Assignment 2: Manual Motion Observation Scientific Experimentation and Evaluation

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1 Introduction

This report presents the execution and results of Assignment 2, where we conducted manual measurements of our LEGO EV3 differential drive robot's end poses across three different motion types: straight, left arc, and right arc. Each motion was repeated 25 times to gather statistical data on the robot's behavior and positioning accuracy.

2 Program and Parameters

The robot was controlled using the provided EV3 control program with the following predefined parameters:

- **Wheel diameter:** 5.30 cm
- **Distance between wheels:** 12.00 cm
- **Pen refill offset X:** 5.50 cm
- **Pen refill offset Y:** 6.40 cm
- **Motion types:** Left arc, Straight line, Right arc
- **Trials per motion:** 25 trials each (75 total)

The MAIN_AXIS_LENGTH variable was verified to match our robot's design (12.00 cm) before executing the experiments.

3 Observations During Execution

During the experimental runs, the following observations were made:

1. **Surface consistency:** The cardboard surface remained stable throughout all trials, providing a reliable measurement platform.
2. **Marking precision:** The pen refill mechanism produced consistent marks with minimal ink spreading. The fine tip allowed for precise position recording.

3. **Start position repeatability:** Using a fixed template ensured consistent starting positions across all trials, minimizing systematic errors.

4. **Robot behavior variations:** Slight variations in end positions were observed, likely due to:

   - Motor encoder resolution limitations
   - Battery voltage variations affecting motor performance
   - Minor inconsistencies in floor levelness

5. **Motion characteristics:**

   - *Straight motion:* Generally consistent forward movement .
   - *Left arc:* Smooth curved trajectory with good repeatability
   - *Right arc:* Similar behavior to left arc, symmetric results observed

4 Offset Compensation Method

To accurately determine the final pose of the robot's axle center rather than the positions of the pen refills, we applied an offset compensation procedure to each measurement.

During data collection, two pen refills were mounted on the left and right sides of the robot, producing two contact points on the surface at the end of each trial. These two points represent the locations of the left and right pen tips relative to the robot body.

For each trial, the following steps were performed:

1. Record the coordinates of the two pen marks:

$$(X1, Y1) \quad and \quad (X2, Y2)$$

2. Compute the midpoint between the two marks to represent the approximate center between pen refills:

$$AvgX = \frac{X1 + X2}{2}, \quad AvgY = \frac{Y1 + Y2}{2}$$

3. Apply the known physical offset between the midpoint of the pen refills and the robot's axle center. As given in the Program and Parameters section:

   - Pen refill offset in X direction: 5.50 cm
   - Pen refill offset in Y direction: 6.40 cm

   The axle center is located 5.50 cm behind (X direction) and 6.40 cm behind (Y direction) the midpoint of the refills, depending on robot orientation. Therefore, we subtract these offsets from the averaged position to obtain the true robot center:

$$CompX = AvgX - 5.50$$

$$CompY = AvgY - 6.40$$

4. The resulting compensated coordinates (Comp X, Comp Y) represent the final pose of the robot's axle center in the global coordinate system.

This transformation ensures that all subsequent statistical analysis and comparisons are based on the true robot position rather than the pen tip locations. The compensated values are reported in the data tables and used throughout the analysis.

The radius of curvature is:

$$r = \frac{x^2 + y^2}{2x}$$

The orientation angle θ is defined as:

$$\theta = \{\, 0 \,, if |x| < \varepsilon \, [\arctan 2\,(y,\ x - r) - \arctan 2\,(0,\ -r)] \times \frac{180}{\pi}, otherwise$$

Finally, the orientation is rounded to two decimal places:

$$\theta_{final} = round(\theta, 2)$$

5 Data Visualization

The collected data has been visualized in three comprehensive plots showing the robot's behavior for each motion type. The visualizations include both the manually measured end poses and the complete paths recorded by the encoder data.

5.1 Manual Markings on paper

Figure presents the markings of robot position.

