Università degli Studi di Genova

DIBRIS - Department of Informatics, Bioengineering, Robotics and Systems Engineering

# Statistical Comparison of Bug-0 Algorithm with Left and Right Turn Preferences

Milad Rabiei (S7215122)

*Professor:* Dr. Carmine Recchiuto

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*Degree:* Robotics Engineering MSc

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# Chapter 1

# Introduction

## 1.1 Problem statement

Bug-0 is one of the simplest motion planning algorithms for mobile robots, operating under the principle of navigating directly towards a goal until an obstacle is encountered, at which point the robot follows the boundary of the obstacle until it can resume its direct path. A critical component of this strategy is the choice of obstacle-following behavior, which is typically implemented with either a right-turn or left-turn preference. Although both variants adhere to the same high-level logic, the specific turning direction may lead to markedly different behaviors in environments with complex obstacle geometries.

In this study, I analyze the performance characteristics of the left-turn and right-turn variants of the Bug-0 algorithm using statistical hypothesis testing. Instead of relying on anecdotal comparisons or deterministic outcomes, I adopt a rigorous experimental design involving repeated randomized trials. Performance metrics such as elapsed time, aggregated distance, angular deviation, and goal accuracy are recorded for successful trajectories. I employ both parametric tests and non-parametric alternatives guided by preliminary normality checks using the Lilliefors test. This methodology enables us to evaluate whether observed differences between the two strategies are statistically significant.

## 1.2 Organization of the report

Chapter 2 describes the experimental setup and outlines the data collection process, including some parameters and evaluation metrics. It also presents the statistical analysis methods used to compare the two variants, including both parametric and non-parametric hypothesis tests. Chapter 3 demonstrates the results and interprets the results for future robotic navigation systems.

# Chapter 2

# Methodology

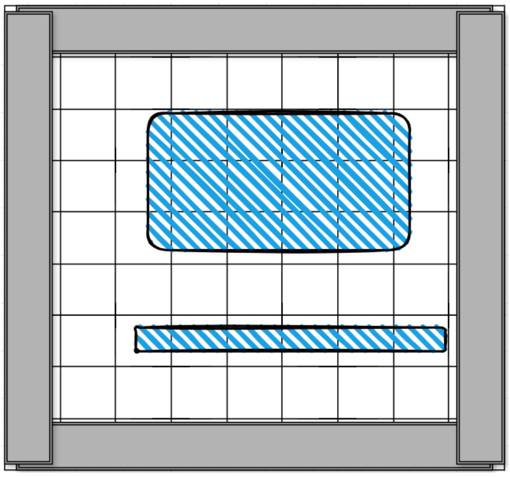

Figure 2.1: Map of the environment. The original map is [-8.5, 8.5]x[-8.5, 8.5], yet it has been cropped to [-7, 7] due to wall geometry. The colored areas include some obstacles.

## 2.1 Data Collection and Processing

To compare the performance of the left-turn and right-turn variants of the Bug-0 algorithm, I designed a reproducible data collection pipeline using ROS. The robot was launched using a `roslaunch` configuration file, with the turning behavior passed as a launch parameter. Each run assigned independent random initial and goal positions, constrained to valid zones in the map to avoid collisions at spawn time or issues such as robot flipping. The initial positions were sampled outside **generalized** obstacle regions to ensure physical plausibility and algorithm safety.

Three sampling strategies were tested: fully independent random positions for each algorithm, paired positions where the same initial-goal pair was evaluated with both algorithms (with seed), and a fixed uniform grid of start-goal points. The latter proved unsuitable for statistical analysis due to spatial bias and lack of randomness. Note that **initial positions** excluded the obstacle areas, due to the robot's unknown behavior when spawned there (it would jump out of the obstacles and might flip, rendering the experiment moot), yet only the spawn points and not the goals. For the main statistical purposes only paired-random data was selected due to higher information value. Each run was limited to 150 seconds; trials exceeding this time were marked as cancelled. Approximately **400 paired trials** were executed per algorithm, and data was collected over several hours of simulated time. To avoid excessive memory usage, relevant performance metrics were computed in real-time within the ROS nodes (early disambiguation), and results were saved in lightweight CSV format.

