CHAPTER VIII. EVALUATION OF THE USE OF LIDAR

VIII.A. Configuration of the simulation environment

A world file was generated containing the first mesh created during evaluation of 2004 GCE course segment 2570-2571-2572, which included an outer radius of 7.924 m (twice the lateral boundary offset) tangent to the outer wall at the intersection of the two adjacent course segments. The first mesh was representative of the actual course boundaries established by DARPA in 2005.

A tower obstacle was located so the tower was at the center of a circle with radius 2.0 m tangent to the inner wall at the intersection of 2004 GCE course segments 2570-2571 and 2571-2572. This is representative of towers encountered during the 2005 GCE (see Figures 9 and 10 for examples). The tower model file was revised to include a `<laserFiducialId>` declaration of "1" and `<laserRetro>` declaration of "0.5".

The world file was revised to attach a SICK LMS 200 model to the representative challenge vehicle model. The world file was revised to relocate the SICK LMS 200 model through the trials which followed, and the SICK LMS 200 model file was revised to adjust the field-of-view and angular resolution through the trials which followed, as documented below.

The Player configuration file was revised to include a driver for the laser device and to add the laser device to the `writelog` driver used to log output.

VIII.A.1. Selection of scanning frequency

The scanning frequency of SICK LMS 200 or 291 LIDAR sensors is 37.5 Hz with an angular resolution of 0.5º and 75 Hz with an angular resolution of 1º. As documented below, angular resolutions of 0.5º and 1º were used when evaluating the revised simulation target. However, the author was unable to determine the scanning frequency in use by teams participating in the 2004 or 2005 GCE. Team 2005-18 stated: "[SICK LMS-221-30206] LADARs have a maximum range of 80 meters and a scanning rate of 75 Hz." ([26], p. 10). Three other teams referred indirectly to a SICK LIDAR sensor scanning frequency of 75 Hz: Teams 2005-05, 2005-08, and 2005-19.

However, an informal review of technical proposals for teams participating in the 2007 Urban Challenge indicate a scanning frequency of 10 Hz was not uncommon. As a result, the author concluded, although the maximum scanning frequency of a LIDAR sensor was 75 Hz, it was likely that LIDAR sensors in use by teams participating in the 2004 and 2005 GCE were operated at a reduced scanning frequency, and that a scanning frequency of 20 Hz was reasonable, and revised the `<updateRate>` declaration of the representative challenge vehicle model XML file steering controller and SICK LMS 200 model file laser controller to change the update rate of both controllers to 20 Hz. An update rate of 10 Hz was not considered due to problems encountered with simulation fidelity when validating the steering controller.

VIII.A.2. Selection of parameters `rayCount` and `rangeCount`

As described via paragraph V.A., the author reviewed files `Sensor.cc`, `Controller.cc`, `RaySensor.cc`, and `MultiRayShape.cc` (and corresponding header files) to determine valid parameters used by the simulated SICK LMS 200 LIDAR sensor. Although the author was able to generate a list of potential parameters, he was unable to determine the effect of some parameters, specifically `rayCount` and `rangeCount`, without review of documentation for a much earlier version of Gazebo (version 0.5).

However, based on a review of documentation for Gazebo 0.5, parameters `rayCount` and `rangeCount` were set equal to the same value through the trials that followed.

VIII.A.3. Selection of parameter `maxRange`

Parameter `maxRange` was set to "30", the typical range with ten percent reflectivity for SICK LMS 291 LIDAR sensors.

VIII.B. Revision of the simulation target

The original simulation target was: "Use Player and Gazebo to evaluate the use of LIDAR, in particular the quality of the point map created by SICK LMS 200 and 291 LIDAR sensors, and increase in the number of SICK LMS 291 LIDAR sensors". See paragraph IV.E.

However, while configuring the simulation the author determined that there would be no difference between the quality of the point map generated by SICK LMS 200 and 291 LIDAR sensors in simulation based on the results of several trial runs. Both sensors have a maximum possible scanning angle of 180º and angular resolution of 0.25º, 0.5º, or 1.0º, and both sensors have identical response times and scanning frequencies ([45]).

Gazebo uses a generic "ray" sensor to simulate a LIDAR sensor. As a result, the point map generated by SICK LMS 200 LIDAR sensors would be virtually identical to the point map generated by SICK LMS 291 LIDAR sensors with the same parameters in simulation.