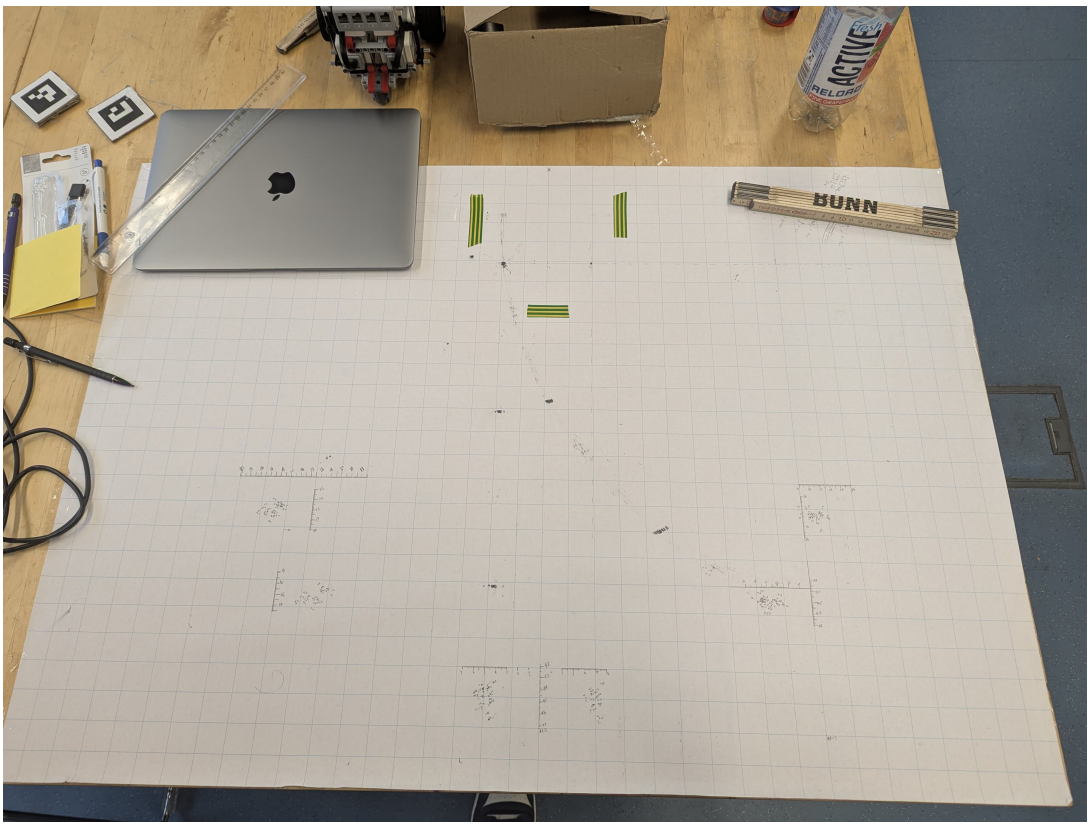

Figure 1: Manual Measurements and markings for each run of robot

5.2 End Poses Visualization

Figure 2 shows the distribution of the robot's end poses for all three motion types from the manual measurements. This plot illustrates the spread and clustering of final positions, providing insight into the precision of the robot's motion control.