## 2.2 Data Format

Each CSV file contains per-trial results, structured with the following columns:

| Field | Description |
|---|---|
| iteration | Unique trial index |
| initial_x, initial_y | Initial robot position (in map frame) |
| goal_x, goal_y | Assigned goal position |
| cancelled | Boolean flag indicating timeout or failure |
| goal_accuracy | Euclidean distance to goal upon task completion |
| aggregated_distance | Total path length traveled |
| aggregated_angle | Sum of absolute angular changes |
| elapsed_time | Total task completion time in seconds |

Table 2.1: Fields recorded for each trial in the experiment

These variables were selected to provide comprehensive insight into navigation performance. Elapsed time captures efficiency, aggregated distance reflects path optimality, aggregated angle indicates maneuver complexity, and the cancelled flag separates successful and failed trials for filtered analysis. Goal accuracy ensures that results include final positioning fidelity, despite the fact that it is **technically not affected** by turning preference.

## 2.3 Hypotheses

Two hypotheses types are most known. The Null hypothesis (H0) declares no significant difference, while the Alternate hypothesis (H1) states the opposite, about the statistics at hand. The following null and alternative pairs are defined to evaluate performance differences between the two algorithm variants:

- **Null Hypothesis (H0):** There are no significant differences between the algorithm with right and left turn, in elapsed time, aggregated distance, and aggregated angle, in **paired** trials.
  **Alternative Hypothesis (H1):** There are significant differences between algorithm with right and left turn, in elapsed time, aggregated distance, and aggregated angle, in **paired** trials.

- **Null Hypothesis (H0):** There are no significant differences in the success rates between left-turn and right-turn algorithms in **paired** trials.
  **Alternative Hypothesis (H1):** There is a significant difference in the success rates between left-turn and right-turn algorithms in **paired** trials.

To test these hypotheses, I compare distributions of the recorded metrics using both parametric and non-parametric statistical methods. Preliminary normality checks are conducted using the Lilliefors test, on both paired and independent only for the sake of providing more analysis; However, paired datasets are chosen as the main samples. Paired T-test and

Wilcoxon signed-rank test are exercised later. Categorical outcomes such as success vs. failure are analyzed using the Chi-square test for independence.

## 2.4 Performance Metrics

Each of the following metrics is computed per trial and evaluated across the dataset:

- **Elapsed Time (s)**: The duration between start and successful goal arrival. For each trial:
$$\text{Elapsed Time} = t_{\text{end}} - t_{\text{start}}$$
- **Aggregated Distance (m)**: Sum of Euclidean distances between consecutive position updates:
$$\sum_{i=1}^{N-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$$
- **Aggregated Angle (rad)**: Cumulative absolute angular change over the trajectory:
$$\sum_{i=1}^{N-1} |\theta_{i+1} - \theta_i|$$
- **Goal Accuracy (m)**: Euclidean distance from the robot to the goal at termination time:
$$\text{Goal Accuracy} = \sqrt{(x_{\text{final}} - x_{\text{goal}})^2 + (y_{\text{final}} - y_{\text{goal}})^2}$$
- **Success Rate**: Proportion of non-cancelled trials. Binary outcome analyzed via Chi-square test.

Each metric captures a different aspect of navigation performance: time for efficiency, distance and angle for path smoothness and control load, and goal accuracy for precision.

## 2.5 Statistical Analysis Methods

To draw valid and reliable conclusions from the experimental data, a range of statistical analysis techniques were employed. The choice of method depended on the characteristics of the data (e.g., distribution, pairing) and the nature of the metric being evaluated (continuous or categorical). Below, each test and its purpose in the context of the study is discussed:

- **Chi-Square Test of Independence:** This non-parametric test is used to determine whether two categorical variables are independent. In our study, it was applied to evaluate whether the success or failure rates (cancelled vs. non-cancelled trials) are statistically different between the two algorithm variants. The test compares observed and expected frequencies in a contingency table.
- **Lilliefors Test for Normality:** A variation of the Kolmogorov–Smirnov test, Lilliefors is used to assess whether a sample comes from a normally distributed population when the population mean and variance are unknown. It was used on each continuous metric (elapsed time, distance, angle, and accuracy) to determine whether parametric or non-parametric tests should be applied.