SICK LMS 200 LIDAR sensors have a typical range with ten percent reflectivity of 10 m and SICK LMS 291 LIDAR sensors have a typical range with ten percent reflectivity of 30 m ([45]). The author determined the difference in the quality of the point map generated by SICK LMS 200 or 291 LIDAR sensors at ranges typical of the two sensors in simulation was self-evident from review of logged data based on the results of several trial runs.

SICK LMS 200 LIDAR sensors do not have one feature SICK LMS 291 LIDAR sensors have: fog correction ([45]). Gazebo makes use of OGRE. As a result, a Gazebo world file may be configured to include fog through use of the `<rendering>` declaration. However, the author did not have data with which to correlate the accuracy of the range returns from a simulated SICK LMS 200 or 291 LIDAR sensor through fog. Although SICK provided reflectivity in fog data ([46]), the author was unable to correlate it with intensity data returned by Gazebo, which was one of two values "0" and "1", with a value of "0" being typical.

Team 2005-06 stated: "Rather than pointing the LADAR devices at the ground horizontally, we mounted the LADAR devices vertically. We chose to align them vertically because it made obstacle detection much easier. In the simplest case, by analyzing the measurement data beam by beam in angular order, obstacles were easy to locate as either clusters of similar distance or gaps in distance." ([47], p. 513). No other environment sensors were in use by Team 2005-06. However, Team 2005-06 successfully completed the 2005 GCE.

This was atypical. Several other teams stated vertically-aligned LIDAR sensors were in use as terrain analysis or ground profile estimation sensors, but no other team relied on vertically-aligned LIDAR sensors as the only obstacle and path detection sensors. As a result, the simulation target was revised: "Use Player and Gazebo to evaluate the use of a single SICK LMS 291 LIDAR sensor in various configurations in simulation to determine if the vertical LIDAR configuration in use by Team 2005-06 provided a competitive advantage over the horizontal LIDAR configurations in use by the majority of teams, and if an alternate configuration combining aspects of a horizontal and vertical configurations would be more effective".

VIII.C. Simulation procedure

The author then started Gazebo, started Player, started the `playerv` utility, accelerated the model past the tower obstacle, and analyzed log output to evaluate the quality of the point map generated for various LIDAR configurations. Specifically, the author counted the number of range returns, and recorded the maximum range when the obstacle was first detected and minimum range when the obstacle was last detected.

VIII.D. Results

Three runs of the first trial were completed. The author determined the results from each run were virtually identical, with almost no variation (typically less than the range resolution of the simulated SICK LMS 291 LIDAR sensor) in range reported from one run to the next and no variation in the number of range returns. The author concluded it was unnecessary to complete multiple runs for each trial.

Six trials in total were completed. The results are summarized in Table II below. As an objective measure of the quality of each configuration, the ratio of the number of returns to the number of rays ("Quality") was calculated.

- Trial 1

The SICK LMS 291 LIDAR model was located at the front left corner of the roof of the representative challenge vehicle model with a rotation of -90° around the x-axis and -20° around the z-axis so the beam of the sensor swept a vertical plane at an angle of 20° clockwise across the path of travel of the vehicle. See Figure 11.

The location of the SICK LMS 291 LIDAR model was selected so the beam of the sensor crossed the path of travel of the representative challenge vehicle model to ensure the model would have the ability to detect obstacles directly in front of the model.

An angle of -20° was selected based on visual analysis which indicated obstacles near the inner lateral boundary offset were within the 30-m detection range. Increasing this angle by three degrees to -17° resulted in an inability to detect obstacles within the course boundaries. Decreasing this angle by three degrees to -23° reduced the ability of the sensor to detect obstacles at the maximum range possible. An angle of -20° was selected to ensure obstacle detection at a range slightly exceeding the inner lateral boundary offset.

Parameter `minAngle` was set to "-10", parameter `maxAngle` was set to "25", and parameters `rayCount` and `rangeCount` were set to "36". Parameters `minAngle` and `maxAngle` were selected to limit the beam of the sensor to an area just clearing the hood of the model at left extent to slightly greater than horizontal at right extent. Parameters `rayCount` and `rangeCount` were selected based on an angular resolution of 1°.

- Trial 2

Parameters `rayCount` and `rangeCount` were set to "71". Parameters `rayCount` and `rangeCount` were selected based on an angular resolution of 0.5º. The simulation configuration was otherwise identical to Trial 1.