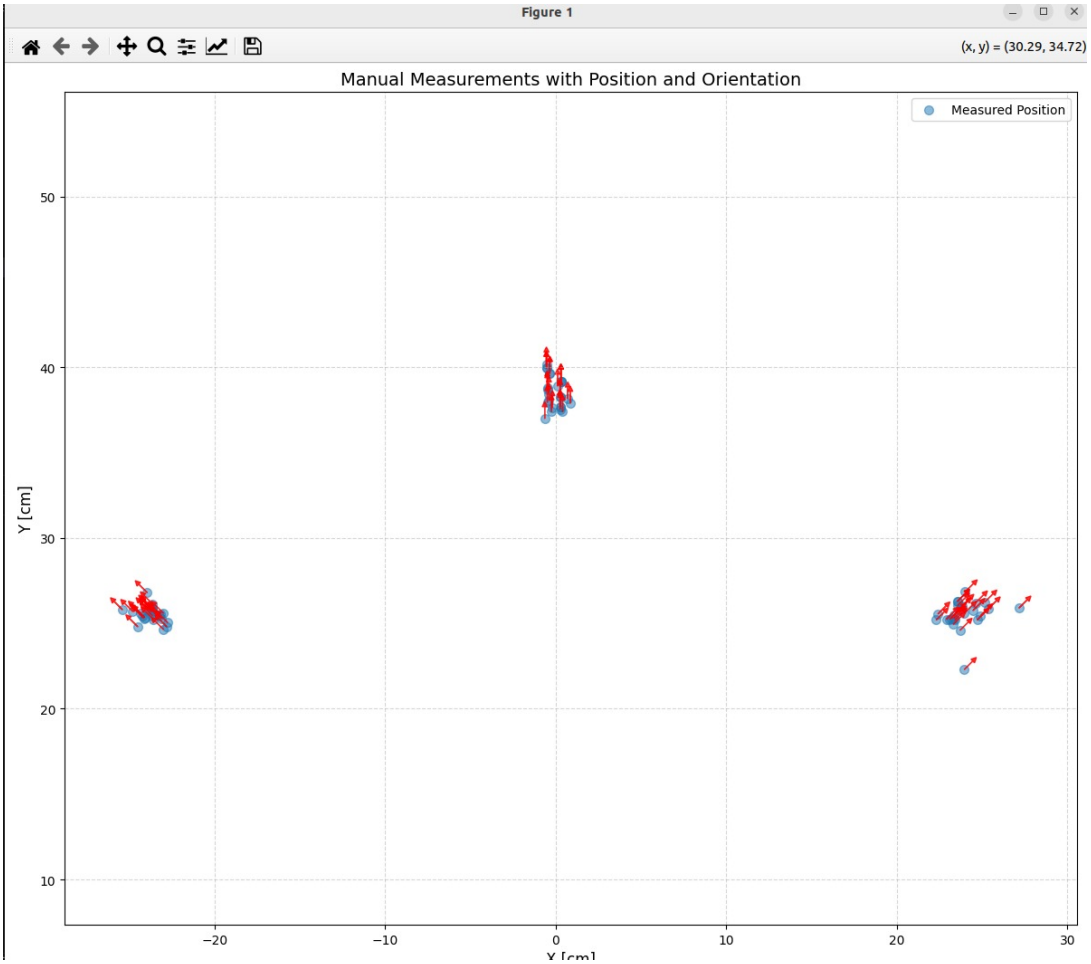

Figure 2: Robot end poses from manual measurements for straight, left arc, and right arc motions. Each point represents the compensated midpoint position between the two pen marks after refill offset correction.

5.3 Complete Robot Paths

Figure 3 displays the complete trajectories of the robot as recorded by the encoder measurements. This visualization shows the continuous path taken by the robot from start to finish for all trials.