- **Paired Student's *t*-Test:** This parametric test compares the means of two related (paired) samples. It assumes normality of the difference between paired values. In our analysis, it was applied to continuous performance metrics from paired experiments, where the same initial-goal positions were used for both algorithms.
- **Wilcoxon Signed-Rank Test:** A non-parametric alternative to the paired *t*-test, used when the assumption of normality is violated. It compares the median of the differences between paired samples. I used it for the same paired comparisons as the paired *t*-test when normality was not satisfied.

These tests collectively enable a robust and statistically valid comparison between the left-turn and right-turn variants of the Bug-0 navigation algorithm under varying experimental designs.

Next, some histograms of the variables included in the analysis are presented in 2.2. It is clear that time and distance distributions of the samples follow similar behavior in the two algorithms. The aggregated angle **may not be the best** representation of robot rotation, yet there is a small difference between them. Goal accuracy is also a variable not necessarily affected by the turning preference, yet it is evident that algorithm left-turn brings the robot closer to the actual goal in this map.

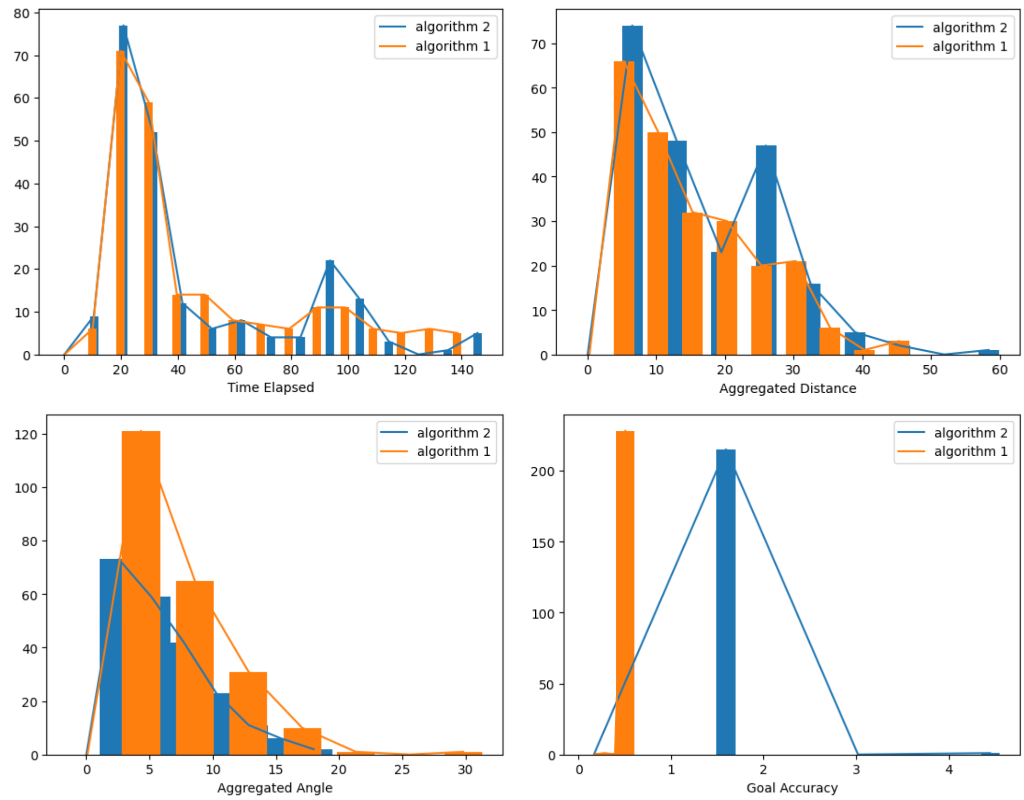


Figure 2.2: Histogram of variables of paired samples
(time top-left, distance top-right, angle bottom-left, and accuracy bottom-right).

