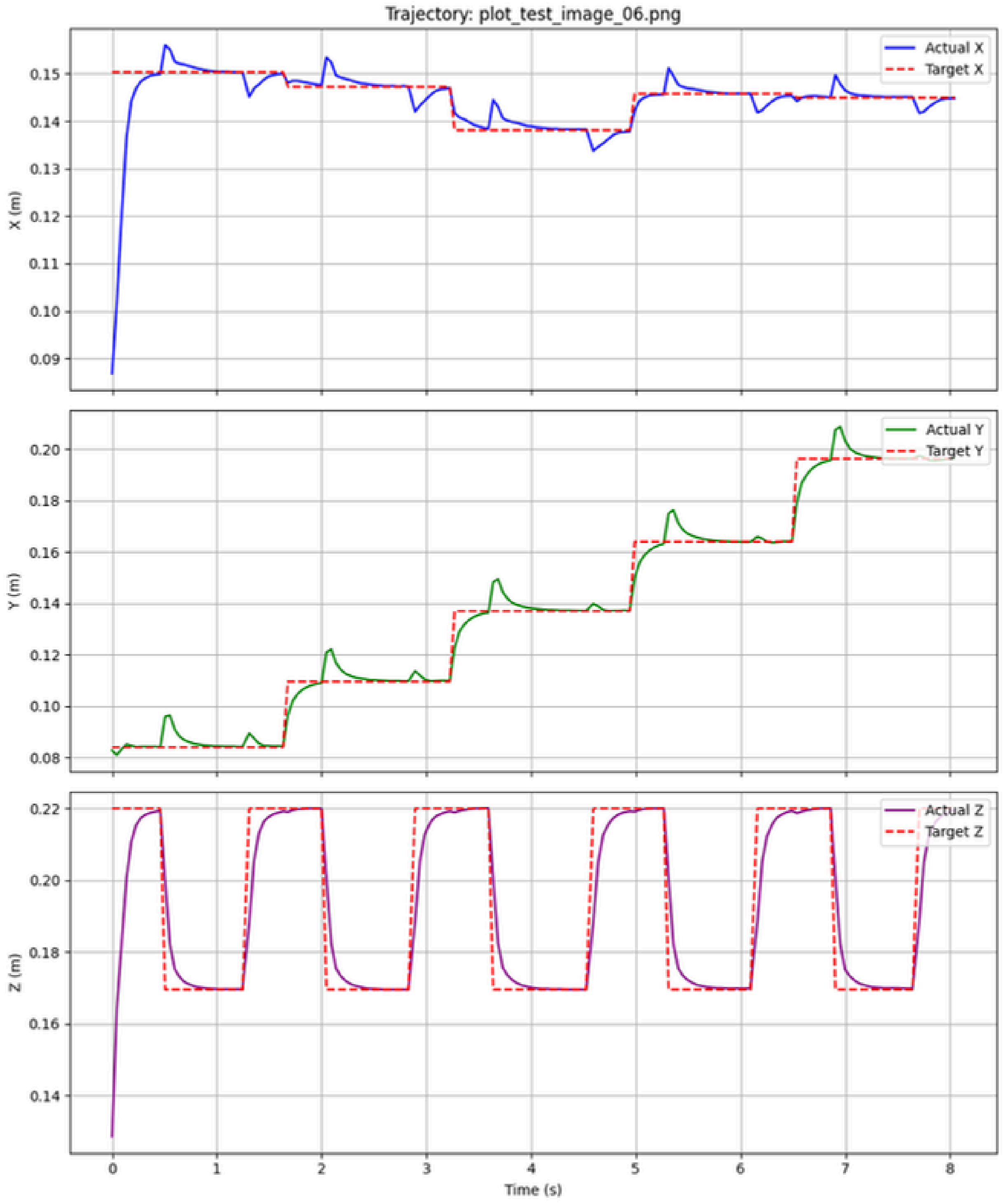
Traditional Control Mechanism: PID

- Role: The “Baseline“ / Industry Standard.
- Mechanism: Mathematical error correction (Proportional, Integral, Derivative).
- Pros: Deterministic, easy to implement, zero training time.
- Cons: Slower execution (tuned conservatively for stability).