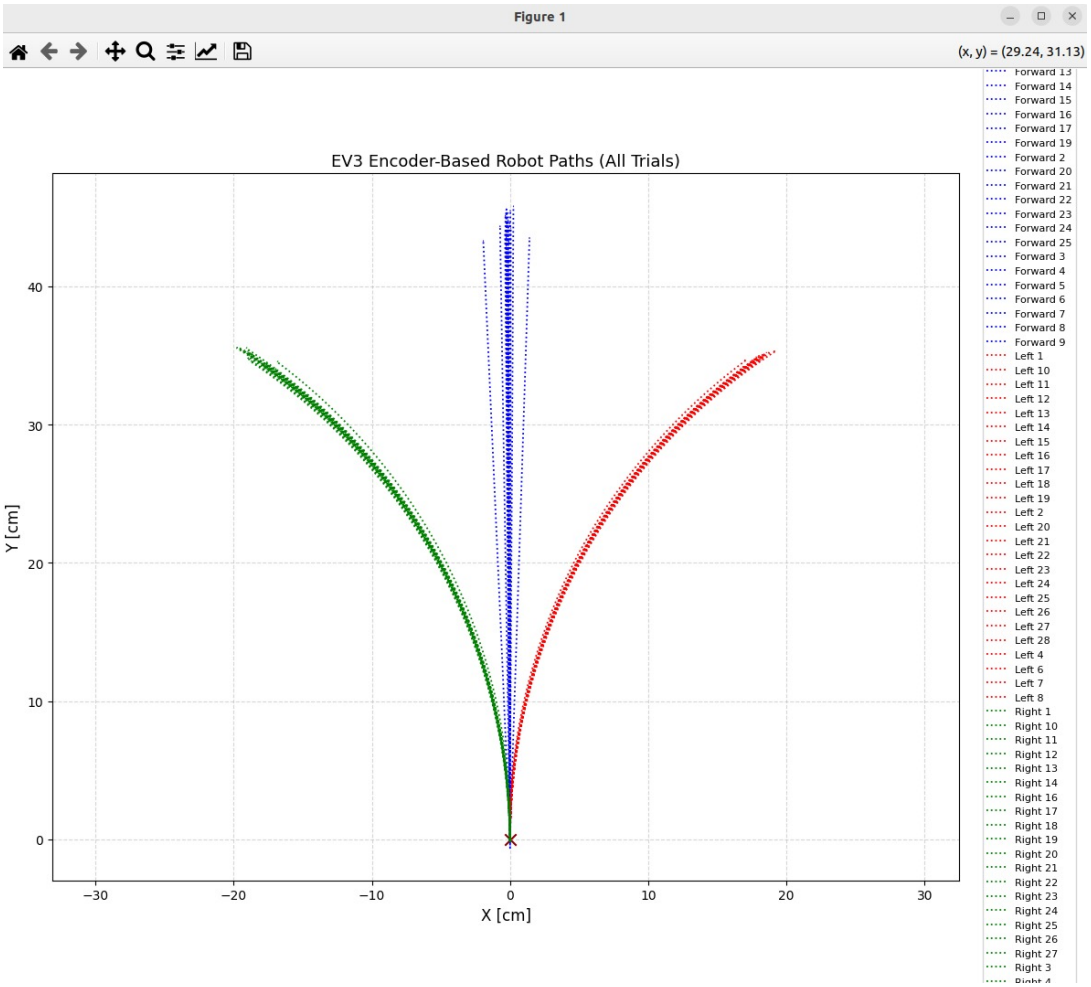

Figure 3: Complete robot paths from encoder measurements showing the trajectories for all three motion types. The paths demonstrate the robot's movement behavior from the starting pose to the final positions.

5.4 Combined Visualization

Figure 4 presents a combined view that overlays the manually measured end poses with the encoder-based path data, allowing for direct comparison between the two measurement methods.

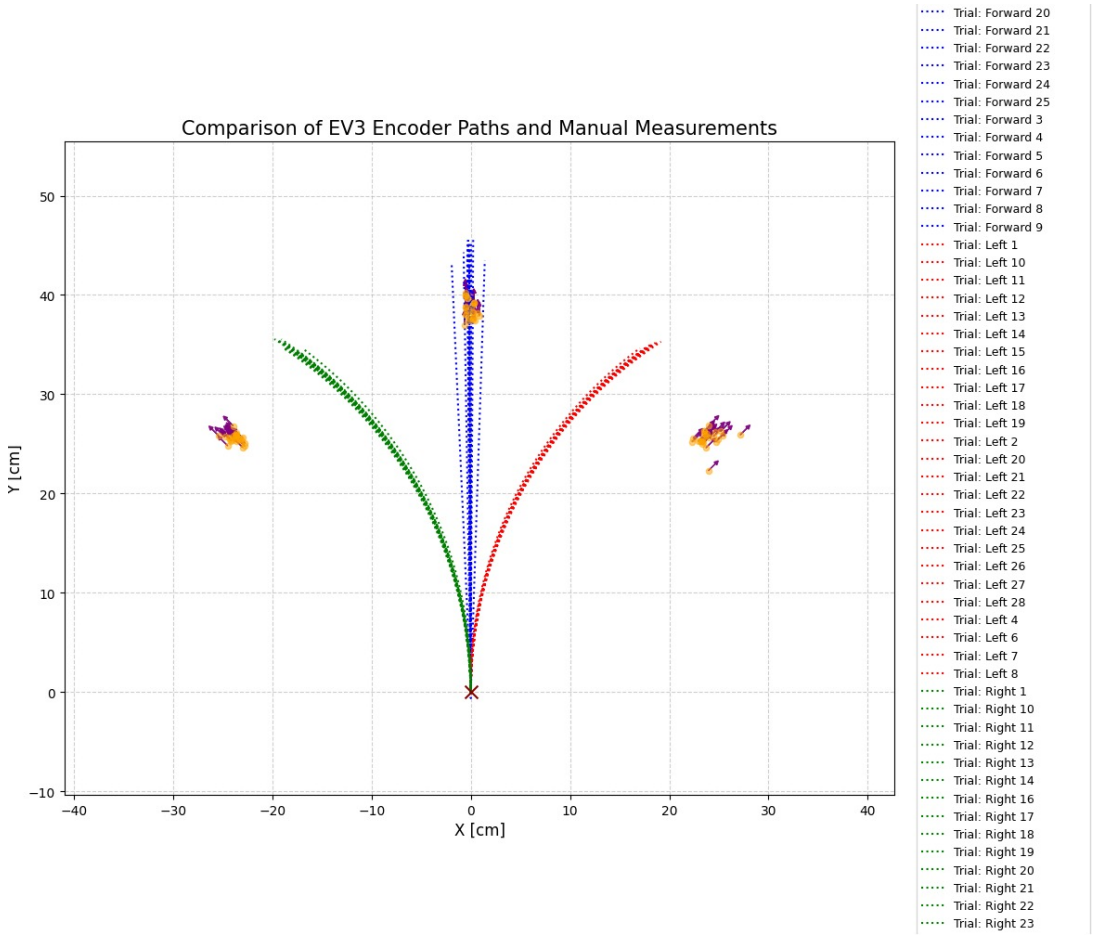

Figure 4: Combined visualization showing both encoder-based paths and manually measured end poses. This allows for comparison between the internal sensor data and external measurements.

5.5 Combined Visualization of all group

Figure 4 presents a combined view of data taken from other groups.