Also as a bonus analysis a small demonstration of the Central Limit Theorem is presented in 2.3 and 2.4. The number of data points is fixed, reducing the number of items as the sample size gets larger. Nevertheless as the sample size increases, the distributions take a more normal shape. The graphs have been centered around 0 for demonstration.

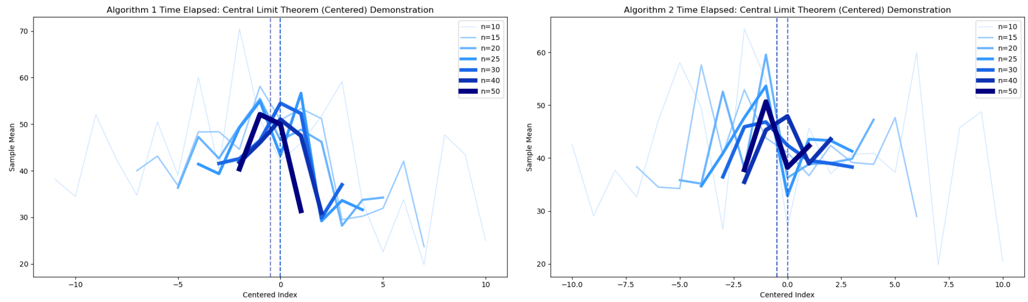


Figure 2.3: Demonstration of the central limit theorem for elapsed time in not-cancelled samples.

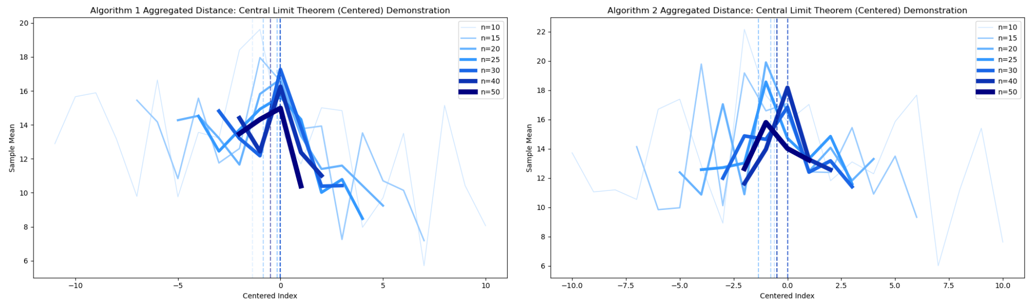


Figure 2.4: Demonstration of the central limit theorem for aggregated distance in not-cancelled samples.

# Chapter 3

# Results and Conclusion

This section presents the outcomes of the statistical analysis conducted to compare the performance of two Bug-0 variants—one using a left-turn strategy and the other using a right-turn strategy for obstacle avoidance. For each of these indicators, data normality was evaluated using the Lilliefors test. Statistical tests—parametric or non-parametric—were applied to assess whether the observed differences were statistically significant. It should be noted that paired samples are preferred for this analysis. However only **successful paired samples** were chosen to compare distance, time, and angle in 3.2, that is, matching trials which were successful in both algorithms. In addition, successful independent samples presented an interesting event through Lilliefors test, which is discussed later.

## 3.1 Empirical Results

Means and standard deviations of the metrics of the left and right turner algorithms were calculated based on their samples. However, they are not sufficient information to hypothesize with.

Table 3.1: Performance summary (mean $\pm$ std dev) for both algorithms

| **Metric** | **Left turner (1)** | **Right turner (2)** |
|---|---|---|
| Elapsed Time (s) | $41.9 \pm 33.9$ | $40.6 \pm 33.7$ |
| Aggregated Distance (m) | $12.7 \pm 9.7$ | $13.5 \pm 10.3$ |
| Aggregated Angle (rad) | $5.3 \pm 4.0$ | $4.9 \pm 3.5$ |
| Goal Accuracy (m) | $0.50 \pm 0.02$ | $0.51 \pm 0.27$ |
| Success Rate (%) | 76.3% | 72.0% |

One of the most important aspects of this analysis is the success rate. Since it is a categorical information -canceled or completed based on elapsed time, Chi$^2$ is chosen as the statistical measure.

