SIEMENS

Line-Following Robot with PID Control

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Course Name : Digital Twin & Its Applications

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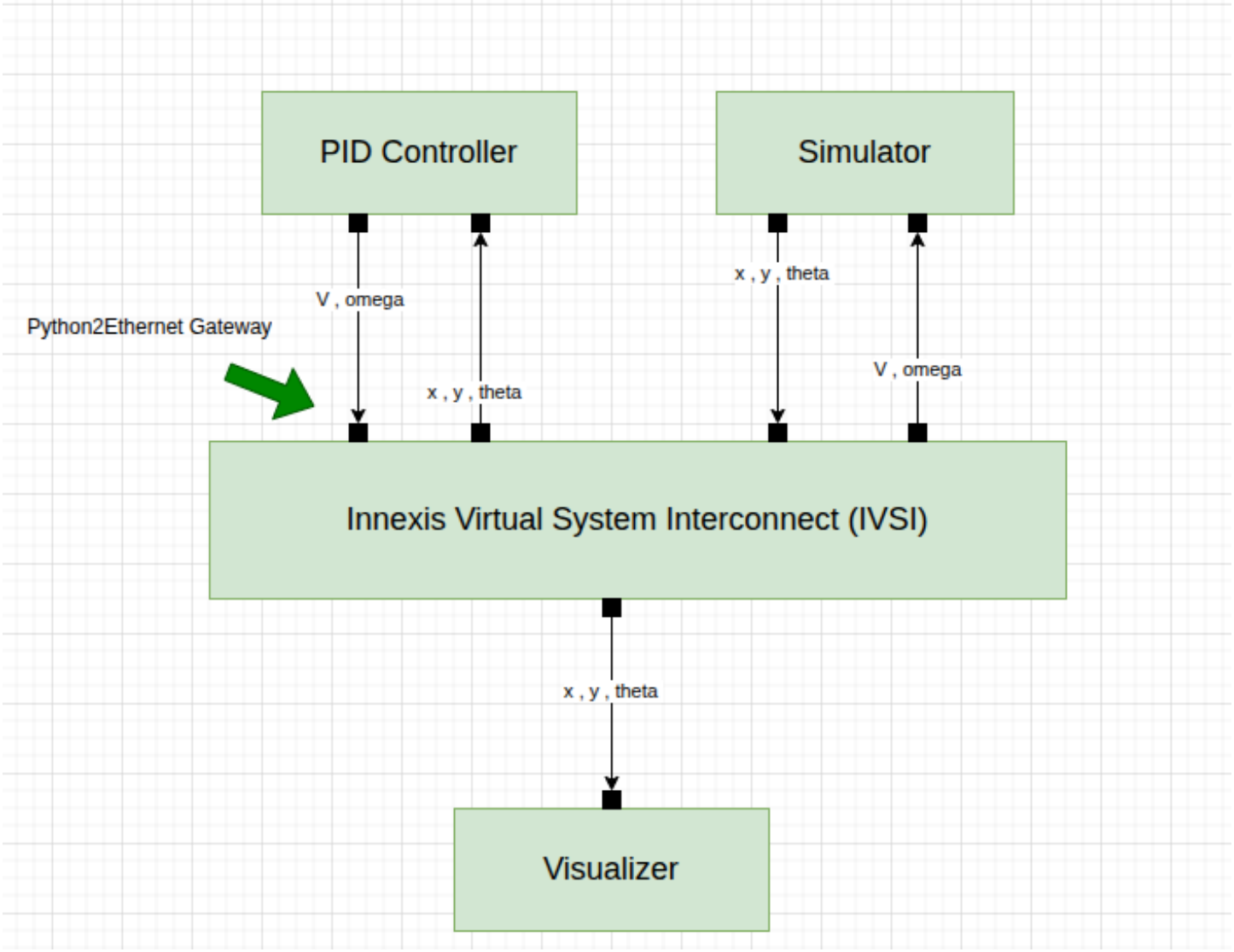
Overview :

A differential-drive robot spawns near a predefined line/path on a 2D plane. The controller steers the robot onto the path and tracks it to the end with minimal lateral error. The system consists of three lightweight clients connected over the VSI fabric.

Architecture :



- **PID Controller (Client 1)**
  - **Inputs:** robot state (x,y,θ) from the Simulator via IVSI.
  - **Outputs:** control commands v,ω (linear and angular velocity).
  - **Function:** Implements a control law to minimize path-tracking error.
    - Computes cross-track and heading error relative to a reference path.
    - Produces corrective velocity commands.
  - **Purpose:** Makes the robot follow the path correctly instead of drifting.

- **Simulator (Client 2)**
  - **Inputs:** control commands v,ω from the PID Controller via IVSI.
  - **Outputs:** robot state (x,y,θ)
  - **Function:** Models the robot's kinematics and environment.
    - Uses differential drive equations.
    - Updates the robot's position and heading over time.
  - **Purpose:** Acts as a "virtual plant" so we don't need physical hardware.

- **Visualizer (Client 3)**
  - **Inputs:** robot state (x,y,θ) from IVSI.
  - **Outputs:** trajectory plots and real-time animation.
  - **Function:** Graphically shows how well the robot follows the desired path.
  - **Purpose:** Helps debug the controller and simulator by providing visual feedback.

- **Innexis Virtual System Interconnect (IVSI)**
  - **Acts as a bus/gateway** between clients.
  - Ensures decoupling: each client only needs to talk to IVSI, not directly to each other.
  - Uses **Python2Ethernet Gateway** for exchanging state/control messages over sockets.

Modeling Equations :

- **Robot Kinematics (Differential Drive):**

$$x_{k+1} = x_k + v_k \cdot \cos(\theta_k) \cdot \Delta t$$
$$y_{k+1} = y_k + v_k \cdot \sin(\theta_k) \cdot \Delta t$$
$$\theta_{k+1} = \theta_k + \omega_k \cdot \Delta t$$

- **Sensor Noise Model:**

$$\tilde{x} = x + \varepsilon_x, \quad \varepsilon_x \sim \mathcal{N}(0, \sigma_x^2)$$
$$\tilde{y} = y + \varepsilon_y, \quad \varepsilon_y \sim \mathcal{N}(0, \sigma_y^2)$$
$$\tilde{\theta} = \theta + \varepsilon_\theta, \quad \varepsilon_\theta \sim \mathcal{N}(0, \sigma_\theta^2)$$

- **Noise Standard Deviations:**

$$\sigma_x = \sigma_y = \sigma_{\text{pos}}, \quad \sigma_\theta = \frac{\sigma_{\text{pos}}}{10}$$

- **PID Control Law:**

$$u_k = K_p \cdot e_k + K_i \cdot \sum_{j=0}^{k} e_j \cdot \Delta t + K_d \cdot \frac{e_k - e_{k-1}}{\Delta t}$$

- Error Definition:

$$e_k = y_k - y_{\text{ref}}$$

- **Straight Line Reference Path:**

$$y_{\text{ref}}(x) = 2.0 \quad \forall x$$

- **Performance Metrics:**

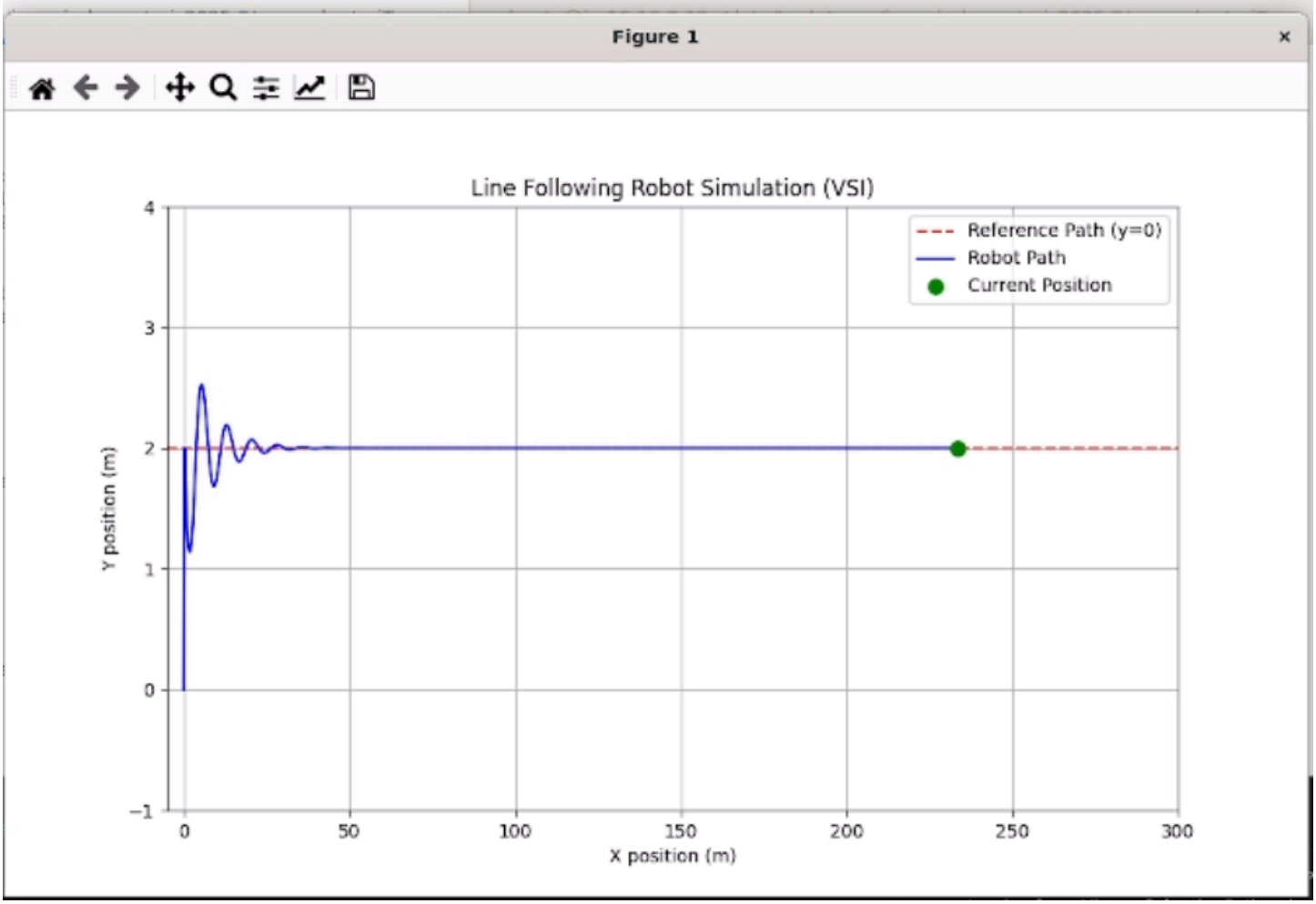
$$\text{OS} = \max_{t \in [0,T]} |y(t) - y_{\text{ref}}|$$