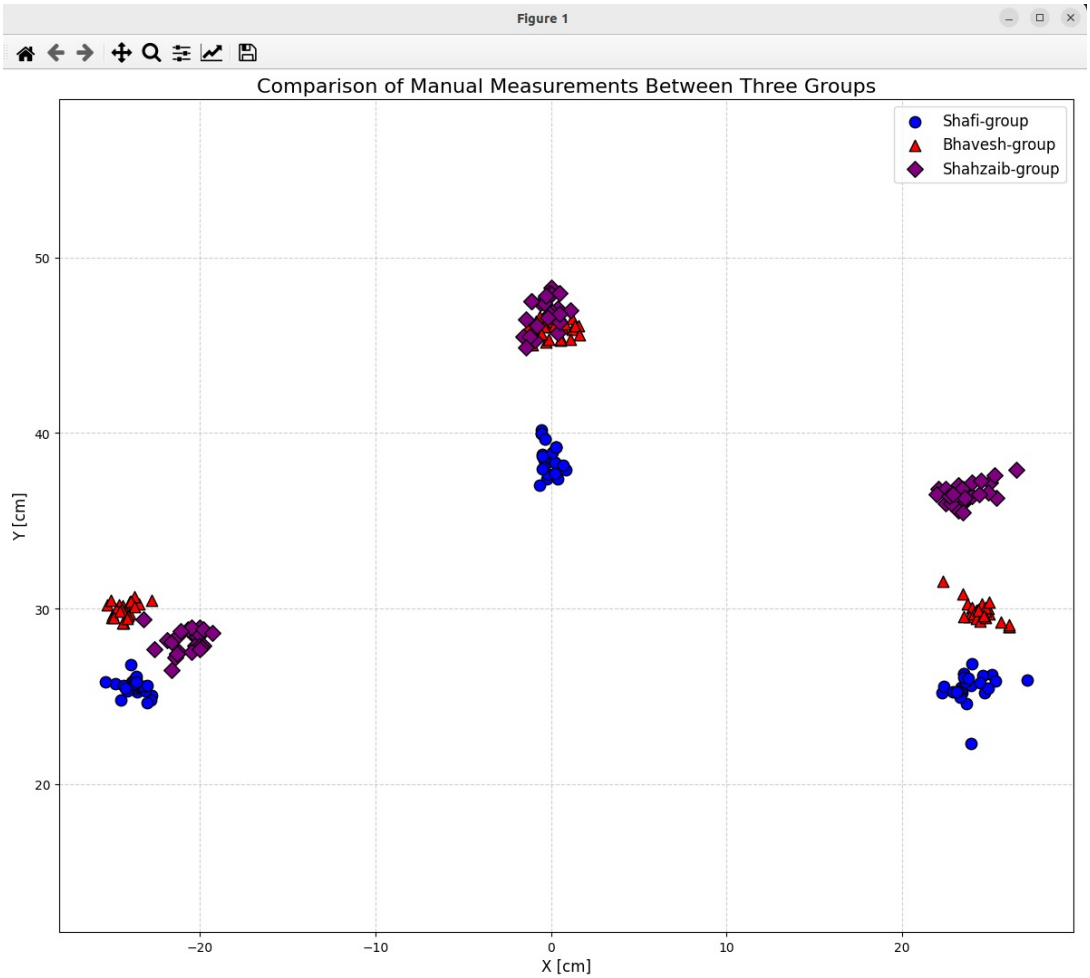

Figure 5: Combined visualization showing manually measured end poses from other groups and comparing with our group.

5.6 Combined Visualization of trajectories

Figure 4 presents a combined view of data taken from other groups.

