

Optimizing Ultrasonic Sensor Placement in Two-Sensor Systems for Reliable Navigation Using Dijkstra's Algorithm

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ABSTRACT: Robotic systems limited to a few sensors focus on balancing sensor coverage with general reliability. In our two-sensor system, a critical area of focus is the angle between ultrasonic sensing cones, where narrow placement tends to limit peripheral awareness, while wider placement limits frontal awareness and creates frontal blind spots. Moderate placements around 60° are expected to achieve the best overall awareness. This study tests six inter-sensor angles (0°, 30°, 45°, 60°, 90°, 120°) on a simulated robot in ROS 2 paired with Gazebo Fortress that uses Dijkstra's algorithm to plan out a path. In this experiment, metrics including success rate (based on the number of collisions), path completion time, and path deviation were used to evaluate performance. Overall, moderate angles closer to 60° yielded the most promising outcomes, with paths that were more efficient and more in line with the optimal path laid out by Dijkstra's algorithm. Narrower angles tended to result in sideward impact, while wider angles led to delayed forward detection. Generally, these results demonstrate the significant impact that even small physical design choices can have on improving navigation in low-cost robotics—information that can inform the development of accessible and efficient robotics platforms.

KEYWORDS: Robotics, Autonomous Navigation, Ultrasonic Sensors, Sensor Placement, Path Planning.

■ Introduction

Navigation remains a critical challenge in autonomous robotics, requiring robots to respond to certain environments by accordingly planning routes and detecting obstacles nearby. Navigation is not only about getting from point A to B but also about ensuring that the robot can do so in a manner that is safe, efficient, and repeatable. Foundational tests confirm navigation as a basis for higher-level capabilities, including exploration, search-and-rescue missions, and even multi-robot coordination.¹ These higher-level functions are only made possible with reliable navigation.

To achieve robust navigation, platforms rely on systems with complex sensor arrays like LiDAR as well as vision, which offer rich perception but at a high cost. LiDAR works by emitting laser pulses and noting the time lapse between an outgoing pulse and the detection of the reflections to produce 3D maps.² Though these sensors enable high-accuracy localization and obstacle detection, sensors themselves can cost thousands of dollars, making them unattainable for hobbyist- or student-designed robots.³ On the other hand, vision-based systems provide insight into colors, textures, and features, though they require real-time processing for accurate image capture.⁴ Though these systems provide perceptual data, they often require more computational power in comparison to simpler robotics platforms. In practice, these limitations make advanced sensors suitable for grander projects like those conducted in research labs or in the industry, but unsuitable for classrooms, small-scale designs, and other cases.

Due to these constraints, ultrasonic sensors have emerged as a staple for low-cost and educational robotics purposes.⁵ These sensors operate by emitting short bursts of sound above the

standard human hearing range and then measuring the delay of the resulting echoes to estimate distance.⁶ An ultrasonic sensor's conical detection field, as shown in Figure 1, allows for basic coverage of the frontal space and is easily mountable.⁷ However, the simplicity associated with using these sensors comes with its own tradeoffs. Ultrasonic sensors are prone to environmental noise, limited effective range (not more than a couple of meters), and misreadings that occur when surfaces reflect sound away rather than back.⁸ Thus, the placement of these sensors in a system becomes especially critical because poorly chosen angles can make the difference between a functional system and one that yields orientational issues, blind spots, and other features that degrade the robot's navigational performance.

The geometry of the placement of these sensors becomes critical. When two ultrasonic sensors are mounted in proximity to each other, their detection cones overlap, leaving the forward region accounted for, but the side areas neglected. This sensor configuration improves frontal detection, but degrades lateral detection, making the robot more vulnerable to side collisions. On the other extreme, when there is hardly any overlap between detection cones—a situation occurring with sensors placed far apart—a frontal blind spot is introduced.⁹ Both extremes are problematic, with narrow-angle placement sacrificing side coverage, and wide-angle placement sacrificing frontal awareness and delayed obstacle detection directly ahead. Studies emphasize placement geometry as a fundamental determinant of system reliability, as ultrasonic reflections and cone spread can amplify detection errors.⁹

This interplay is increasingly important when considered alongside path planning algorithms. Deterministic algorithms

like Dijkstra's are designed to guarantee optimal path planning.¹⁰ If obstacles are left undetected due to poor sensor placement, then even the "optimal" path leaves the robot susceptible to collisions. Thus, without reliable sensing, even the most elaborate algorithms don't guarantee efficient navigation.