$$T_s = \min \{t : |y(\tau) - y_{\text{ref}}| \leq 0.05 \cdot \text{SSE},\ \forall \tau \geq t\}$$

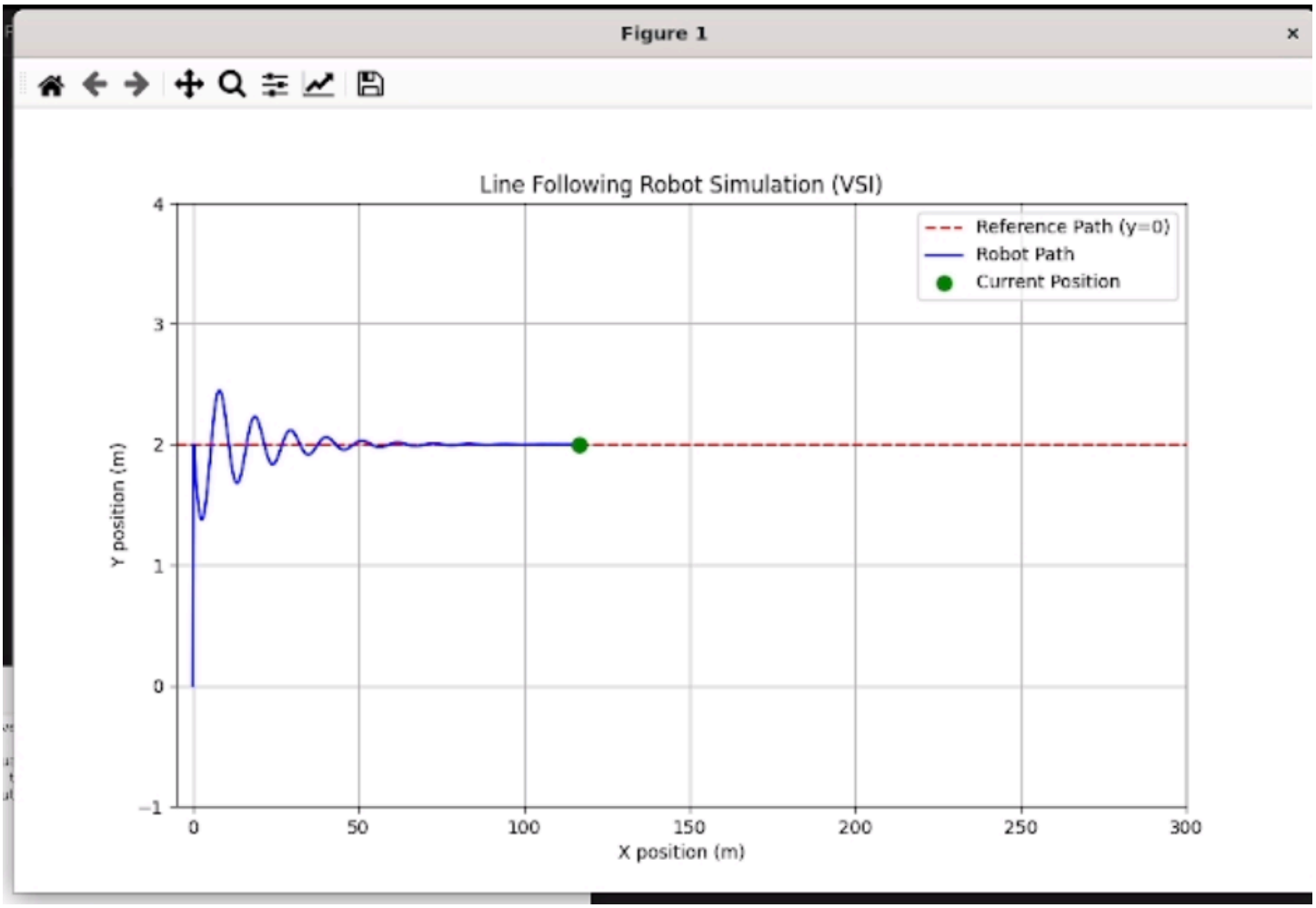
$$\text{SSE} = \lim_{t \to \infty} |y(t) - y_{\text{ref}}| \approx \frac{1}{N} \sum_{i=k-N+1}^{k} |y_i - y_{\text{ref}}|$$

Experiments :

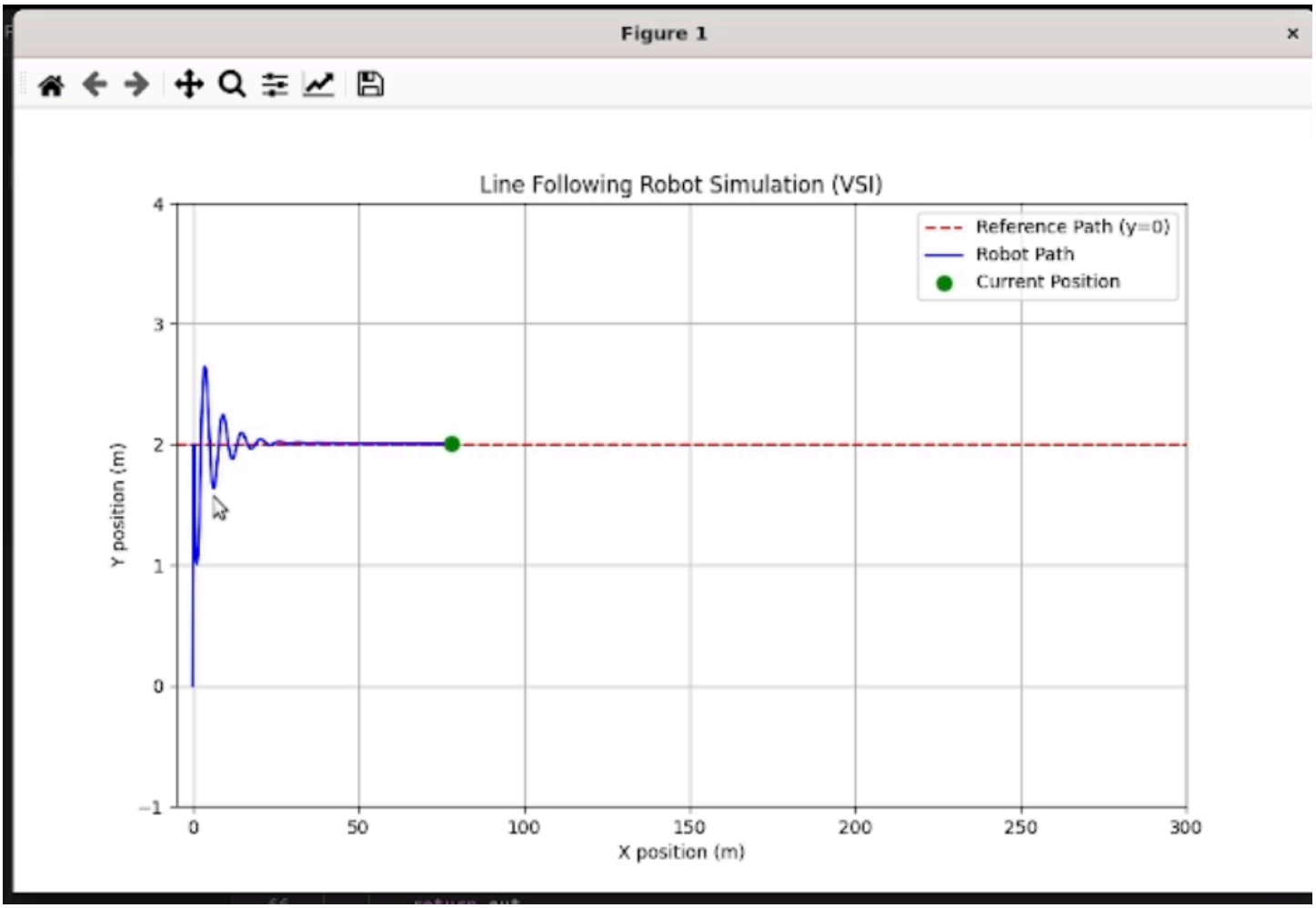
- **Experiment one, Trail one :**
  - Values used for the PID controller → Kp = 1.5 , Ki = 0.0, Kd = 0.4
  - ref_path → y = 2
  - No noise
  - Video Link for the experiment → Siemens_DT - Google Drive (E1-T1)
  - Results :
    - Maximum Overshoot: 200.00 cm
    - Settling Time (5%): 6.01s
    - Steady-State Error: 0.0001 cm
  - Plot :



