INTEGRATING COMPUTER VISION AND ROBOTICS FOR AUTOMATED ROOT ANALYSIS AND INOCULATION

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PROBLEM DEFINITION

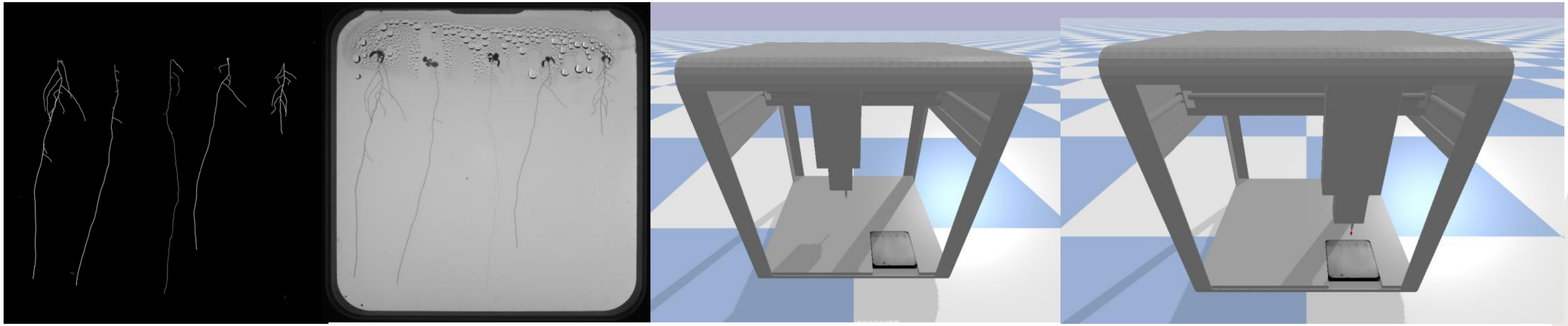
- **Key Challenges:**
- Analyzing **root system architectures** in high-throughput environments.
- Automating **precise inoculations** using liquid-handling robots.

- **Context:**
- Focus on *Arabidopsis thaliana* grown in Petri dishes.
- Images show **complex root overlaps**, complicating analysis.

- **My Solution:**
- Scalable approach for **automated segmentation** and measurement.
- Integration of **robotic inoculation** for precision and efficiency.

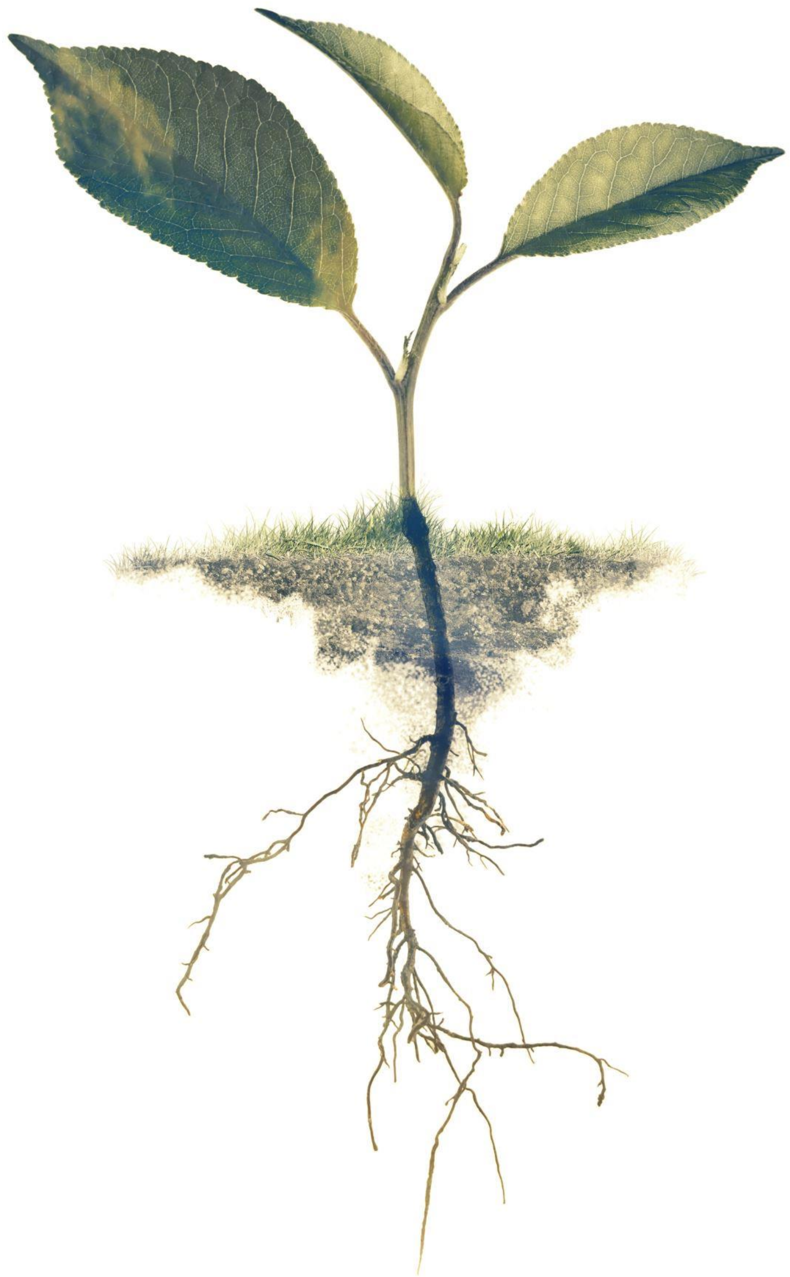
OVERVIEW OF PROPOSED SOLUTION

- **Root Segmentation**: Detect, segment, and measure root lengths.
- **Robotics**: Use PID and RL controllers for precise inoculations.
- **Integration**: Combine computer vision outputs with robotic inputs.