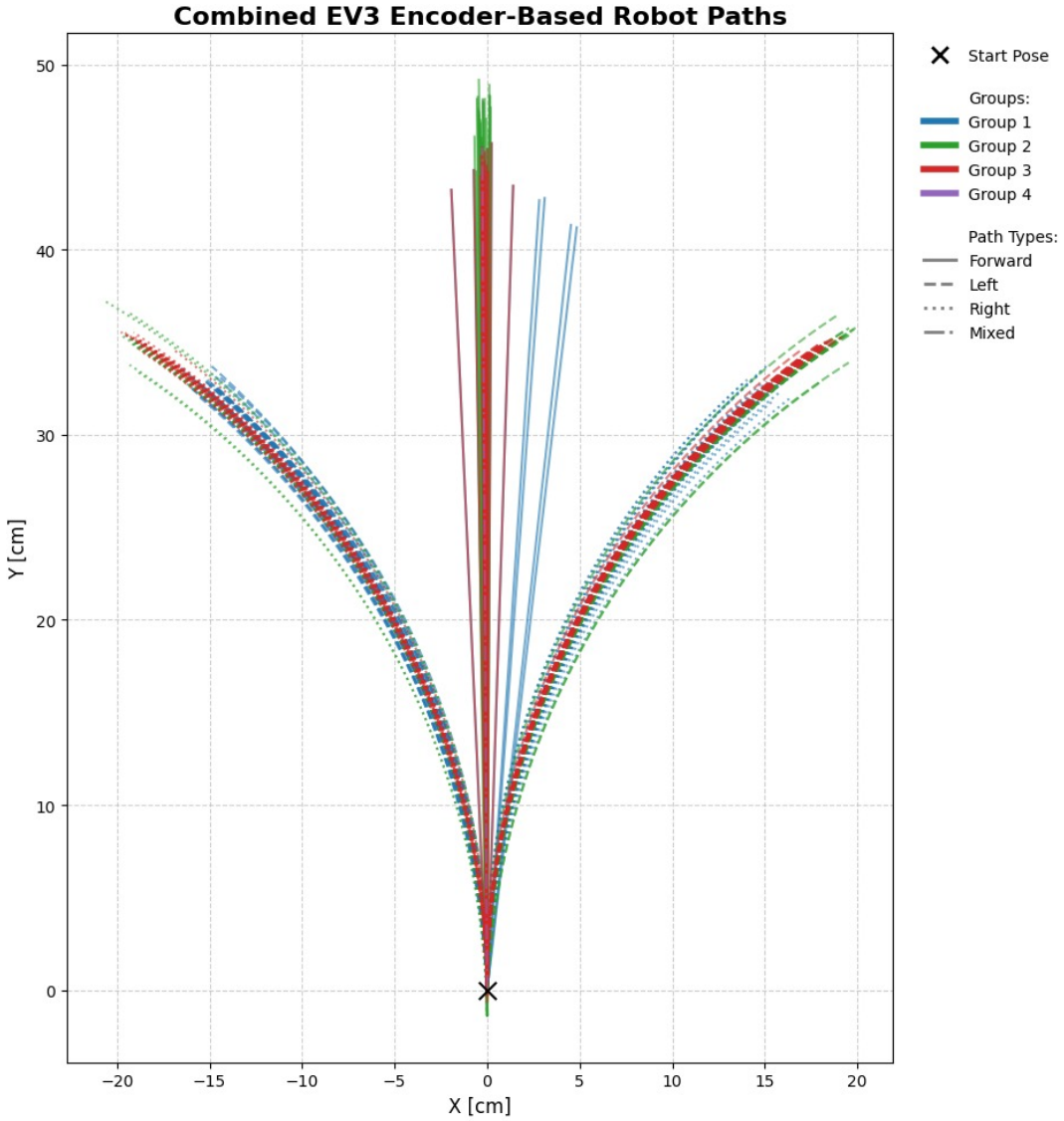

Figure 6: Combined visualization showing encoder data from other groups and comparing with our group.

6 Manual Measurement Data

The following sections present the complete raw measurement data collected during the experiment. All measurements are relative to the fixed coordinate system established on the grid-lined cardboard sheet, with the Y-axis aligned with the robot's initial forward direction and the X-axis perpendicular to it (following the right-hand rule).

6.1 Coordinate System Convention

- **Origin:** Fixed at the robot's starting position
- **Y-axis:** Aligned with robot's forward direction at start
- **X-axis:** Perpendicular to Y-axis (right-hand rule)

- **X1, Y1:** Coordinates of left pen mark
- **X2, Y2:** Coordinates of right pen mark
- **Average X, Y:** Midpoint between the two marks
- **Compensating X, Y:** Position corrected for refill offset to represent robot's axle center

6.2 Straight Motion Data

Table 1: Straight Motion - Manual Measurements (All values in cm)