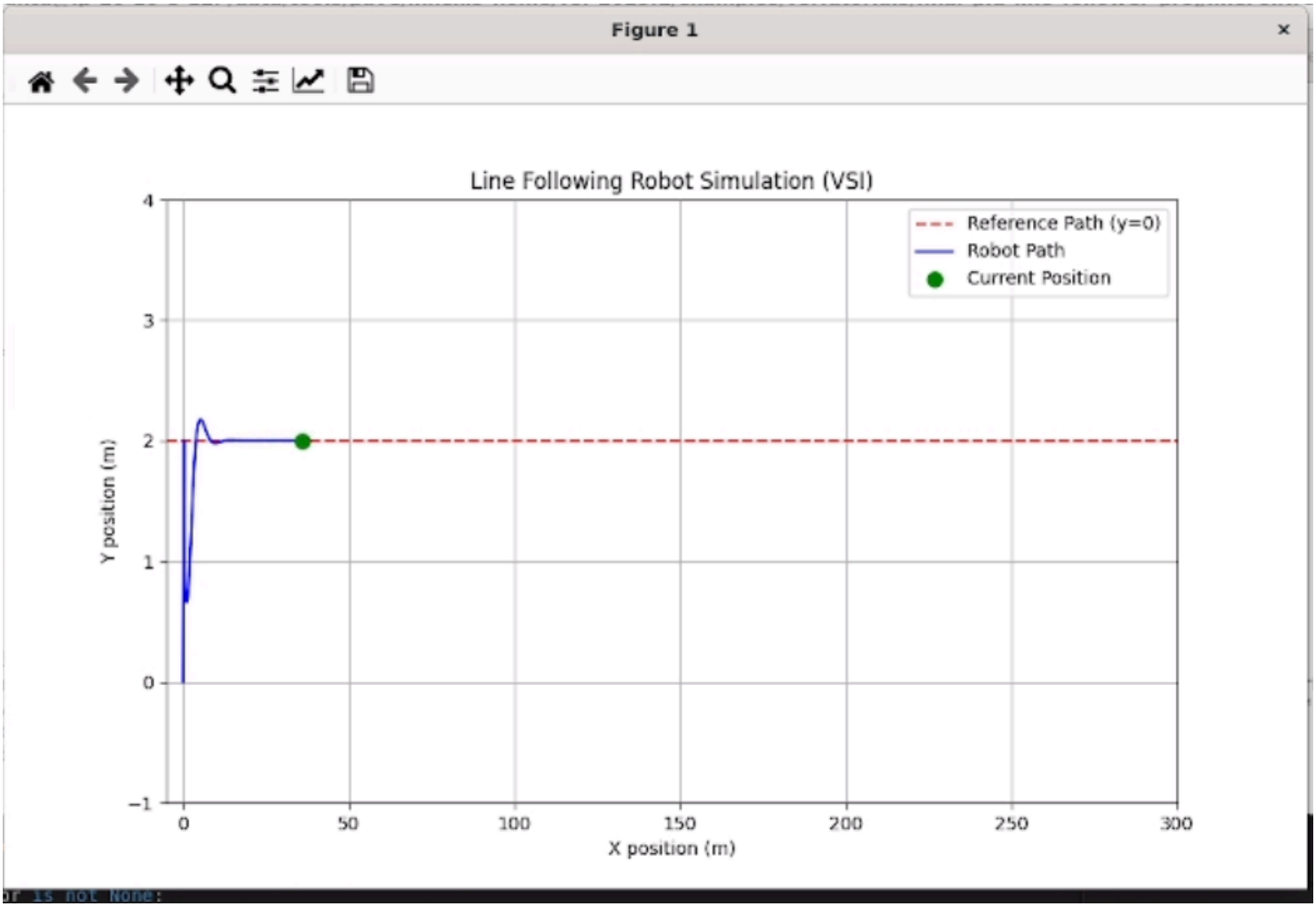
- **Experiment one, Trail Two :**
  - Values used for the PID controller → kp = 0.8, ki = 0.0, kd = 0.2
  - ref_path → y = 2
  - No noise
  - Video Link for the experiment → Siemens_DT - Google Drive (E1-T2)
  - Results :
    - Maximum Overshoot: 199.99 cm
    - Settling Time (5%): 6.21s
    - Steady-State Error: 0.0110 cm
  - Plot :



- **Experiment one, Trail Three :**
  - Values used for the PID controller → kp = 2.5, ki = 0.1, kd = 0.6
  - ref_path → y = 2
  - No noise
  - Video Link for the experiment → Siemens_DT - Google Drive (E1-T3)
  - Results :
    - Maximum Overshoot: 199.78 cm
    - Settling Time (5%): 7.01s
    - Steady-State Error: 0.2239 cm
  - Plot :



- **Experiment one, Trail Four :**
  - Values used for the PID controller → kp = 1.2, ki = 0.0, kd = 0.8
  - ref_path → y = 2
  - No noise
  - Video Link for the experiment → Siemens_DT - Google Drive (E1-T4)
  - Results :
    - Maximum Overshoot: 200.00 cm
    - Settling Time (5%): 5.31s
    - Steady-State Error: 0.0001 cm
  - Plot :



- **Experiment Two, Trail one :**
  - Values used for the PID controller → Kp=-1.2, Ki=0.0, Kd=0.8
  - ref_path → curved → y = 2sin(0.15x)
  - Noisy sensor used with standard deviation = 0.01 (very low noise)
  - Video Link for the experiment → Siemens_DT - Google Drive (E2-T1)
  - Results :
    - Maximum Overshoot: 0.2959 m
    - Settling Time (5%): 26.10 s
    - Steady-State Error: -0.0022 m