HOW MY SOLUTION WILL HELP THE CLIENT

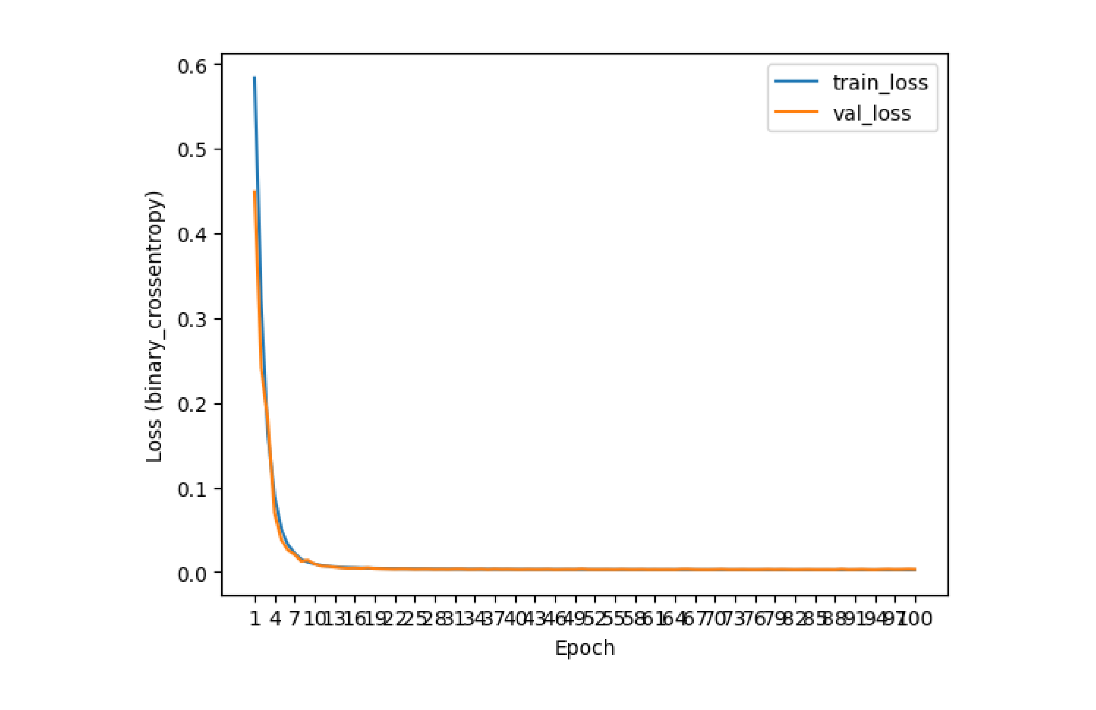
- **High-throughput phenotyping**: Measure thousands of roots efficiently.
- **Precision inoculation**: Deliver microbes to root tips accurately.
- **Scalable experiments**: Enable large-scale plant-microbe studies.

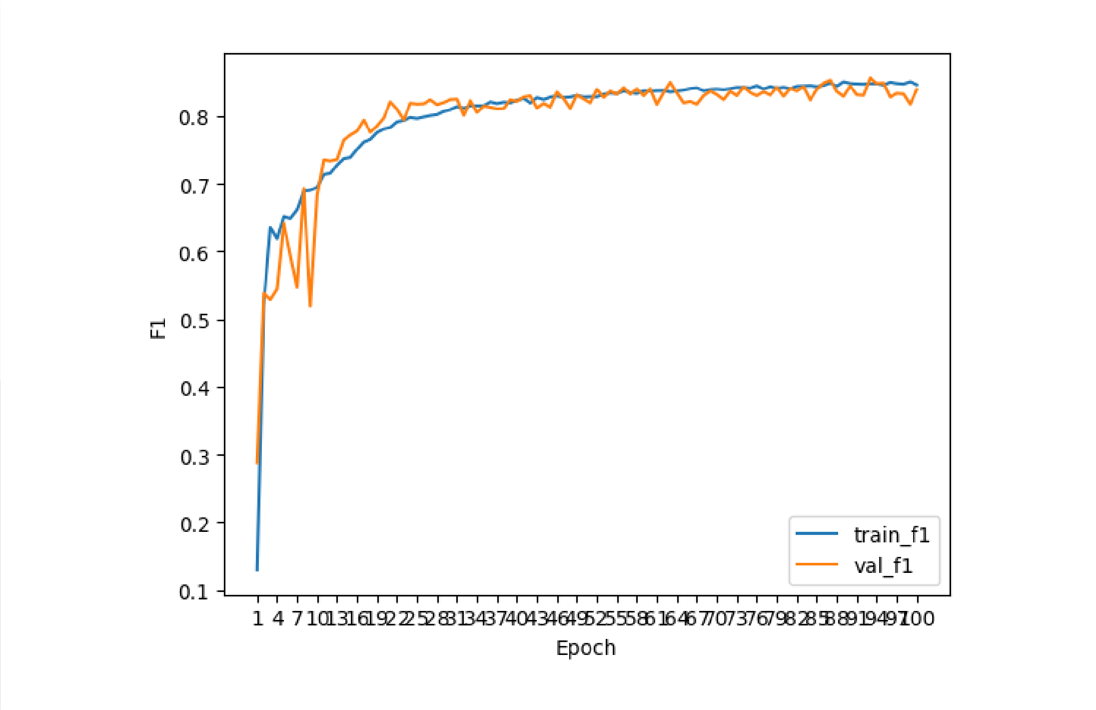


RESULTS & EVALUATION

- **Root Model**: F1 score of 0.856.
- **CV Pipeline**: Achieved sMAPE of 5.12% (public leaderboard) using zone-based root assignment.
- **Controller Performance**: RL and PID controller reached goals with 1mm accuracy.
- **Reinforcement Learning**: Hyperparameter optimization within the group resulted in an RL model that combined stability and speed for efficient task execution.
- **Integration of Computer Vision and Robotics**: Successfully integrated segmentation pipeline with robotics for automated inoculations.