Table 3.2: Categorical statistical analysis of canceled and passed trials using the Chi-square test, in the random-paired mode.

| **Algorithm** | **Canceled** | **Finished** | **Sum** |
|---|---|---|---|
| **Left turner (1)** | 71 | 229 | 300 |
| **Right turner (2)** | 84 | 216 | 300 |

| | |
|---|---|
| **Chi$^2$ Statistic** | 1.2526 |
| **p-value** | 0.2631 |
| **Degrees of freedom** | 1 |

Lilliefors is a method of estimating if the sample belongs to a Normally distributed population. In spite of other results, the numbers in the independent samples declare that left and right turner algorithms do not belong to the same population.

Table 3.3: Lilliefors test results for normality of paired and independent samples.

| | Paired | | Independent | |
|---|---|---|---|---|
| **Metric** | **Algorithm 1** | **Algorithm 2** | **Algorithm 1** | **Algorithm 2** |
| Time | 0.0010 | 0.0010 | 0.0010 | 0.0010 |
| Distance | 0.0010 | 0.0010 | 0.0041 | **0.2591** |
| Angle | 0.0010 | 0.0010 | 0.0010 | **0.2501** |

Finally the T-test and Wilcoxon test on the numerical values of the two algorithms are presented. P values under 0.05 are informative for rejecting hypotheses.

Table 3.4: Statistical test results comparing algorithms using paired data.

| | Paired Tests | |
|---|---|---|
| **Metric** | **T-Test (p)** | **Wilcoxon (p)** |
| Time | 0.2872 | 0.9961 |
| Distance | **0.0137** | **0.0170** |
| Angle | 0.8019 | 0.7455 |

## 3.2 Hypothesis Tests

- Regarding the differences between algorithms with right and left turn in *elapsed time*, *aggregated distance*, and *aggregated angle*, in the *paired* trials.
  - Paired T-Test:
    - *Time:* $p = 0.2872 \Rightarrow$ Not significant
    - *Distance:* $p = 0.0137 \Rightarrow$ Significant
    - *Angle:* $p = 0.8019 \Rightarrow$ Not significant
  - Wilcoxon Test:
    - *Time:* $p = 0.9961 \Rightarrow$ Not significant
    - *Distance:* $p = 0.0170 \Rightarrow$ Significant
    - *Angle:* $p = 0.7455 \Rightarrow$ Not significant
  - **Conclusion:**
    - *Time:* Reject H1 $\Rightarrow$ No significant difference
    - *Distance:* Reject H0 $\Rightarrow$ Significant difference
    - *Angle:* Reject H1 $\Rightarrow$ No significant difference
- Regarding the success rates between the algorithms with right and left turns in the *paired* trials.
  - Chi-Square Test:
    - $\chi^2 = 1.2526$, $p = 0.2631 \Rightarrow$ Not significant
  - **Conclusion:**
    - *Time:* Reject H1 $\Rightarrow$ No significant difference

# Chapter 4

# Conclusions

This study presented a statistical comparison between two Bug-0 algorithm variants distinguished by their obstacle-avoidance turn preference (left vs. right). Multiple randomized and controlled simulations were executed to assess differences in performance using key metrics such as task completion time, aggregated distance, and angle turned.

Normality tests showed that most variables do not follow a normal distribution, however parametric tests suffice since the sample sizes are large enough. In paired experiments, only the aggregated distance showed statistically significant differences, with the left-turning variant demonstrating marginally better efficiency. No significant differences were observed for time or angle. Additionally, categorical analysis using the Chi-square test revealed no significant disparity in success rates between the two strategies.

Overall, the results suggest that while both turn strategies perform comparably in most aspects, the left-turning variant may have a slight advantage in minimizing traveled distance under matching initial conditions. Further studies in more complex environments may be needed to generalize these findings.