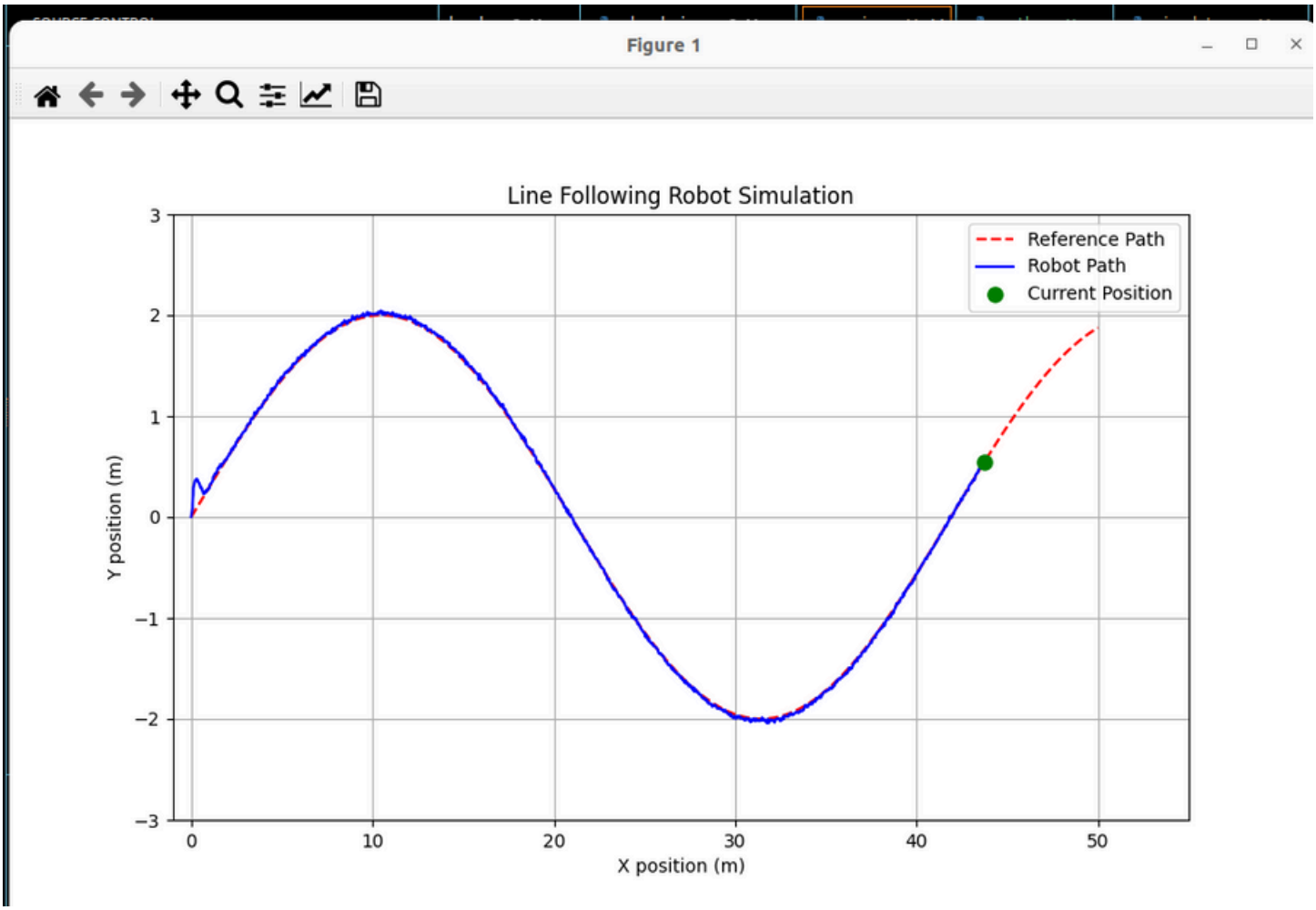
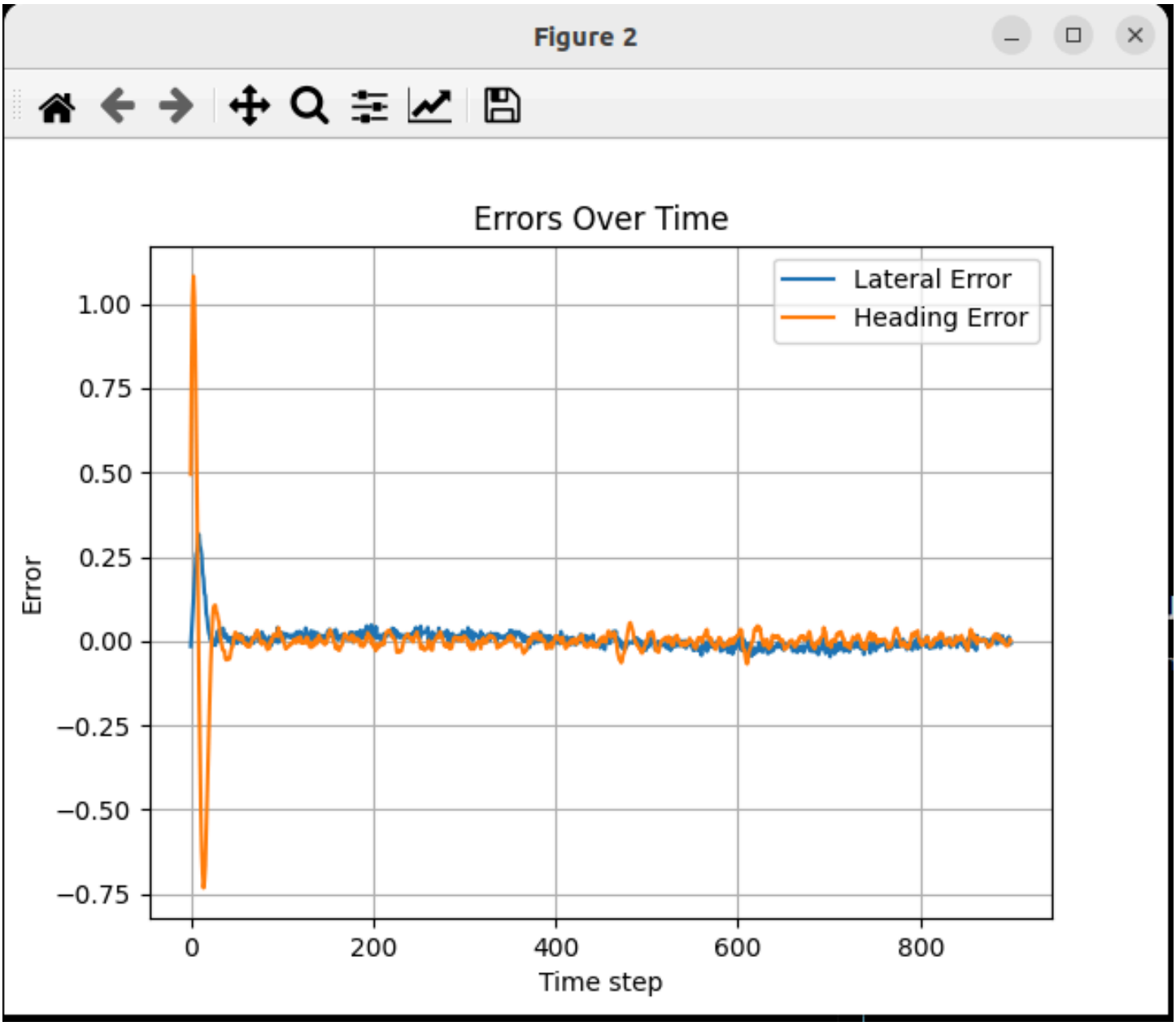


Figure 1
Line Following Robot Simulation
Reference Path
Robot Path
Current Position
Y position (m)
X position (m)
3
2
1
0
−1
−2
−3
0
10
20
30
40
50



- **Experiment Two, Trail Two :**
  - Values used for the PID controller → Kp=-2.5, Ki=0.1, Kd=0.6
  - ref_path → curved → y = 1.5sin(0.05x)
  - Noisy sensor used with standard deviation = 0.5 (NOISY)
  - Video Link for the experiment → Siemens_DT - Google Drive (E2-T2)
  - Results :
    - Maximum Overshoot: 2.0876 m
    - Steady-State Error: 0.4073 m
    - System did not settle within the tolerance.

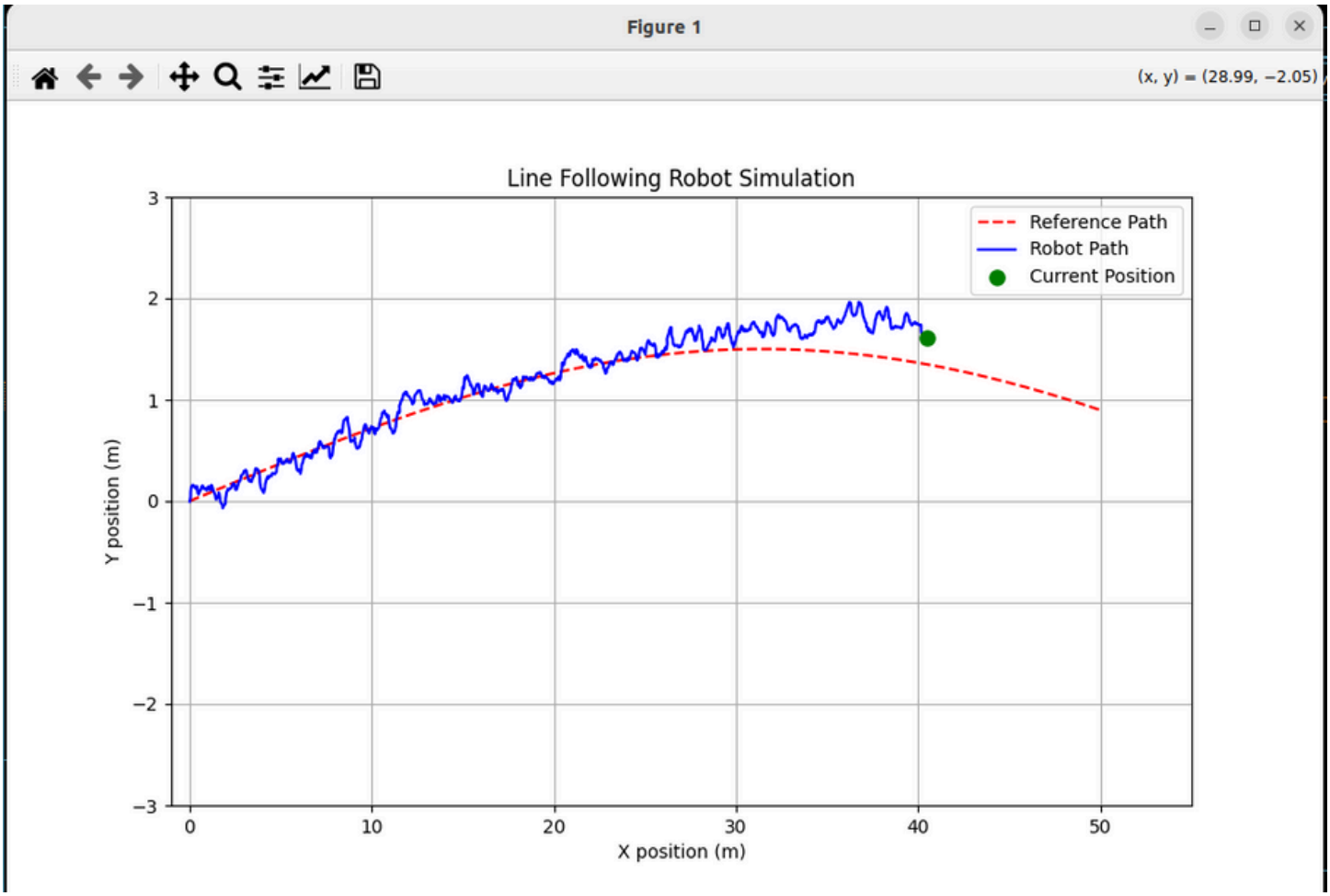
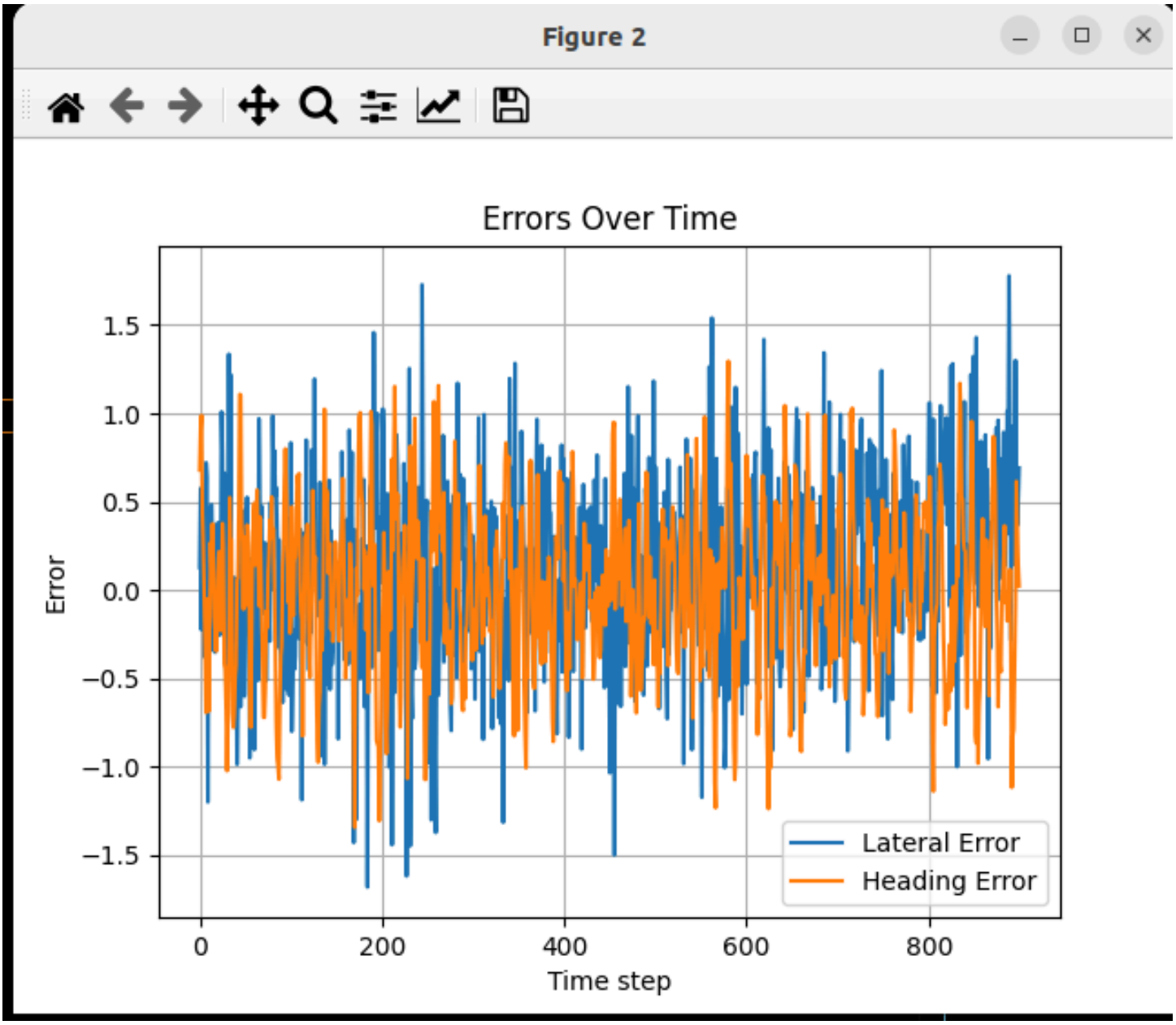