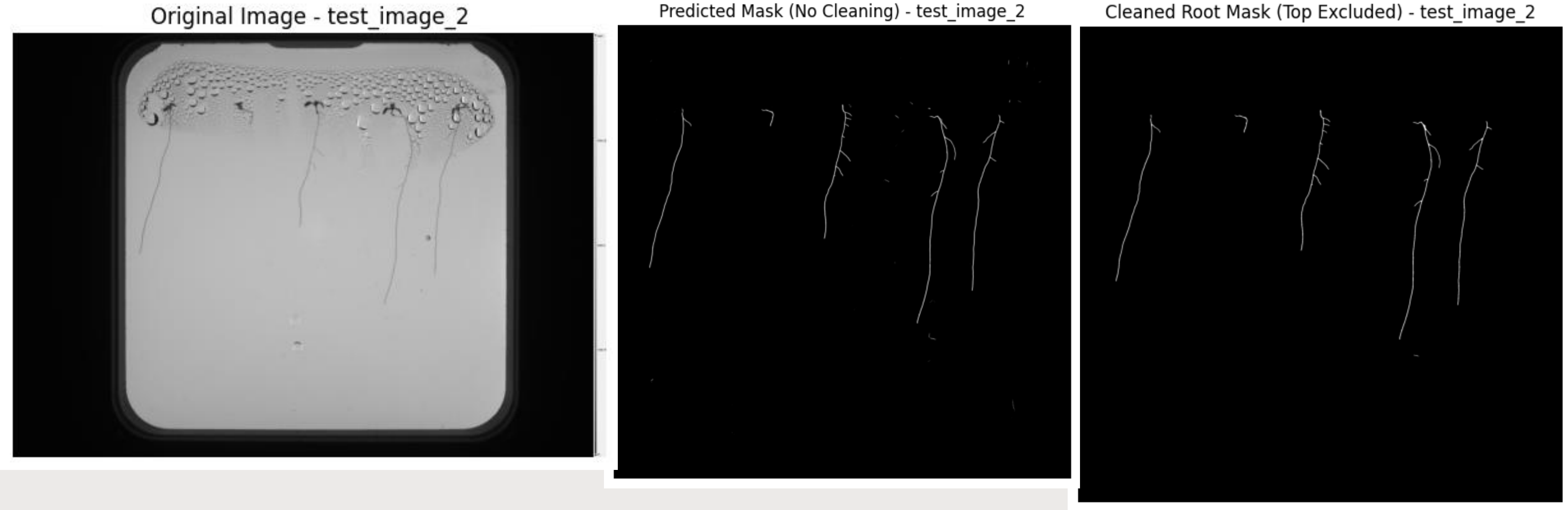
ROOT MODEL PERFORMANCE





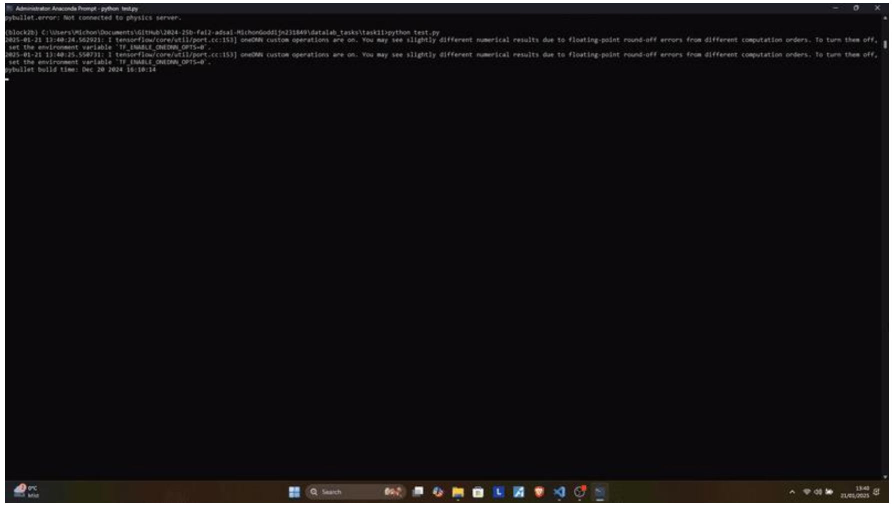
Best validation loss: 0.0027233962900936604
Best validation F1: 0.8563873171806335
Learning rate: 1e-4
Batch size: 32
Epochs: 100