This issue is evident in educational robotics, in which students work with predesigned kits. Platforms like LEGO Mindstorms and VEX introduce ultrasonic sensors mounted in fixed positions.¹² While this eases beginner students into the design process, it introduces geometric limitations that students are unaware of contributing to the robot's performance. The result can be collisions or incorrectly linking this issue to "bad code" rather than suboptimal hardware placement. Identifying and addressing these limitations opens the door to an overlooked opportunity: with simple adjustments, designers can achieve better performance, reliability, and insight that can inform their takeaways and allow them to gain more educational value from low-cost systems.

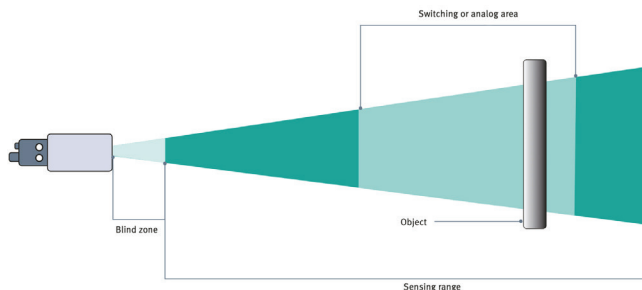


Figure 1: Ultrasonic sensor: conical field of view. This geometry presents the detection pattern of objects with respect to distance and angle.

While extensive research exists on advanced sensor and path planning, as well as a fair amount of research on sensor geometry, little prior work focuses on the effect of adjusting inter-sensor angles in minimalist systems, which in this case entails a simple box robot with two adjustable ultrasonic sensors. Most published work identifies sensor placement as a fixed design choice rather than an experimental factor. This gap is crucial for entry-level robots, as designs may be constrained to a minimal number of sensors and thus must optimize the placement of those sensors accordingly.

The objective of this study is to evaluate the effect of varied inter-sensor angles on the navigational performance of the robot in a controlled environment. A simulated robot with two ultrasonic sensors was tested across various trials in which angles were adjusted for a robot that maneuvered around a single obstacle and used Dijkstra's algorithm for path planning. Metrics, including success rate, path length deviation, collisions, and path completion time, helped quantify the robot's relative performance. We hypothesize that moderate angles between and near 45° and 60° will provide the most effective tradeoff between frontal and peripheral coverage.

■ Methods

This experiment was conducted in ROS 2 Humble simulation software paired with Gazebo Fortress. The robot, a simple box robot with two front-mounted ultrasonic sensors, was simulated on this software. Each sensor was simulated as

a cone with a fixed field of view and range, and uniform sensitivity throughout. To simplify the experimentation process, the robot was not equipped with any actuators or wheels, and instead, path execution was computed on the grid that was discretized parallel to the direction of motion. This design choice helped to separate the effects of sensor placement from actuation variables.

Experimental Design:

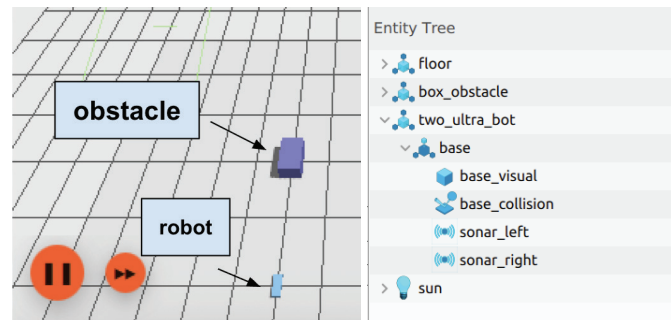


Figure 2: Simple ROS 2 simulation environment showing the simple robot, obstacle, and grid to traverse. (Left) The entity tree depicts a simple box robot with two ultrasonic sensors (not pictured in the simulation). By maintaining consistent environmental conditions across trials, performance differences can be attributed to shifts in sensor placement.