Technical info

- Tuned for X, Y, Z axes independently.
- Gains:
  - X:
    - P (present error): 8.06
    - I (past error): 0.051
    - D (future error): 0.15
  - Y:
    - P: 5.5
    - I: 0.008
    - D: 0.1
  - Z:
    - P: 3.78
    - I: 0.062
    - D: 0.18

Robotics Controller: RL



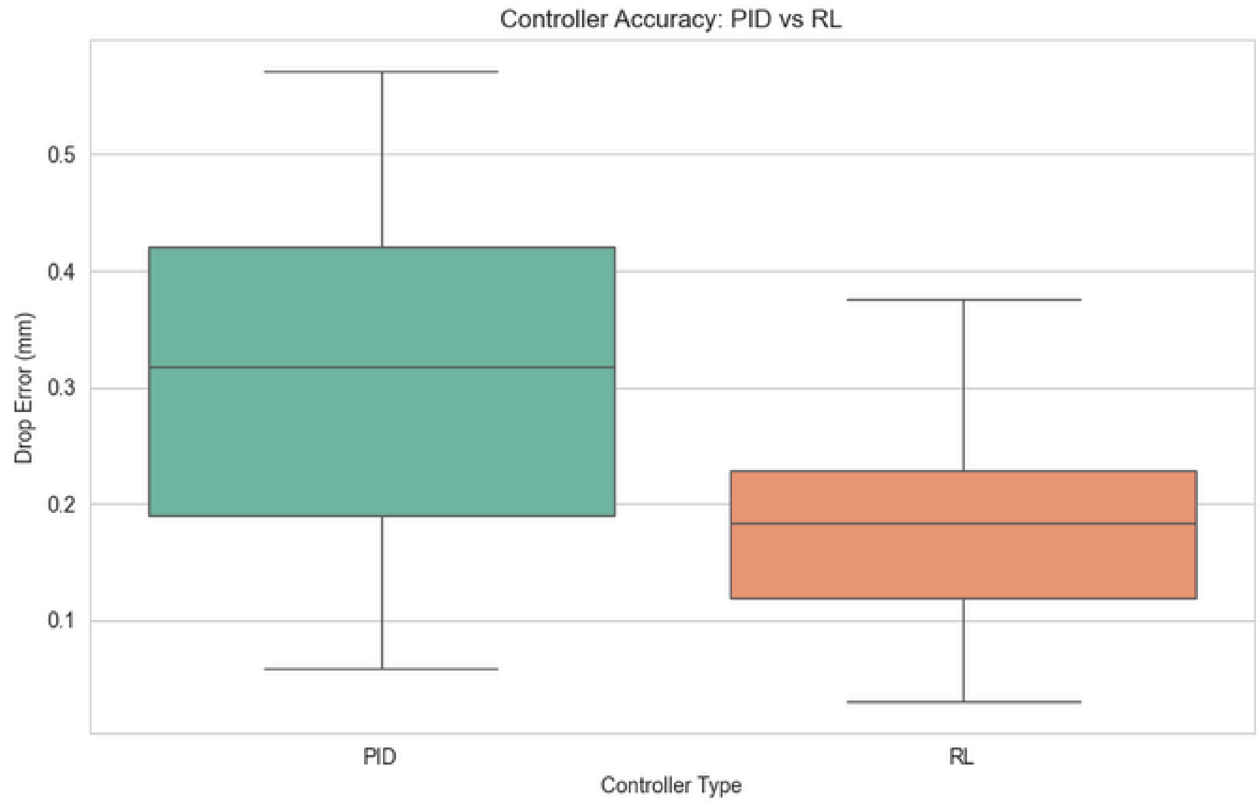
Reinforcement Learning

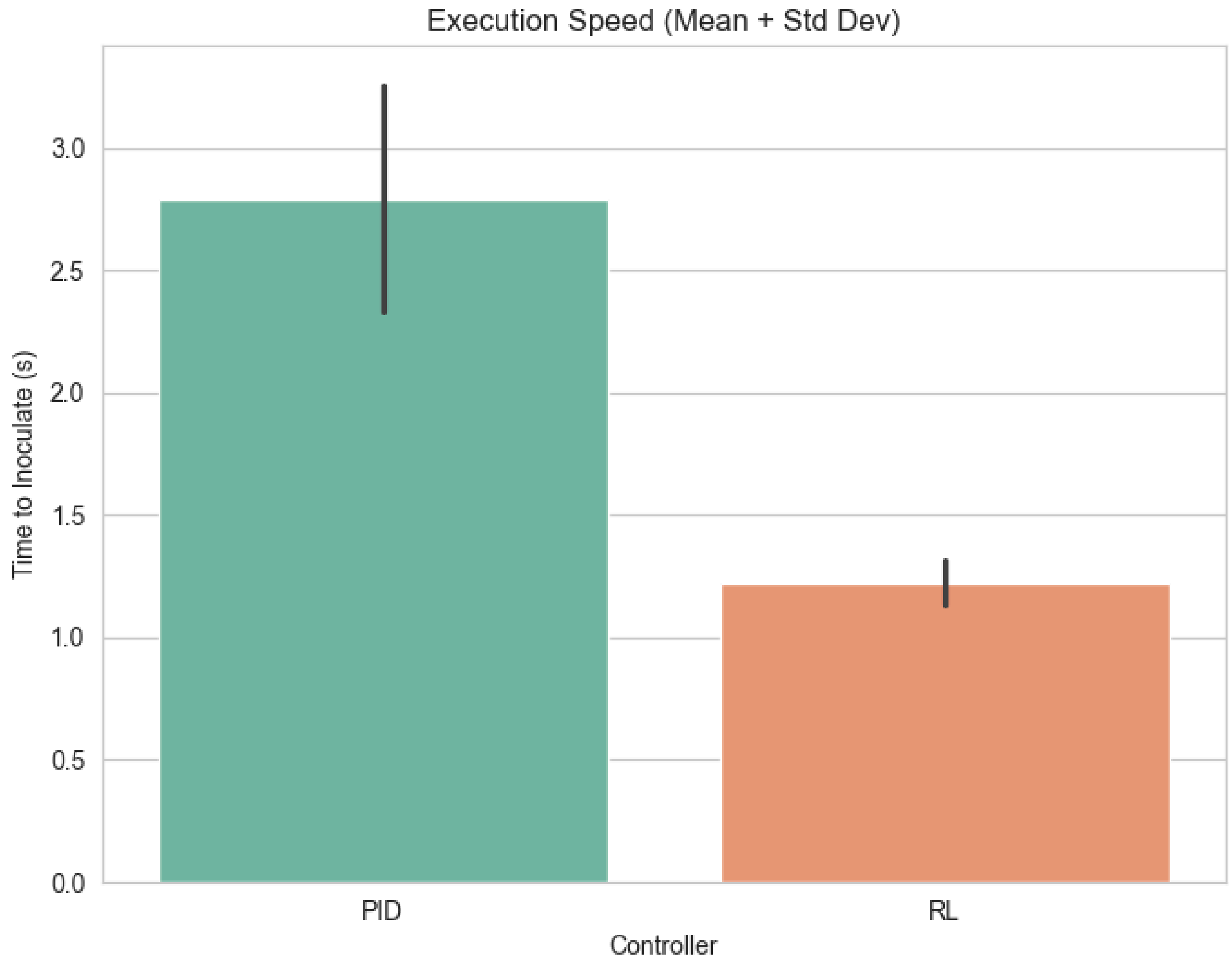
- Role: The “Optimizer.“
- Mechanism: Deep Neural Network (SAC Algorithm).
- Pros: Significantly faster (~2x speed), accurate (0.18mm)
- Cons: High computational cost (training), non-deterministic (harder to debug).

Technical info

- Curriculum Learning: Baseline 2mm → Hyperparameter Tuning (LR only) 1mm → Polishing The Winner (<1mm)
- Reward Function:
  - Base reward: -distance
  - Success: +50
  - Stuck in the wall: -5
  - No time or timeout penalty
- Parameters:
  - Learning Rate: 3e-4 → 7.7e-6 → 5e-6
  - Timesteps: 5M → 400K → 500K
  - Buffer size: 1M

Benchmarking Performance





Engineering Insight

- **Performance Win:** RL achieved superior execution time (~1.2s).
- **Complexity Cost:** RL is overkill for simple coordinate-positioning.

Assumptions and Limitations

Assumptions

- Always 5 plants per Petri dish (spaced evenly)
- Roots do not cross
- Assumes fixed camera orientation

Limitations

- It works only on one type of plants.
- Both PID and RL implementations would need additional tuning after Simulation-to-Reality bridging.

Future Development Steps

Improve CV

Implement plant-agnostic RSA model to work regardless of amount of plants in Petri dish.

Consult the client

Consult the client to receive a detailed feedback from them.

Thank You!

Questions?

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