COMPUTER VISION PIPELINE

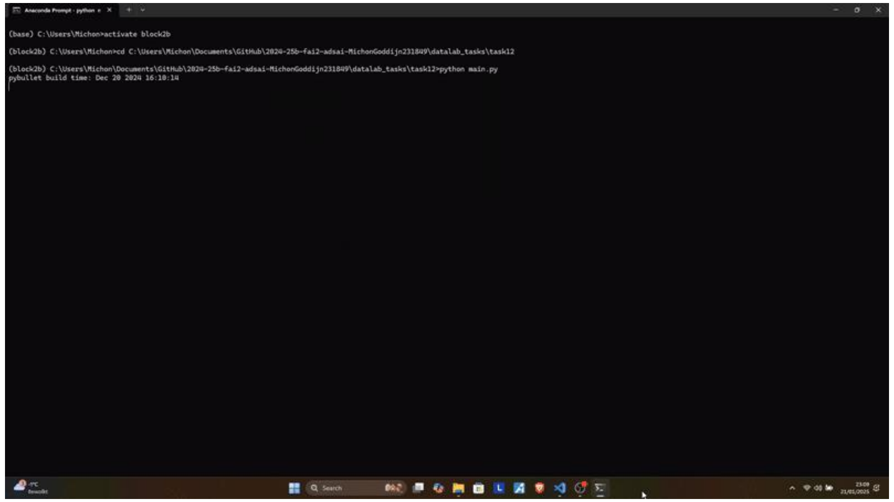


COMPUTER VISION PIPELINE

CONTROLLER PERFORMANCE



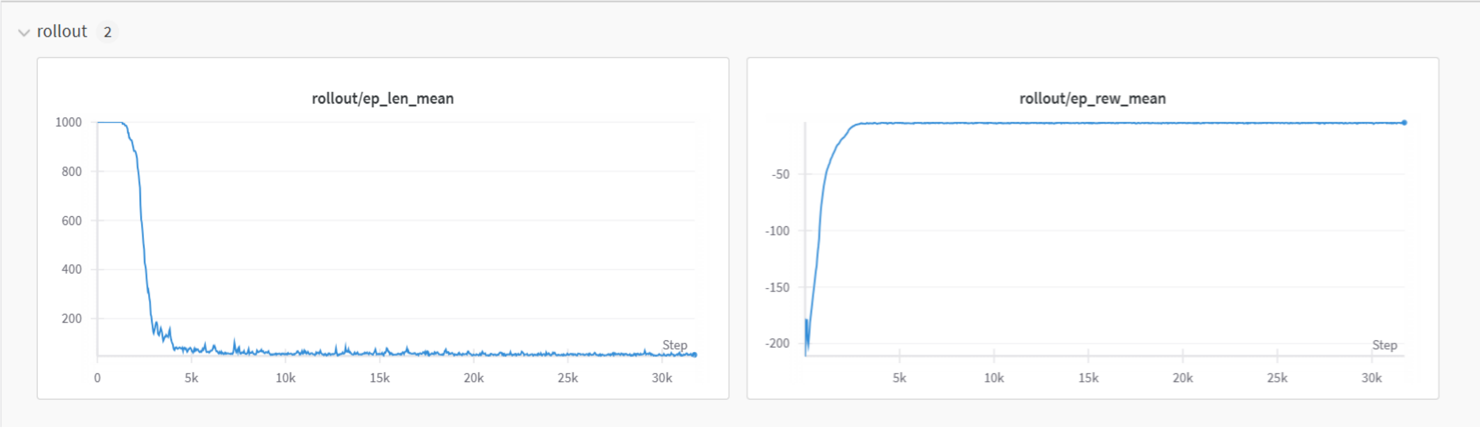
RL CONTROLLER



PID CONTROLLER

Best Performing Gains:
KP: 20.0
KI: 0.1
KD: 0.005

REINFORCEMENT LEARNING

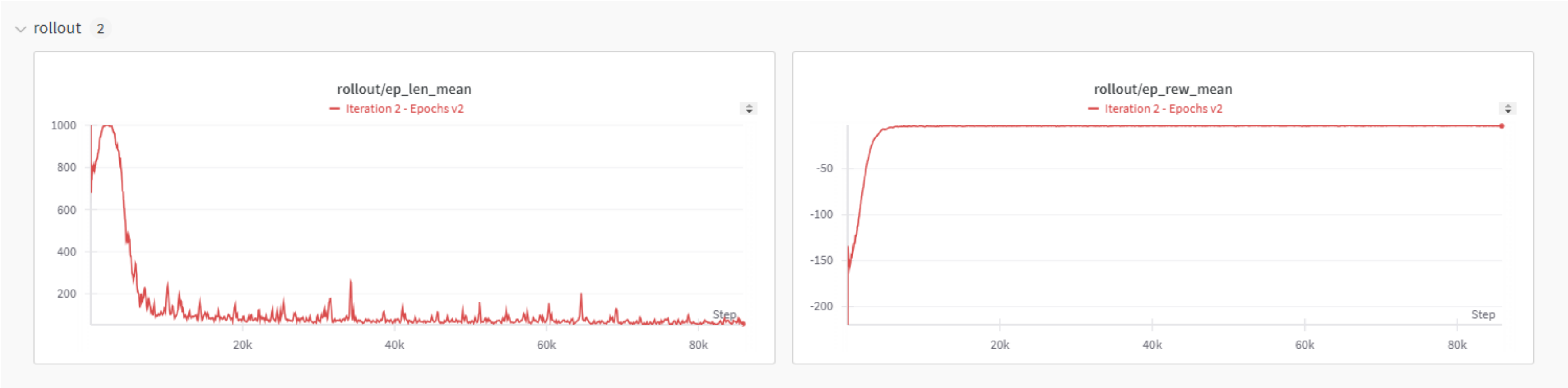


Group Model

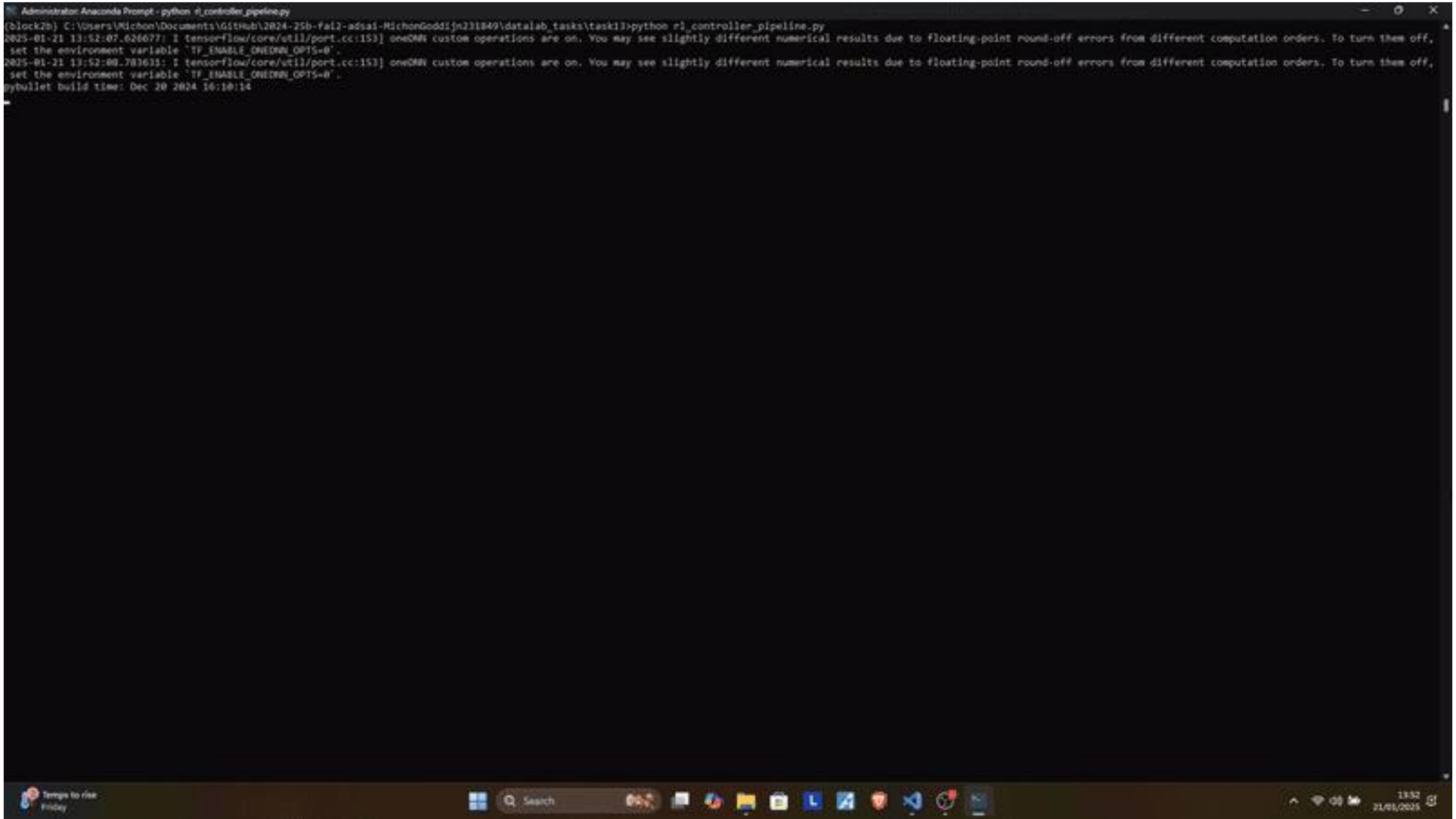
Learning Rate: 0.0001
Batch Size: 64
Steps: 2048
Epochs: 50
Gamma: 0.8
Policy: MlpPolicy
Clip Range: 0.1
Value Coefficient: 0.75