In this study, the independent variable was the inter-sensor angle (θ), which was tested at 0°, 30°, 60°, 90°, and 120°. The robot operated in a perpendicularly discretized grid environment as outlined in Figure 2, consisting of a cube-shaped obstacle, small enough for the sensors to detect it within their conical field of view, and a fixed starting and ending point. In this experiment, variables such as obstacle and robot size, grid resolution, and sensor range were all held constant across the trials. At each θ , six simulation runs were conducted. The reported results represent the average values of those runs to reflect consistent behavior, rather than outliers, across trials.

The navigation path was generated using Dijkstra's algorithm, which helped identify the shortest path to a goal. While the algorithm accounted for obstacles in the grid, it did not change based on missed sensor detections, thus ensuring that any differences in performance could be solely attributed to sensor placement instead of path computation variability.

Each inter-sensor angle was tested across various trials. The following metrics were recorded using ROS 2 logging tools to evaluate performance:

- **Success rate:** percentage of trials completed without collisions
- **Path length deviation:** difference between the actual traveled distance and the "optimal" path laid out by Dijkstra's algorithm
- **Collision count:** number of recorded collisions with obstacles
- **Completion time:** total time taken to reach the goal

■ Results

Across all runs, each sensor configuration registered at least one collision with the wall, indicating a uniform success rate of 0. Despite this, other observed metrics, including

path completion time and deviation, helped to distinguish between intersensor angle placement to provide meaningful insight (Table 1). For example, the lowest deviation (0.502) was achieved at an intersensor angle of 60°, and the fastest completion time (4.97s) was achieved at a sensor placement of 90°, indicating that optimal and time-effective paths were followed most closely at these moderate angles. In contrast, the 0° sensor configuration produced the longest completion time (93.27s) and the greatest deviation (1.126), confirming inefficiency when sensors are placed directly on top of one another. At the other extreme, the 120° sensor placement also proved inefficient, with equally high path deviation (1.126) and slower runs (6.00s). This is consistent with delayed frontal detection in wider placements.

Intermediate angle (between 30° and 90°) yielded mixed outcomes that generally proved to be more promising. At 30°, the robot followed an average path completion time of 6.78s with moderate deviation (0.711), while at 45° the robot took 8.61s, a greater amount of time, to complete the path, but at the same deviation (0.711). Quicker navigation did not correlate with the straightest paths. Such inconsistencies depicted that though moderate angles generally outperformed extreme ones, performance was variable and usually depended on what metric efficiency was measured by.

Table 1: Simulation data representing navigation performance metrics across varied intersensor angles, with each value representing the average across six simulation runs.

Success	Time (s)	Path Deviation	Collisions	Angle (degrees)
0	93.27	1.126	1	0
0	6.78	0.711	1	30
0	8.61	0.711	1	45
0	5.03	0.502	1	60
0	4.97	0.711	1	90
0	6	1.126	1	120

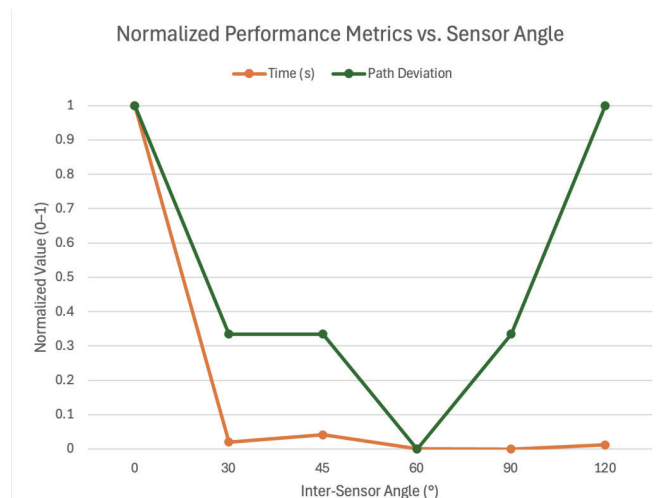


Figure 3: Comparison of normalized performance metrics—time and path deviation—against inter-sensor angle. Lower values indicate stronger performance, with 60° achieving the best overall balance across both metrics.