Figure 1
(x, y) = (28.99, −2.05)
Line Following Robot Simulation
Reference Path
Robot Path
Current Position
Y position (m)
X position (m)
3
2
1
0
−1
−2
−3
0
10
20
30
40
50



- **Experiment Two, Trail Three :**
  - Values used for the PID controller → Kp=-2.5, Ki=0.1, Kd=0.6
  - ref_path → curved → y = 2sin(0.15x)
  - Noisy sensor used with standard deviation = 0.01 (very low noise)
  - Video Link for the experiment → Siemens_DT - Google Drive (E2-T3)
  - Results :
    - Maximum Overshoot: 0.4308 m
    - System did not settle within the tolerance.
    - Steady-State Error: 0.3547 m

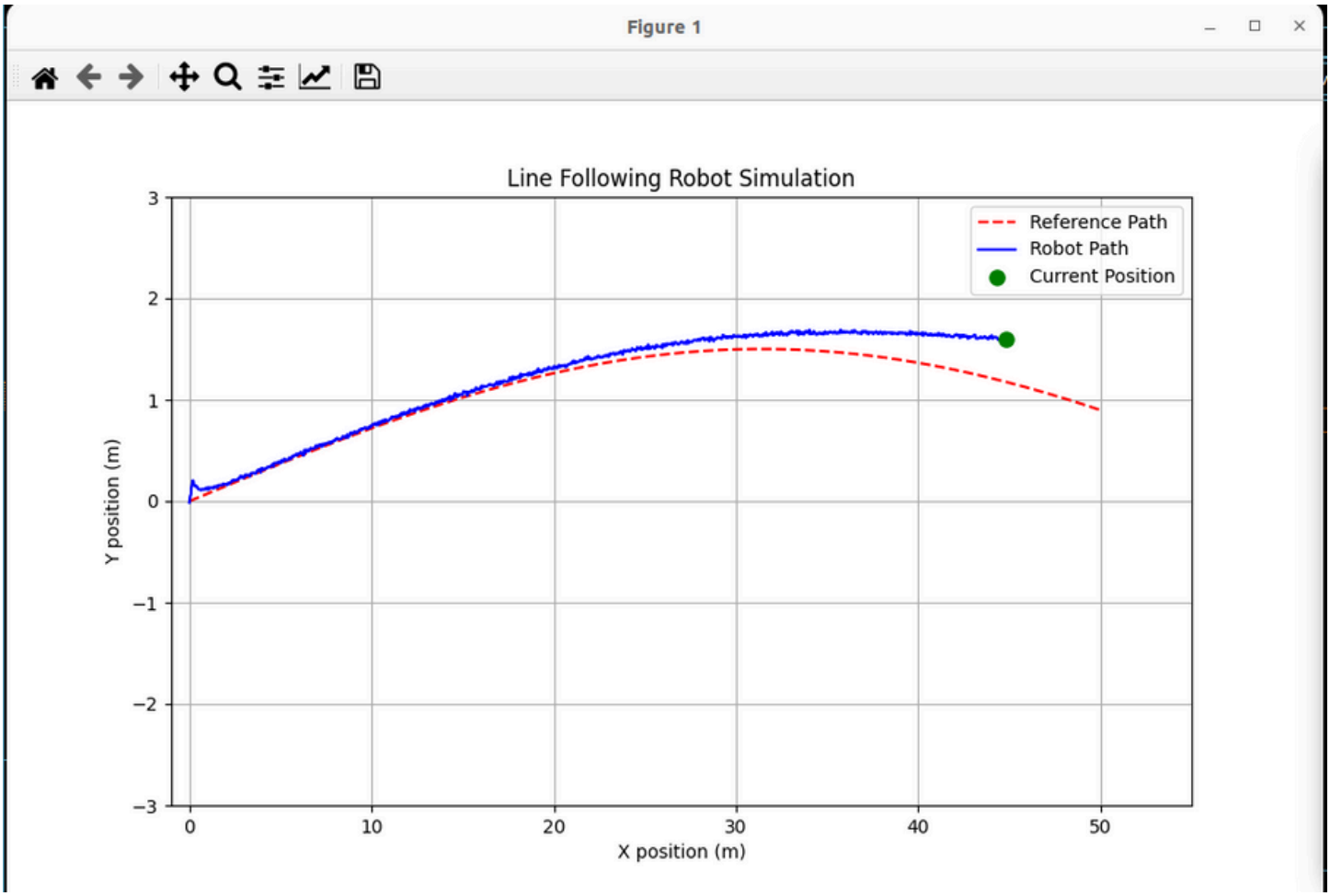
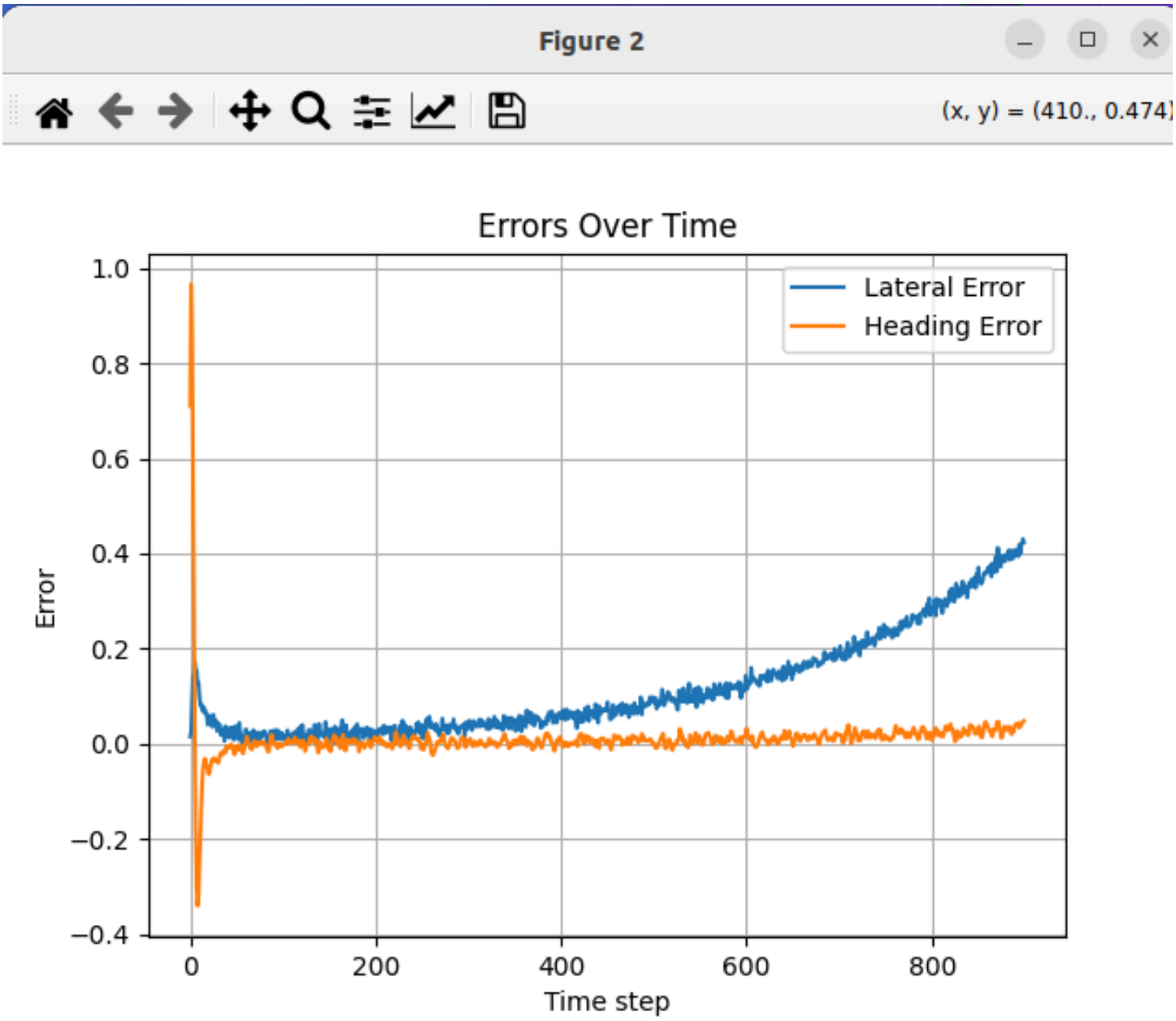
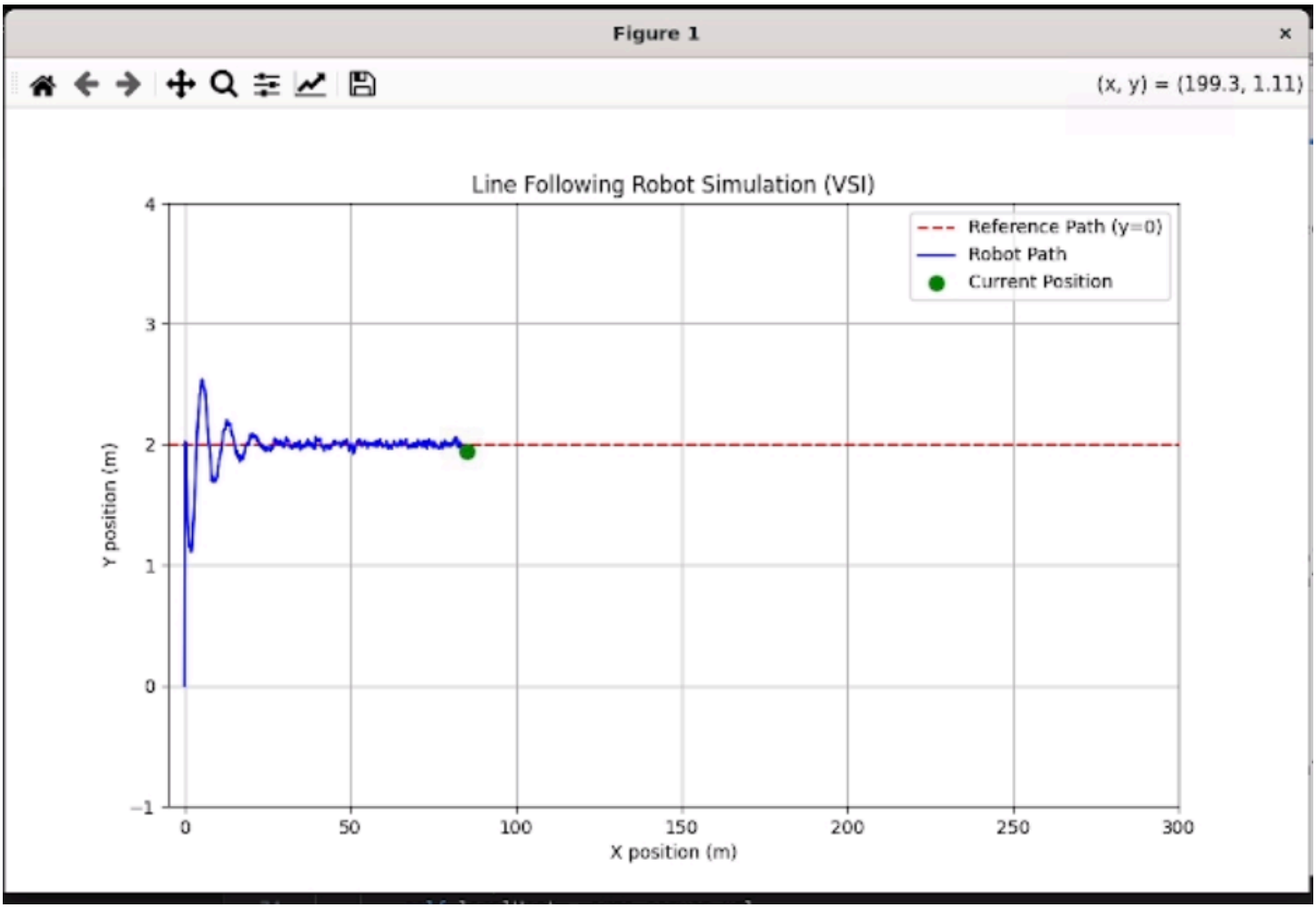


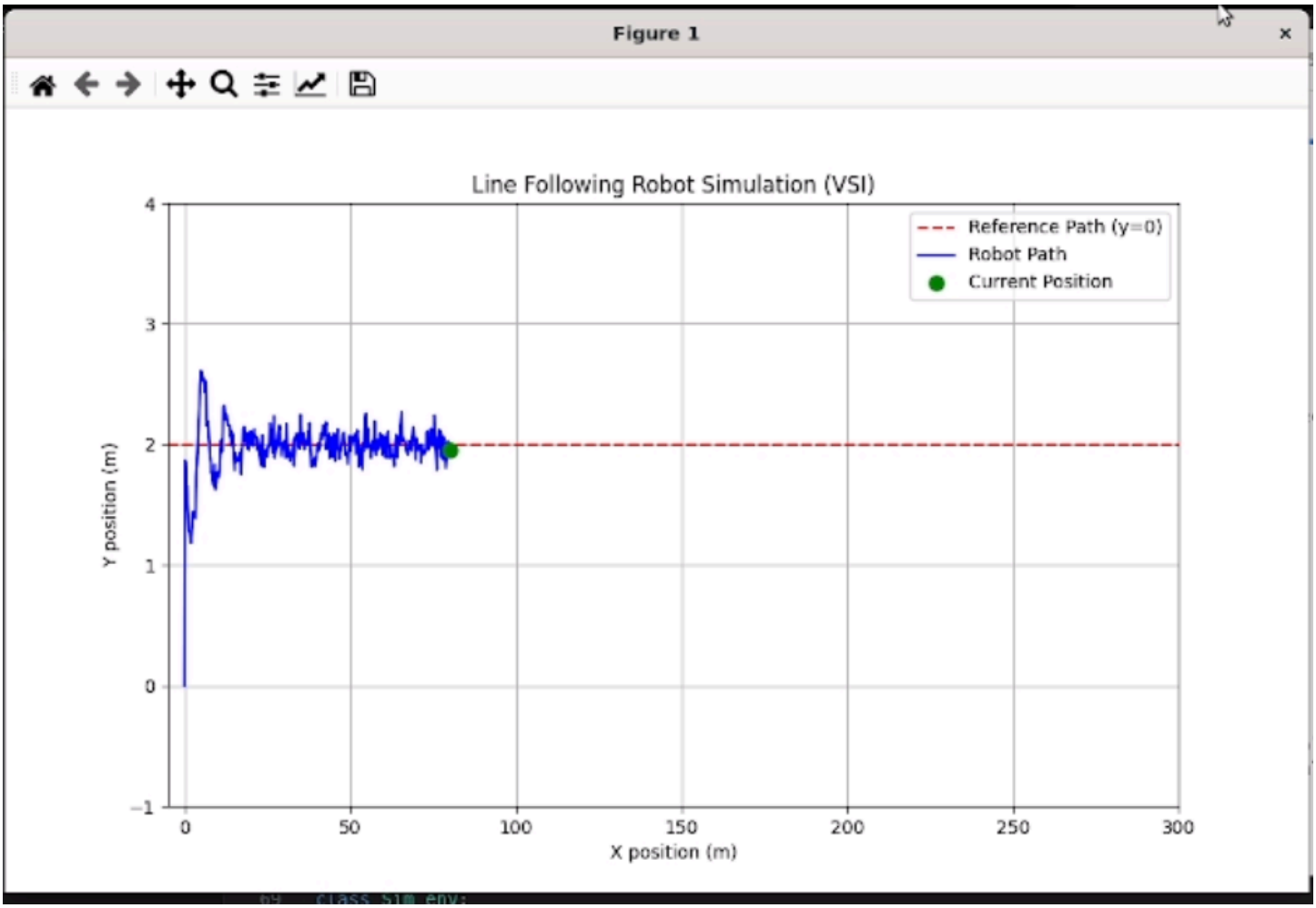
Figure 1
Line Following Robot Simulation
Reference Path
Robot Path
Current Position
Y position (m)
X position (m)
3
2
1
0
−1
−2
−3
0
10
20
30
40
50