My Best Model

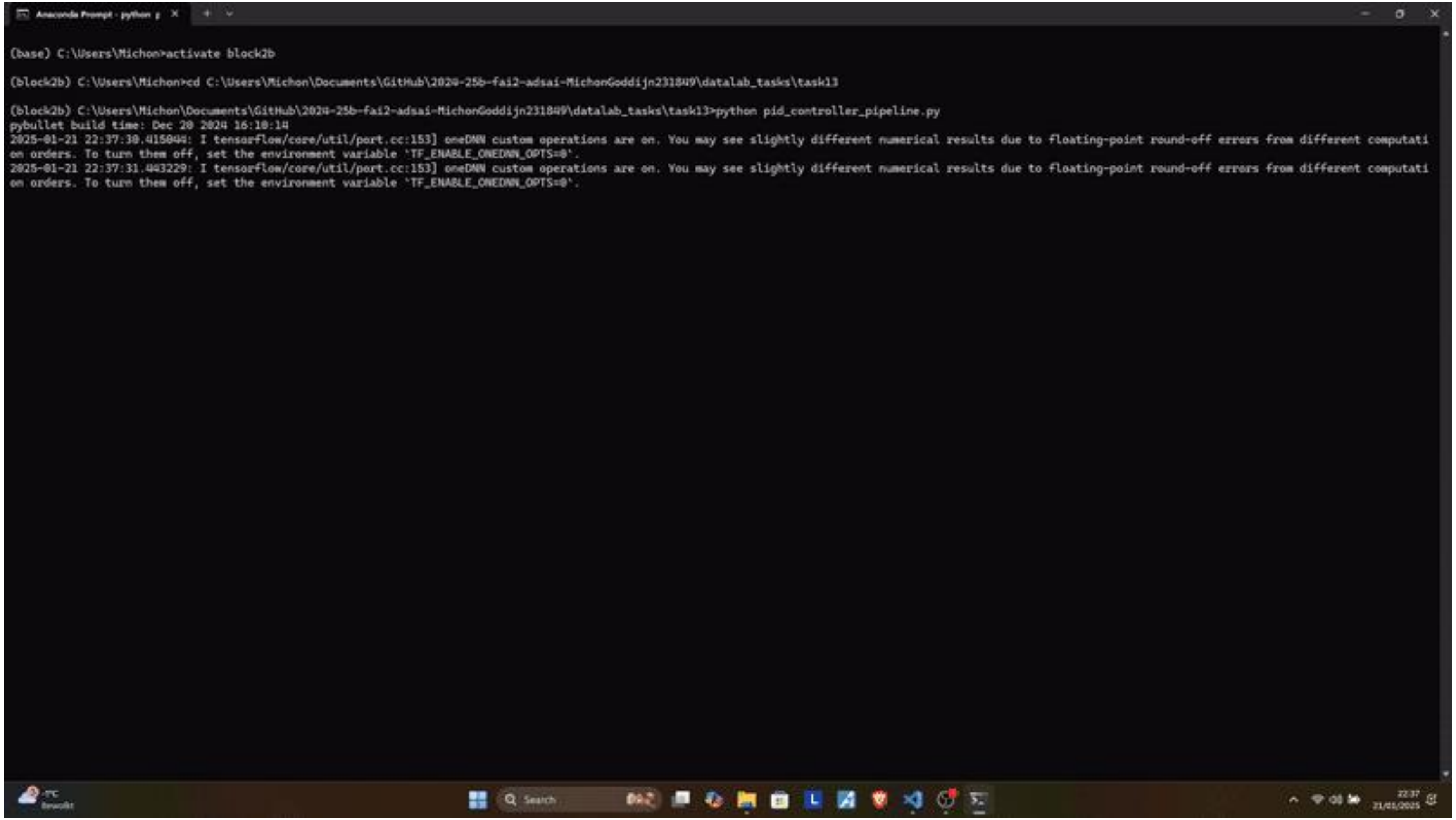
Learning Rate: 0.0001
Batch Size: 32
Steps: 2048
Epochs: 15
Gamma: 0.98
Policy: MlpPolicy
Clip Range: 0.2
Value coefficient: 0.5