- Trial 3

The SICK LMS 291 LIDAR model was relocated at the front center of the roof of the representative challenge vehicle model with a rotation of 5º around the y-axis so the beam of the sensor swept a horizontal plane at a down angle of 5º across the path of travel of the model. See Figures 12 and 13.

An angle of 5º was selected based on visual analysis which indicated the beam of the sensor completely crossed the path of travel at the maximum range possible. Increasing this value to 6º resulted in a reduced ability to detect obstacles near the ground because the beam did not intersect the ground within 30 m, which was the maximum range of the simulated SICK LMS 291 LIDAR sensor. Decreasing this value to 4º reduced the ability of the sensor to detect obstacles near the ground plane at the maximum range possible. See Figure 14.

Geometric analysis confirms this. At a height of 2.142 m and angle of 4º, the beam intersects the ground at a range of 30.6 m, exceeding the typical range with ten percent reflectivity for a SICK LMS 291 LIDAR sensor. At a height of 2.142 m and angle of 6º, the beam intersects the ground at a range of 20.4 m. An angle of 5º was selected to ensure obstacle detection at a range of 24.5 m, the maximum range at which the sensor completely crossed the path of travel.

Parameter `minAngle` was set to "-90", parameter `maxAngle` was set to "90", and parameters `rayCount` and `rangeCount` were set to "181". Parameters `minAngle` and `maxAngle` were selected based on the maximum scanning angle of SICK LMS 291 LIDAR sensors ([45]). Parameters `rayCount` and `rangeCount` were selected based on an angular resolution of 1^{o}.

- Trial 4

Parameter `minAngle` was set to "-45", parameter `maxAngle` was set to "45", and parameters `rayCount` and `rangeCount` were set to "91". Parameters `rayCount` and `rangeCount` were selected based on an angular resolution of 1^{o}. The simulation configuration was otherwise identical to Trial 3.

- Trial 5

Parameter `minAngle` was set to "-30", parameter `maxAngle` was set to "30", and parameters `rayCount` and `rangeCount` were set to "61". Parameters `minAngle` and `maxAngle` were selected to limit the beam of the sensor to an area including the outer wall and inner wall used to mark the lateral boundary offset. Parameters `rayCount` and `rangeCount` were selected based on an angular resolution of 1^{o}. The simulation configuration was otherwise identical to Trial 3.

- Trial 6

The SICK LMS 291 LIDAR model was relocated at the front left corner of the roof of the representative challenge vehicle model with a rotation of -20^{o} around the x-axis, 2^{o} around the y-axis, and -10^{o} around the z-axis so the beam of the sensor swept a diagonal plane across the path of travel of the model. These values were determined experimentally by making changes to the world file, loading the simulation, and observing the result. See Figures 15 and 16.

Parameter `minAngle` was set to "-10", parameter `maxAngle` was set to "45", and parameters `rayCount` and `rangeCount` were set to "56". Parameters `minAngle` and `maxAngle` were selected to limit the beam of the sensor to an area including the outer wall used to mark the lateral boundary offset to slightly greater than horizontal at right extent. Parameters `rayCount` and `rangeCount` were selected based on an angular resolution of 1°.

Table II. Results of the evaluation of the use of LIDAR.

Trial number	Number of range returns	Number of rays	Quality	Maximum range[a] (m)	Minimum range[b] (m)
1	33	36	0.917	20.5	14.6
2	65	71	0.915	20.5	14.6
3	150	181	0.829	24.0	4.1
4	104	91	1.143	24.0	6.1
5	88	61	1.443	24.0	8.3
6	19	56	0.339	29.6	17.6

Notes:

[a] Maximum range when the tower obstacle was first detected.

[b] Minimum range when the tower obstacle was last detected.

An immediate reduction in the ratio of simulation time to real time from approximately 0.4 for the previous evaluation to 0.2 during this evaluation was observed. Although Gazebo documentation stated: "Reducing the number of rays is a good way to save CPU cycles (at the expense of simulation fidelity).", the author did not find this to be the case. Through the trials documented above, changing the number of rays had little observable effect on the ratio of simulation time to real time. The author also observed no effect when initially reducing the update rate of the steering and laser controllers from 50 Hz to 20 Hz. The author concluded it was possible some other factor resulted in the reduction, such as frequent filesystem access caused by logging data.