- **Experiment three, Trail one :**
  - Values used for the PID controller → Kp = 1.5 , Ki = 0.0, Kd = 0.4
  - ref_path → y = 2
  - Noisy sensor used with standard deviation = 0.02
  - Video Link for the experiment → Siemens_DT - Google Drive
  - Results :
    - Maximum Overshoot: 197.45 cm
    - Settling Time (5%): 5.91s
    - Steady-State Error: 2.5506 cm
  - Plot :



- **Experiment three, Trail Two :**
  - Values used for the PID controller → Kp = 1.5 , Ki = 0.0, Kd = 0.4
  - ref_path → y = 2
  - Noisy sensor used with standard deviation = 0.08 (More noise than trial one)
  - Video Link for the experiment → 🌐 Siemens_DT - Google Drive
  - Results :
    - Maximum Overshoot: 191.08 cm
    - Settling Time (5%): 47.11s
    - Steady-State Error: 8.9246 cm
  - Plot :



- **Experiment Four, Trail One : (PD Controller)**
  - Values used for the PID controller → Kp=-2.5, Ki=0.0, Kd=0.6
  - ref_path → y = 1.5sin(0.2x)
  - Noisy sensor used with standard deviation = 0.2
  - Video Link for the experiment → 🌐 Siemens_DT - Google Drive (E4-PD)
  - Results :
    - Maximum Overshoot: 0.7304 m
    - System did not settle within the tolerance.
    - Steady-State Error: 0.0174 m
  - Plot :

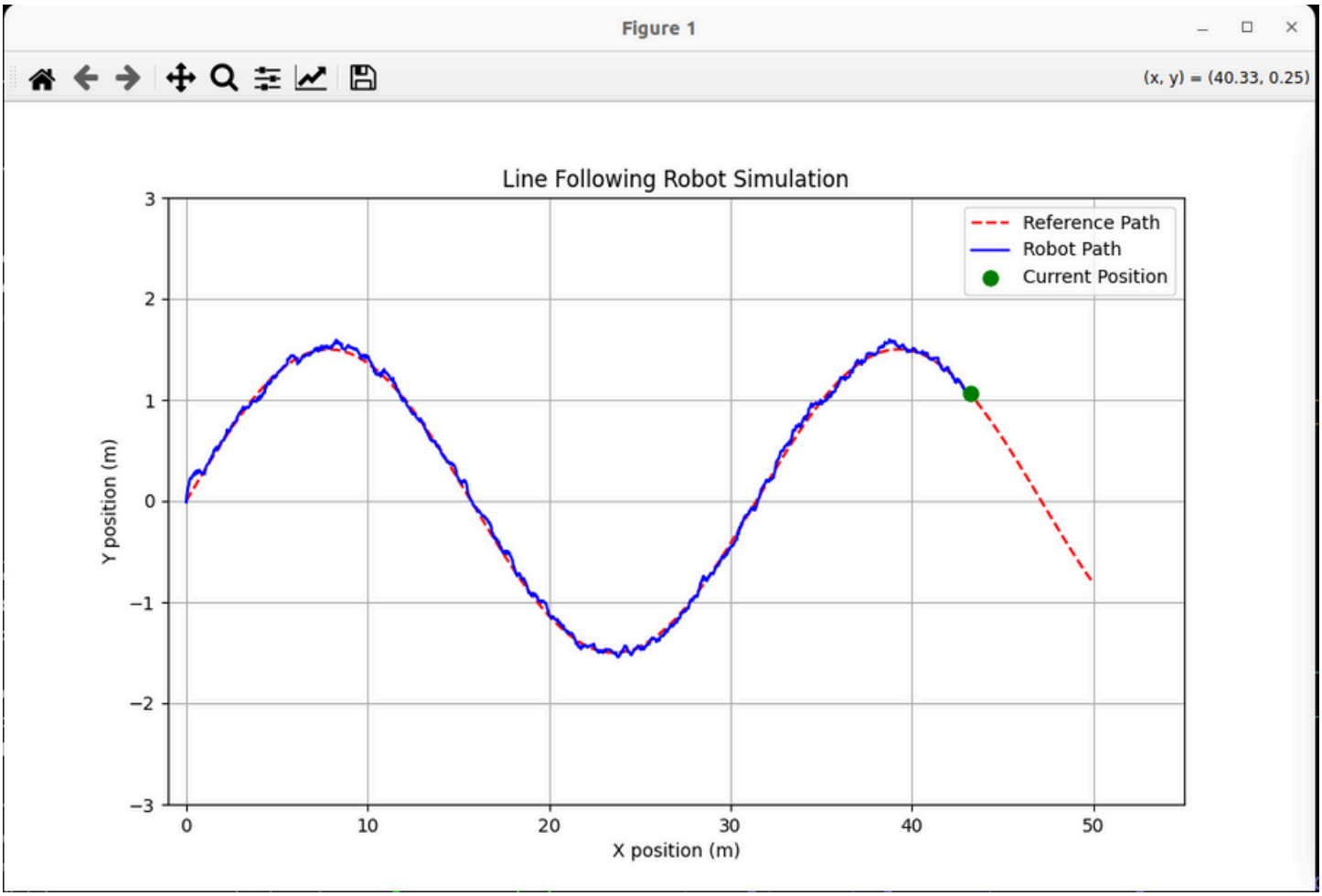
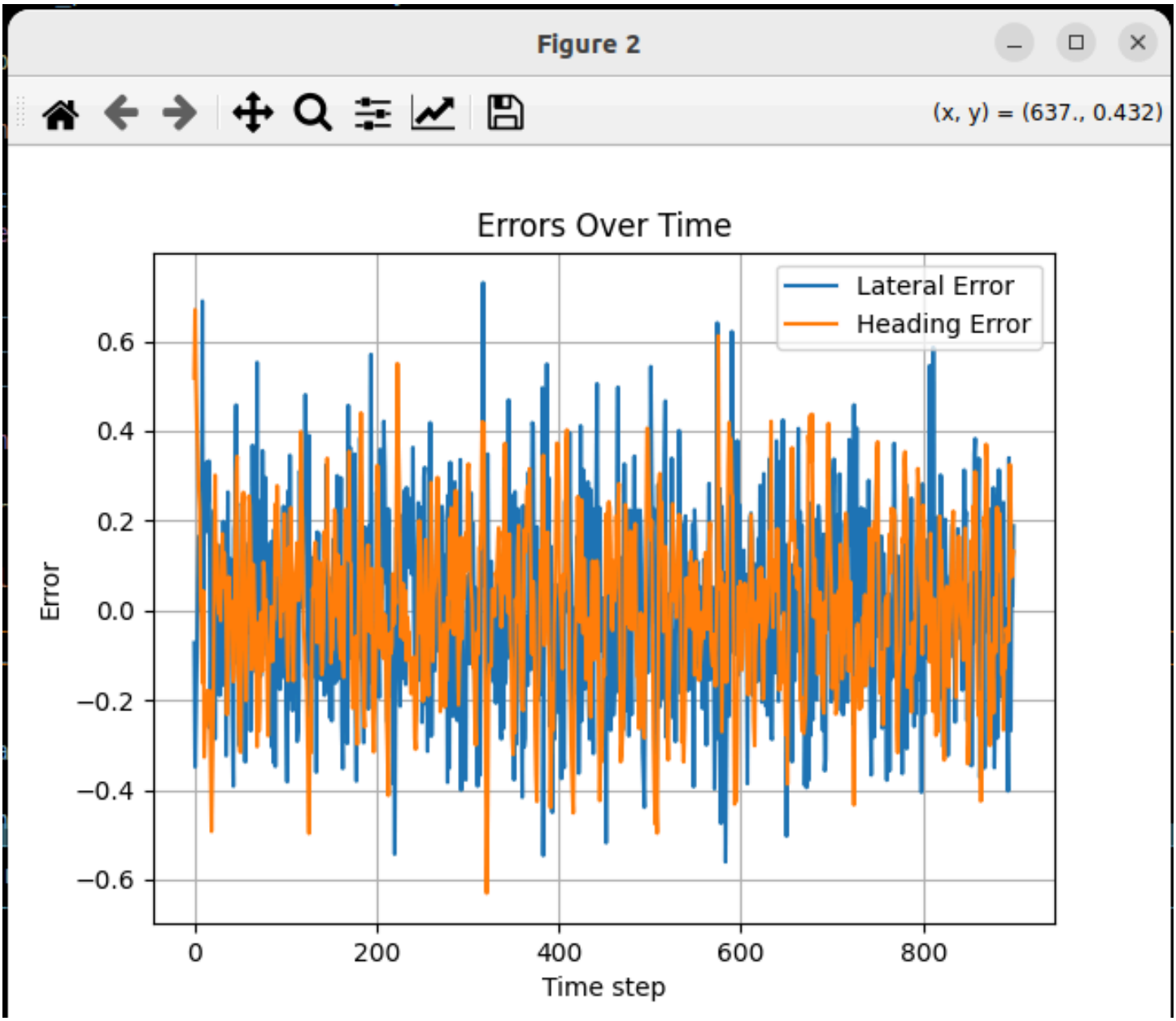