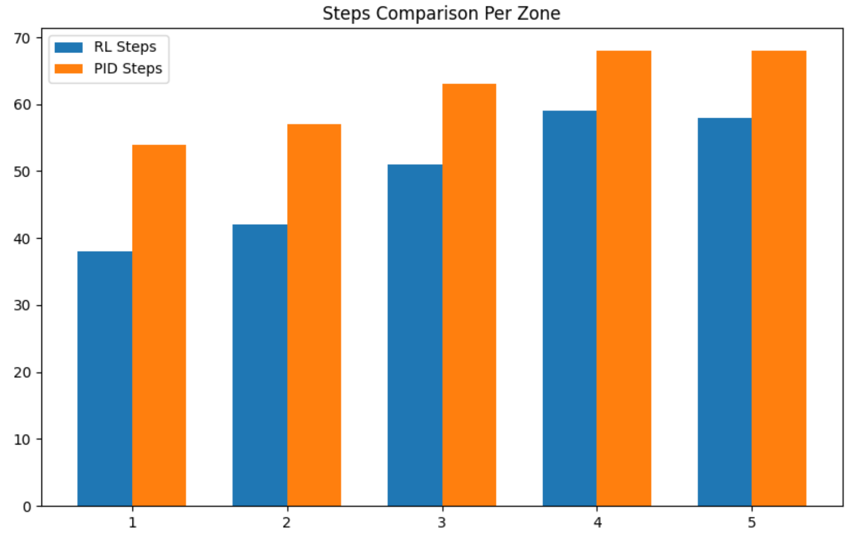
INTEGRATION OF COMPUTER VISION AND ROBOTICS RL CONTROLLER PIPELINE



INTEGRATION OF COMPUTER VISION AND ROBOTICS PID CONTROLLER PIPELINE



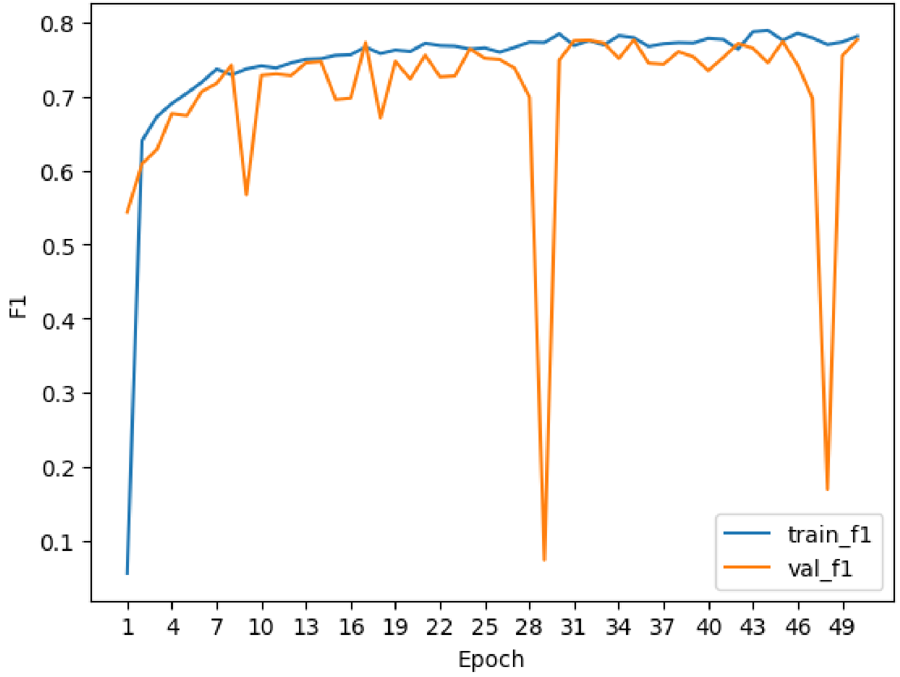
INTEGRATION OF COMPUTER VISION AND ROBOTICS
BENCHMARK RESULTS

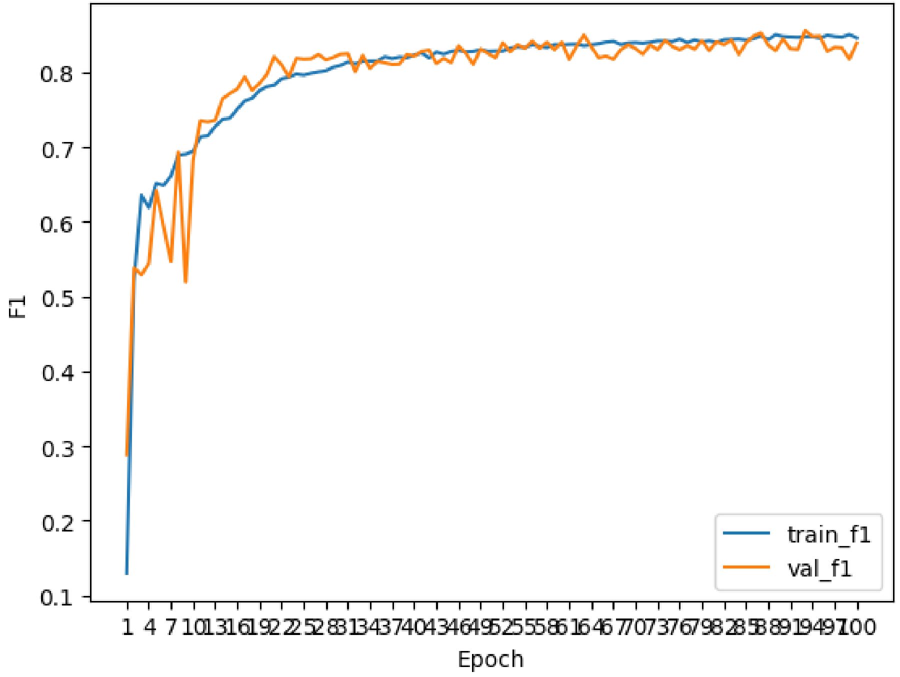



```
=== Benchmark Results (Per Zone) ===
   zone  rl_steps  rl_distance  rl_time_sec  rl_success  pid_steps  pid_distance  pid_time_sec  pid_success
0     1        38     0.000933     5.188570        True         54      0.000875      6.089450         True
1     2        42     0.000856     5.587958        True         57      0.000873      6.879905         True
2     3        51     0.000834     6.538404        True         63      0.000834      7.511728         True
3     4        59     0.000728     7.372252        True         68      0.000831      8.043357         True
4     5        58     0.000990     7.254793        True         68      0.000831      8.039656         True

=== Summary ===
Avg RL Time:     6.388 s
Avg PID Time:    7.313 s
Avg RL Steps:    49.6
Avg PID Steps:   62.0
RL Successes:    5 / 5
PID Successes:   5 / 5
```