Trial	X1	Y1	X2	Y2	Avg X	Avg Y	Comp X	Comp Y
1	-4.50	45.60	5.10	45.60	0.30	45.60	0.30	39.20
2	-4.60	44.00	5.10	43.90	0.25	43.95	0.25	37.55
3	-4.60	44.30	5.10	43.90	0.25	44.10	0.25	37.70
4	-4.60	44.80	5.10	44.60	0.25	44.70	0.25	38.30
5	-4.40	43.90	5.20	43.70	0.40	43.80	0.40	37.40
6	-5.10	43.90	4.60	43.70	-0.25	43.80	-0.25	37.40
7	-5.20	46.10	4.50	46.00	-0.35	46.05	-0.35	39.65
8	-5.40	45.20	4.40	45.20	-0.50	45.20	-0.50	38.80
9	-5.20	44.80	4.40	44.90	-0.40	44.85	-0.40	38.45
10	-5.00	44.10	4.60	44.00	-0.20	44.05	-0.20	37.65
11	-4.60	44.80	5.10	44.60	0.25	44.70	0.25	38.30
12	-5.30	46.50	4.20	46.70	-0.55	46.60	-0.55	40.20
13	-5.40	46.20	4.30	46.50	-0.55	46.35	-0.55	39.95
14	-4.70	45.30	4.90	45.30	0.10	45.30	0.10	38.90
15	-5.10	44.50	4.30	44.40	-0.40	44.45	-0.40	38.05
16	-4.00	44.30	5.70	44.30	0.85	44.30	0.85	37.90
17	-5.30	44.30	4.30	44.40	-0.50	44.35	-0.50	37.95
18	-5.30	45.00	4.30	45.20	-0.50	45.10	-0.50	38.70
19	-5.40	43.30	4.10	43.50	-0.65	43.40	-0.65	37.00
20	-4.50	45.60	5.10	45.60	0.30	45.60	0.30	39.20
21	-4.20	44.50	5.60	44.60	0.70	44.55	0.70	38.15
22	-5.40	46.20	4.30	46.50	-0.55	46.35	-0.55	39.95
23	-5.20	46.10	4.50	46.00	-0.35	46.05	-0.35	39.65
24	-4.60	44.30	5.10	43.90	0.25	44.10	0.25	37.70
25	-4.50	45.60	5.10	45.60	0.30	45.60	0.30	39.20

6.3 Left Arc Motion Data

Table 2: Left Arc Motion - Manual Measurements (All values in cm)

Trial	X1	Y1	X2	Y2	Avg X	Avg Y	Comp X	Comp Y
1	-25.00	27.20	-20.50	35.70	-22.75	31.45	-22.75	25.05
2	-25.70	27.60	-21.50	35.70	-23.60	31.65	-23.60	25.25
3	-25.60	27.80	-21.70	35.90	-23.65	31.85	-23.65	25.45
4	-25.50	27.20	-20.10	35.20	-22.80	31.20	-22.80	24.80
5	-25.60	27.10	-20.40	35.00	-23.00	31.05	-23.00	24.65
6	-26.00	27.90	-20.80	35.90	-23.40	31.90	-23.40	25.50
7	-27.00	27.10	-22.00	35.30	-24.50	31.20	-24.50	24.80
8	-25.80	27.90	-20.70	35.80	-23.25	31.85	-23.25	25.45
9	-25.80	27.70	-20.40	35.70	-23.10	31.70	-23.10	25.30
10	-25.80	27.90	-20.60	36.00	-23.20	31.95	-23.20	25.55
11	-26.50	28.20	-21.30	36.20	-23.90	32.20	-23.90	25.80
12	-26.00	28.10	-21.30	36.30	-23.65	32.20	-23.65	25.80
13	-26.30	28.30	-21.00	36.30	-23.65	32.30	-23.65	25.90
14	-25.80	28.40	-21.70	36.30	-23.75	32.35	-23.75	25.95
15	-27.30	28.00	-22.30	36.20	-24.80	32.10	-24.80	25.70
16	-26.90	27.80	-21.80	36.20	-24.35	32.00	-24.35	25.60
17	-26.60	27.70	-21.60	35.80	-24.10	31.75	-24.10	25.35
18	-26.70	27.60	-21.60	35.80	-24.15	31.70	-24.15	25.30
19	-26.30	28.50	-21.00	36.60	-23.65	32.55	-23.65	26.15
20	-26.40	28.10	-21.10	36.10	-23.75	32.10	-23.75	25.70
21	-27.90	28.10	-22.90	36.30	-25.40	32.20	-25.40	25.80
22	-26.00	28.10	-21.30	36.30	-23.65	32.20	-23.65	25.80
23	-26.50	29.40	-21.40	37.00	-23.95	33.20	-23.95	26.80
24	-26.80	27.80	-21.70	35.90	-24.25	31.85	-24.25	25.45
25	-25.70	28.10	-20.30	35.90	-23.00	32.00	-23.00	25.60

6.4 Right Arc Motion Data

Table 3: Right Arc Motion - Manual Measurements (All values in cm)