Figure 1
(x, y) = (40.33, 0.25)
Line Following Robot Simulation
Reference Path
Robot Path
Current Position
Y position (m)
X position (m)
3
2
1
0
−1
−2
−3
0
10
20
30
40
50



- **Experiment Four, Trail Two : (PID Controller)**
  - Values used for the PID controller → Kp=-2.5, Ki=0.1, Kd=0.6
  - ref_path → y = 1.5sin(0.2x)
  - Noisy sensor used with standard deviation = 0.2
  - Video Link for the experiment → Siemens_DT - Google Drive (E4-PID)
  - Results :
    - Maximum Overshoot: 0.8990 m
    - System did not settle within the tolerance.
    - Steady-State Error: 0.3575 m
  - Plot :

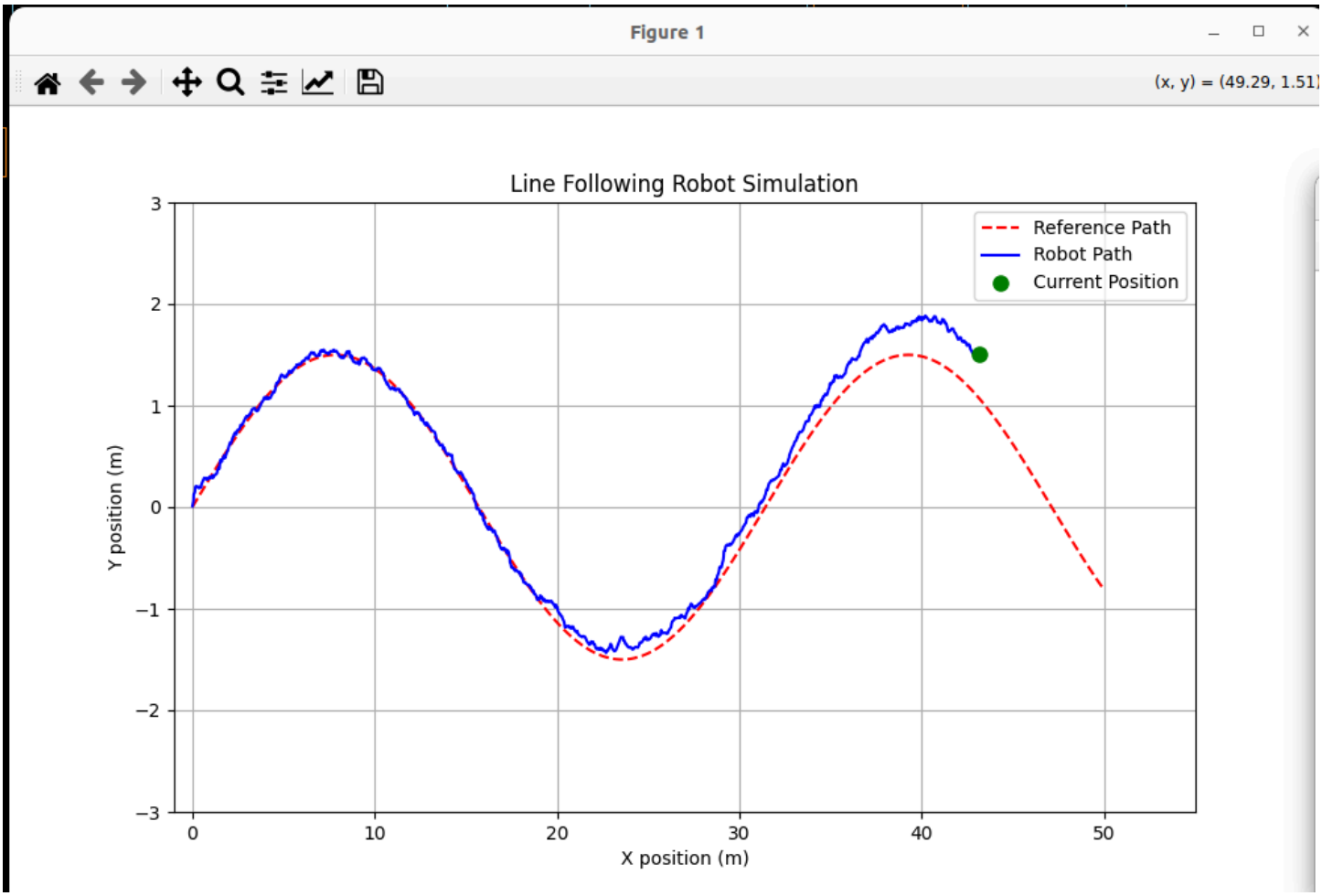


Figure 1
(x, y) = (49.29, 1.51)
Line Following Robot Simulation
Reference Path
Robot Path
Current Position
Y position (m)
X position (m)
3
2
1
0
−1
−2
−3
0
10
20
30
40
50

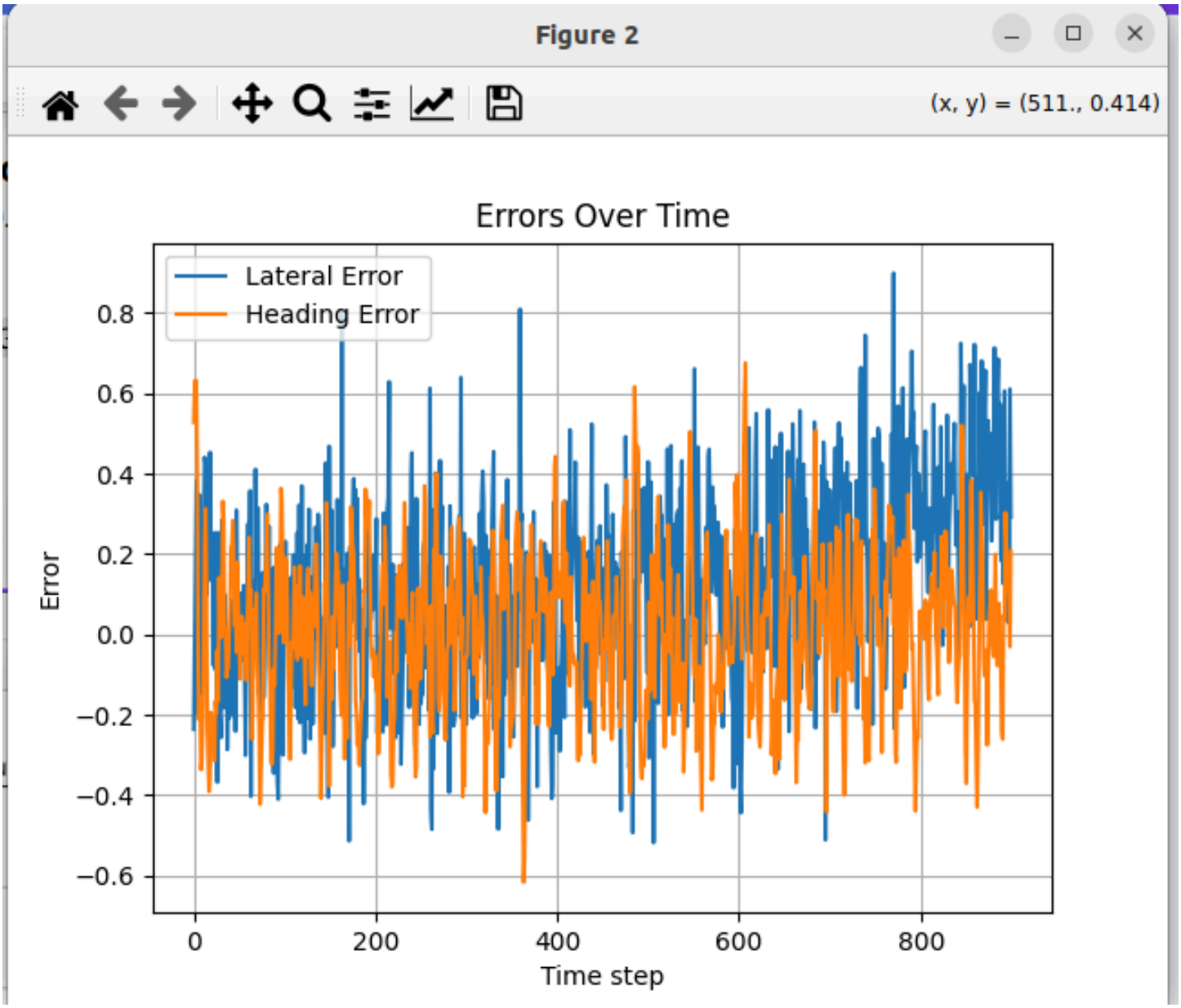


Figure 2
(x, y) = (511., 0.414)
Errors Over Time
Lateral Error
Heading Error
Error
Time step
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
200
400
600
800