ERROR ANALYSIS & ITERATIONS



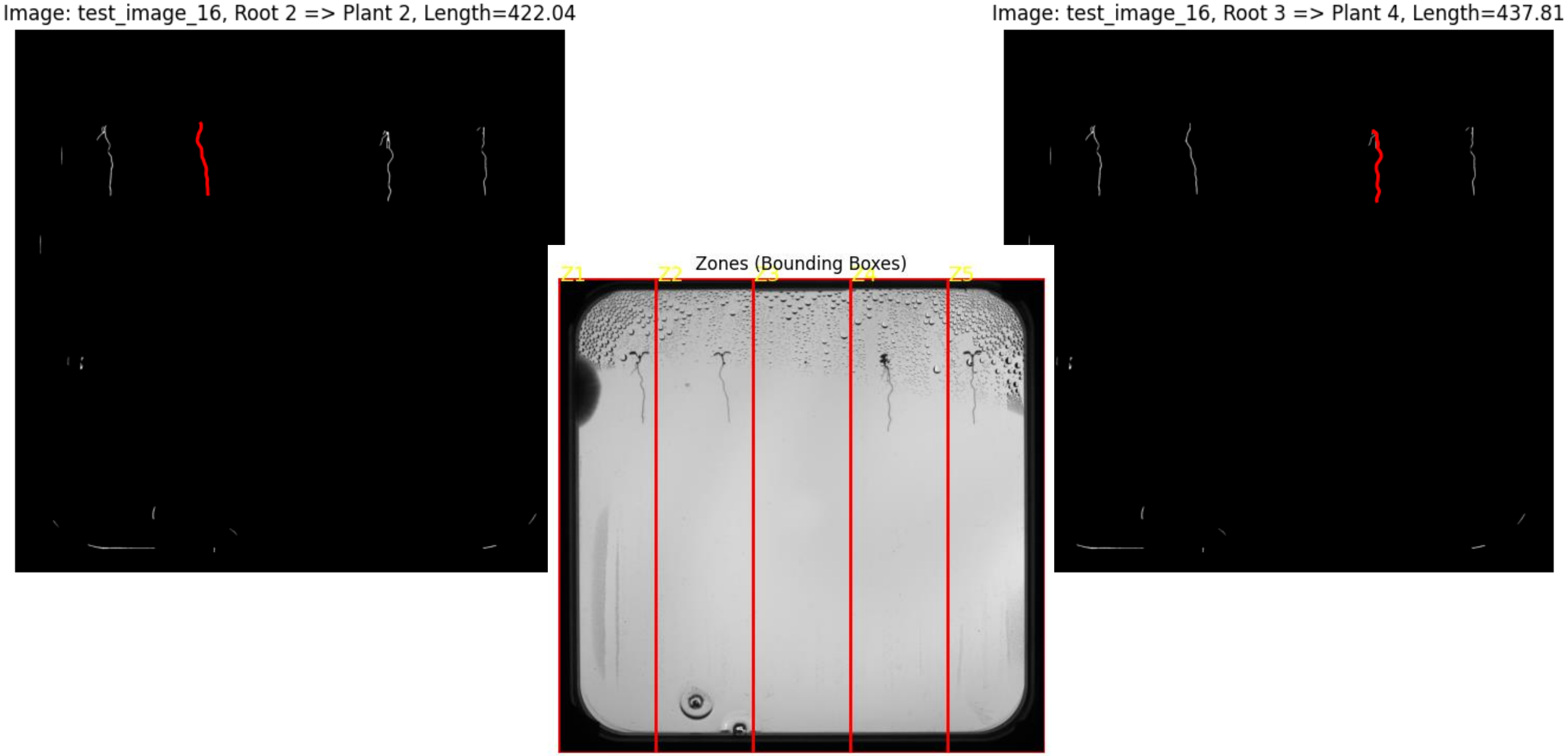


- **Batch size**: 16
- **Epochs**: 50

- **Batch size**: 32
- **Epochs**: 100
- **Learning rate**: 1e-4

Root Model: Validation F1 from 0.77 to 0.85

ERROR ANALYSIS & ITERATIONS



CV Pipeline: Zone mapping improved sMAPE from from 30.007% to 5.12% (public leaderboard)

ERROR ANALYSIS & ITERATIONS

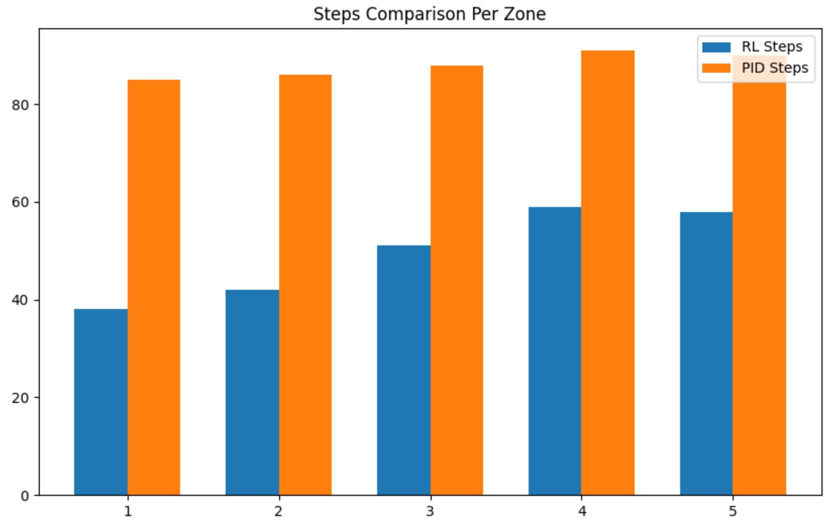
```
Step 104: Current position: [ 0.1714 -0.1296  0.2523], Distance to goal: 0.001239 m
PID outputs: vx=0.015, vy=-0.050, vz=0.018
Action: [ 0.01471868 -0.0497707   0.0177053 ]
Step 105: Current position: [ 0.1715 -0.1298  0.2524], Distance to goal: 0.001024 m
PID outputs: vx=0.014, vy=-0.048, vz=0.017
Action: [ 0.013709   -0.04777577  0.01670529]
Step 106: Current position: [ 0.1715 -0.13    0.2524], Distance to goal: 0.000824 m
PID outputs: vx=0.014, vy=-0.046, vz=0.017
Action: [ 0.01371933 -0.04577999  0.01671545]
Goal reached within 1 mm accuracy at step 106, distance: 0.000824 m
```

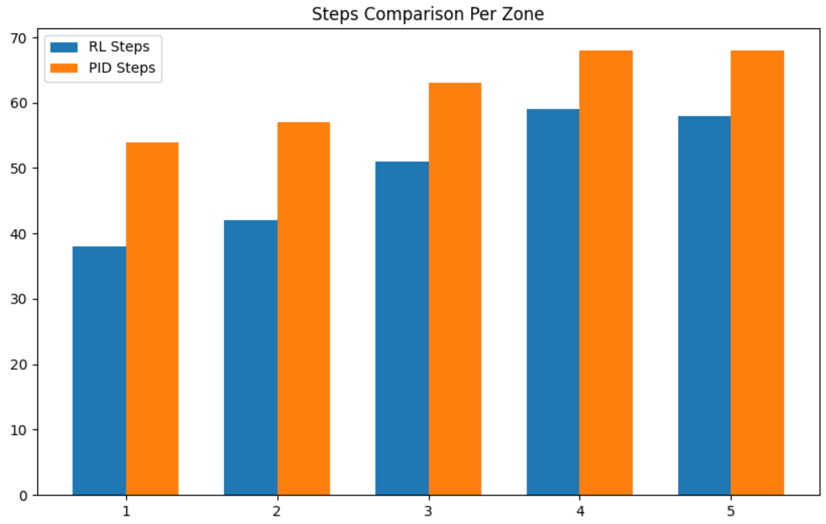


```
Step 52: Current position: [0.0753 0.0569 0.2165], Distance to goal: 0.001261 m
PID outputs: vx=0.001, vy=-0.009, vz=0.032
Action: [ 0.00107362 -0.00946317  0.03173855]
Step 53: Current position: [0.0753 0.0568 0.2166], Distance to goal: 0.001139 m
PID outputs: vx=0.001, vy=-0.007, vz=0.030
Action: [ 0.00107385 -0.00745452  0.02974405]
Step 54: Current position: [0.0753 0.0568 0.2168], Distance to goal: 0.000946 m
PID outputs: vx=0.001, vy=-0.007, vz=0.026
Action: [ 0.00107408 -0.00746583  0.02573852]
Goal reached within 1 mm accuracy at step 54, distance: 0.000946 m
```

PID Controller and Pipeline: Speed improved by around 30% - 40% increasing KP from 10 to 20.