Trial	X1	Y1	X2	Y2	Avg X	Avg Y	Comp X	Comp Y
1	23.00	36.80	27.30	28.50	25.15	32.65	25.15	26.25
2	20.70	35.90	26.00	27.90	23.35	31.90	23.35	25.50
3	19.60	35.60	25.00	27.60	22.30	31.60	22.30	25.20
4	21.10	35.00	26.30	27.00	23.70	31.00	23.70	24.60
5	20.80	35.60	26.00	27.60	23.40	31.60	23.40	25.20
6	19.70	35.90	25.10	28.00	22.40	31.95	22.40	25.55
7	20.80	35.70	25.90	27.70	23.35	31.70	23.35	25.30
8	20.60	35.40	26.00	27.30	23.30	31.35	23.30	24.95
9	20.80	35.70	25.60	27.70	23.20	31.70	23.20	25.30
10	27.20	36.40	27.10	28.20	27.15	32.30	27.15	25.90
11	22.00	36.40	25.90	27.60	23.95	32.00	23.95	25.60

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Table 3 – *Continued from previous page*

Trial	X1	Y1	X2	Y2	Avg X	Avg Y	Comp X	Comp Y
12	21.30	37.30	26.70	29.20	24.00	33.25	24.00	26.85
13	22.00	36.70	27.20	28.50	24.60	32.60	24.60	26.20
14	21.40	28.70	26.50	28.70	23.95	28.70	23.95	22.30
15	20.20	35.70	25.60	27.60	22.90	31.65	22.90	25.25
16	21.00	36.20	26.30	28.20	23.65	32.20	23.65	25.80
17	20.60	35.70	25.60	27.60	23.10	31.65	23.10	25.25
18	20.90	36.70	26.20	28.70	23.55	32.70	23.55	26.30
19	20.90	36.70	26.20	28.70	23.55	32.70	23.55	26.30
20	22.00	36.30	26.90	28.00	24.45	32.15	24.45	25.75
21	20.90	36.50	26.20	28.40	23.55	32.45	23.55	26.05
22	22.90	36.10	27.80	28.40	25.35	32.25	25.35	25.85
23	22.20	35.70	27.20	27.50	24.70	31.60	24.70	25.20
24	22.50	36.30	27.30	27.40	24.90	31.85	24.90	25.45
25	21.20	36.50	26.40	28.30	23.80	32.40	23.80	26.00

7 Statistical Precision of Observed End Poses

7.1 Preliminary Statistical Analysis

Based on the collected data, preliminary statistics for the compensated positions (representing the robot's axle center) are as follows:

7.1.1 Straight Motion

- Mean X position: -0.07 cm
- Mean Y position: 38.39 cm
- Standard deviation (X): 0.39 cm
- Standard deviation (Y): 0.80 cm

7.1.2 Left Arc Motion

- Mean X position: -23.79 cm
- Mean Y position: 25.42 cm
- Standard deviation (X): 0.68 cm
- Standard deviation (Y): 0.37 cm

7.1.3 Right Arc Motion

- Mean X position: 23.76 cm
- Mean Y position: 25.42 cm

- Standard deviation (X): 1.04 cm
- Standard deviation (Y): 0.74 cm

8 Comparison with Expectations

The observed behavior of the robot generally matches our expectations from Assignment 1:

1. **Measurement precision:** The observed standard deviations (0.37-1.04 cm) are consistent with our estimated measurement uncertainty of approximately ±0.4 mm for position measurements.
2. **Motion repeatability:** All three motion types show relatively tight clustering of end poses, indicating good repeatability of the robot's motion control.
3. **Systematic patterns:** The straight motion shows minimal lateral drift (mean X 0), while the left and right arcs show symmetric behavior with respect to the Y-axis, as expected.
4. **Variation sources:** The spread in end positions aligns with anticipated error sources including encoder resolution, wheel slippage, and battery variations.

9 Data Transformation and Combined Dataset

Our data follows the standard coordinate convention agreed upon by all groups:

- Y-axis aligned with forward robot direction
- X-axis perpendicular (right-hand rule)
- All positions transformed to represent the robot's axle center
- All values rounded to 2 decimal places

The data is stored in CSV format (see attached files) and is ready to be merged with data from other groups for combined analysis.

10 Conclusion

The experiment successfully captured 75 data points (25 trials × 3 motion types) documenting the robot's end pose behavior. The pen refill marking mechanism proved reliable and precise, and the observed motion patterns demonstrate good repeatability. The visualizations clearly show the distribution of end poses and provide insight into the robot's motion characteristics. This data will serve as a foundation for statistical analysis in Assignment 3, where we will perform detailed distribution fitting and uncertainty quantification.

11 Appendix: Video Documentation

Three video recordings were captured showing the robot's behavior during the experiment:

- `straight_motion.mp4` - Robot executing straight line motion
- `left_motion.mp4` - Robot executing left motion
- `right_arc_motion.mp4` - Robot executing right arc motion

An image of the marked cardboard sheet is also included as `marked_sheet.jpg`.