To properly enable cross-metric comparison, both path time and deviation were normalized on a 0-1 scale, with lower values indicating greater efficiency and performance (Figure 3).

A sensor configuration of 60° consistently minimized deviation, and a sensor placement at 90° minimized completion time. Angles of 30° and 45° performed decently and occupied an intermediate range, while angles of 0° and 120° significantly underperformed across path time and deviation—the metrics that varied with each inter-sensor angle. Though an inter-sensor angle of 60° between ultrasonic sensors had the best tradeoff between performance metrics, the minimized completion time at 90° demonstrates that optimal placement can vary depending on the metric that is prioritized.

■ Discussion

The results support the hypothesis that moderate inter-sensor angles provide the most effective tradeoff between frontal and peripheral coverage. Though no trial fully avoided collisions, these efficiency metrics offered insight into the relative performance of the robot under various sensor configurations. At 90°, the robot achieved the lowest path deviation, and at 60°, the robot followed the most time-effective paths, indicating that these moderate placements allowed sensors to detect obstacles early enough to ensure a smoother and more effective trajectory.

By contrast, the 0° inter-sensor configuration suffered due to overlap: both sensors consistently monitored the area directly in front of them while neglecting the sides. This configuration created the illusion of redundancy but instead led to a gap in detection and thus long, inefficient runs. On the other extreme, an intersensor angle of 120° produced large blind spots directly ahead. The robot reacted late to the obstacles directly ahead of it, forcing abrupt adjustments to the robot's path and an inflated deviation. The geometry of beam overlap produces an explanation for this phenomenon: narrow angles sacrifice lateral vision, while wider angles prove unreliable in detecting frontal objects.

Even in this simplified simulation environment, such trends confirm that the placement alone of sensors (or ultrasonic ones, in this case) drove the navigational capacity and efficiency of the robot. These trends demonstrate that even with a deterministic algorithm such as Dijkstra's algorithm, which guarantees the optimal route, the robot's performance can be dictated by poor sensing geometry. Path planning alone cannot compensate for sensor misplacement.

In terms of low-cost robots in educational settings or hobby projects, this demonstrates how even small physical adjustments can have meaningful implications. In these budget-constrained settings, individuals may not have the ability to add to their system. With this understanding, individuals can optimize the robot's performance using the materials they already have. By intentionally selecting moderate inter-sensor angles, they can make minor practical adjustments that lead to greater results without any additional investment.

■ Conclusion

Overall, this study yielded the finding that adjusting the inter-sensor angle between ultrasonic sensors in a minimalist controlled environment influences navigational performance. This knowledge can be applied to two-sensor robotic systems

and beyond. Moderate sensor placements, specifically at 60°, minimized path completion time and path deviation consistently, and vastly outperformed narrower and wider sensor placement configurations. Narrower configurations, such as at 0°, proved to be inefficient due to their disregard for lateral regions, while wider configurations, like at 120°, tended to create blind spots for the robot.

The implications of this study can be applied to designers of low-cost robotic systems, who may benefit from the understanding that geometric choices can shape system outcomes. By adjusting sensor placement, a minor but likely overlooked adjustment, designers can make steps towards smoother navigation and more efficient performance.

Future work should apply this knowledge on a broader scale and extend these tests into multi-obstacle environments, test the resilience of systems in the case of sensor failure, and validate whether these moderate inter-sensor angles are truly a “sweet spot” in real-world scenarios. Such experiments can further solidify the guidelines established by this study and apply this understanding to broader educational and practical contexts.

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