ERROR ANALYSIS & ITERATIONS





PID Controller and Pipeline: Speed improved by around 30% - 40% increasing KP from 10 to 20.

ASSUMPTIONS

- Assumed Petri dishes were square, ignoring corner curvatures, to simplify edge detection and cropping.
- Relied on roots being segmented from left to right within predefined zones for plant assignment.
- Assumed consistent lighting and background conditions across datasets to minimize preprocessing variability.
- Assumed a linear transformation could effectively map pixel coordinates to robot positions without accounting for complex distortions.
- Assumed all input images would contain valid, distinguishable roots to prevent errors in segmentation and measurement.

LIMITATIONS

GAPS IN ROOT PREDICTIONS REDUCE SEGMENTATION AND TIP ACCURACY.

STRUGGLES WITH VERY SMALL ROOTS AND COMPLEX OVERLAPS.

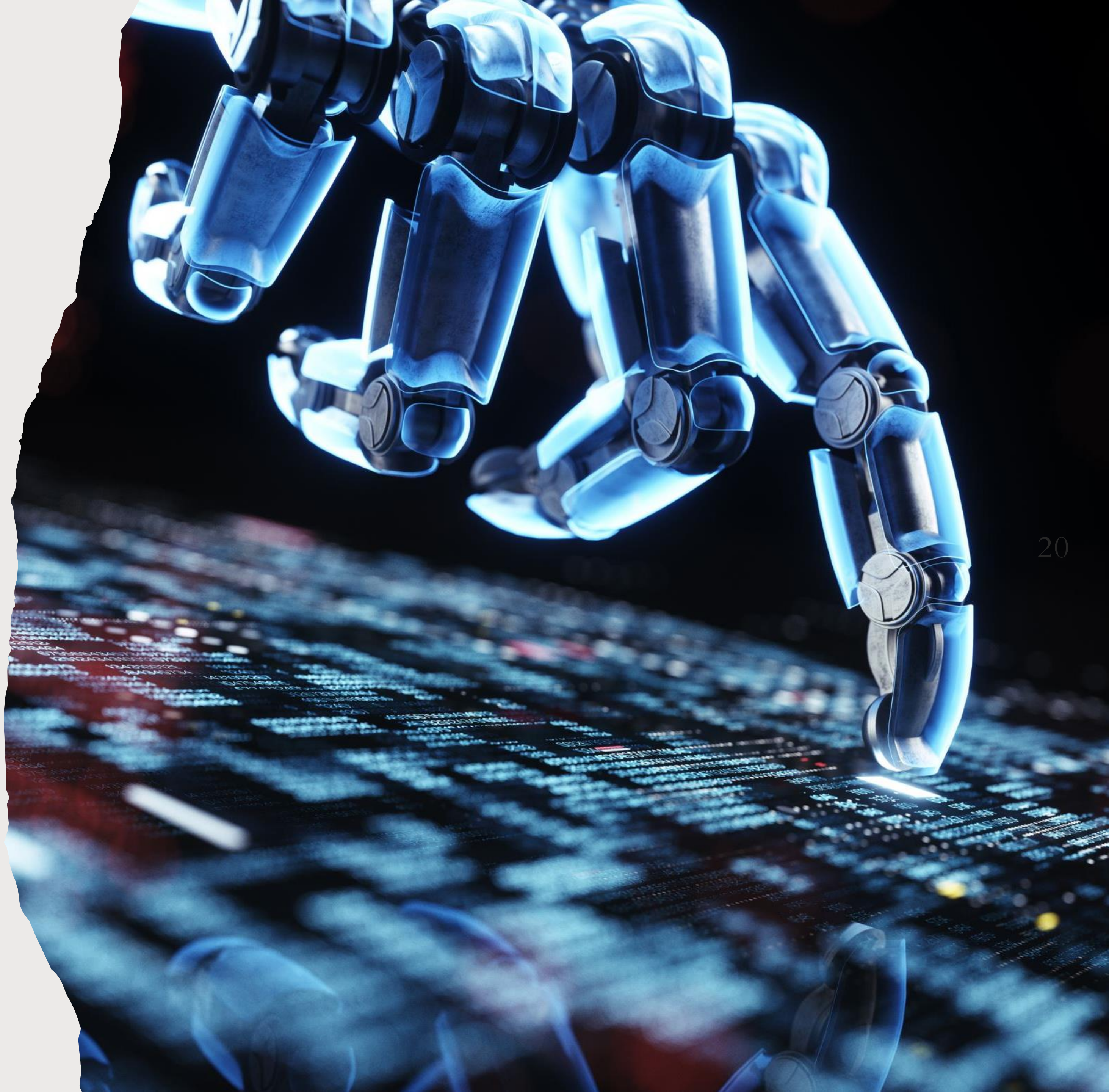
COMPLEX OVERLAPS REMAIN CHALLENGING TO SEGMENT.

ROBOT ARM DOESN’T FULLY DESCEND DURING INOCULATIONS.

PID CONTROLLER IS SLOWER COMPARED TO RL IN REAL-TIME SCENARIOS.

NEXT STEPS

- Data Augmentation
- Hybrid Controllers
- Robotics Refinement
- Advanced Segmentation Models
- Improved Root Tip Localization
- Error Analysis Integration



SUMMARY

- We developed an integrated vision and robotics solution to address challenges in high-throughput phenotyping and precision inoculation of Arabidopsis thaliana.
- The root segmentation pipeline achieved a validation F1 score of **0.856**, effectively distinguishing roots even in complex images with overlaps.
- Our iterative improvements, such as zone-based segmentation, reduced SMAPE from **30.007%** to **5.12%**, significantly enhancing root-to-plant assignment accuracy.
- The robotics system successfully integrated PID and RL controllers, achieving millimeter precision while automating inoculation tasks.
- Despite limitations like gaps in root predictions and challenges with very small roots, the pipeline provides a robust foundation for further refinement.
- Next steps focus on improving root tip localization, handling small root detection, and enhancing robotic inoculation accuracy.