VIII.E. Conclusions

With the vertical or diagonal configurations it was immediately obvious through visual analysis alone that the ability to detect obstacles in the path of travel was compromised, creating a "blind spot" or spots, and that the maximum range at which an obstacle would be detected in the path of the representative challenge vehicle model was greatly reduced. The data reflect this. Of the three configurations tested:

- The vertically-aligned LIDAR configurations produced fewer range returns than every horizontally-aligned LIDAR configuration, even when the scan was completed with twice the angular resolution. The diagonally-aligned LIDAR configuration produced the fewest range returns of any of the three configurations.
- The maximum range when the tower was first detected for the vertically-aligned LIDAR configurations was the least. The maximum range for the diagonally-aligned LIDAR configurations was the greatest. The horizontally-aligned LIDAR configurations detected the tower near the maximum range possible, considering the angle of the sensor was selected to ensure obstacle detection at the maximum range at which the sensor completely crossed the path of travel.

- The minimum range when the tower was last detected was greatest for the diagonally-aligned LIDAR configuration, and slightly less for the vertically-aligned LIDAR configurations. The minimum range when the tower was last detected was least for the horizontally-aligned LIDAR configurations.
- The quality of tested configurations was a maximum for Test 05. This test represented a horizontally-aligned LIDAR sensor with a down angle of 5º, able to detect obstacles with the area including the outer wall and inner wall used to mark the lateral boundary offset, or the entire possible path of travel of the representative challenge vehicle model. This configuration was the most popular LIDAR configuration in use by teams which participated in the 2004 or 2005 GCE.

As a result, the author concluded Player and Gazebo could be used to evaluate LIDAR sensor configurations successfully, allowing a team to very quickly reduce the number of possible configurations to those which best utilize existing computing resources, and to visualize the interaction of the challenge vehicle with the environment.

However, it is easy to misinterpret the results of this evaluation. Several teams reported a greater number of LIDAR sensors were in use oriented so they intersected the ground at different distances from the challenge vehicle, or in fixed horizontal or vertical planes. For example:

- Four SICK LIDAR sensors were in use by Team 2005-18 which were pointed “horizontally”, 3 m, 20 m, and 35 m away.

- Two “nearly horizontal” and three “vertically oriented” unknown SICK LIDAR sensors were in use by Team 2005-05.

By using vertically-aligned LIDAR sensors, Team 2005-06 was able to gain a competitive advantage over other teams, such as Team 2005-18, which reported multiple LIDAR sensors were in use which intersected the ground at different distances from the challenge vehicle. Vertically-aligned LIDAR sensors, by scanning a vertical plane, returned range readings to the maximum effective range of the LIDAR sensors in a horizontal plane despite the attitude of the vehicle, i.e., whether the vehicle was traveling downhill or uphill.

In addition, by using an oscillating mount, Team 2005-06 was able to use two vertically-aligned LIDAR sensors to detect obstacles directly in front of the vehicle and eliminate the field-of-view limitations consistent with fixed-mount vertically-aligned LIDAR sensors noted by Team 2005-05. In reference to the vertically-aligned LIDAR sensors in use by the team, Team 2005-05 stated: “The disadvantage, of course, is that since each ladar looks in only a single azimuthal direction, instantaneous azimuthal coverage is poor and obstacles between the vertical ladar scan planes will be missed.” ([48], p. 6).

Team 2005-06 reported the maximum effective range for the unknown SICK LIDAR sensors in use by the team was “approximately 40 to 50 m” ([47], p. 516). As a result, Team 2005-06 was able to extend the maximum effective range of the LIDAR sensors in use by the team to twice the maximum effective range reported by Teams

2005-13, 2005-14, and 2005-16.

By using an oscillating mount, Team 2005-06 was able to reduce the number of sensors to the minimum necessary, while retaining some redundancy.

The author considers this a key distinguishing factor which differentiated Team 2005-06 from all other teams which participated in the 2004 QID or GCE or 2005 GCE, and which contributed to Team 2005-06 successfully completing the 2005 GCE.

The author did not attempt to simulate the oscillating mount in use by Team 2005-06 due to time constraints, but concluded it would be possible to simulate an oscillating mount using Player and Gazebo. The author identified “Experiment with different LIDAR configurations” as a future research opportunity based on the results of this evaluation, and proposes a greater number of fixed-mount, horizontally-aligned LIDAR sensors may, in fact, provide a less dense point map than fewer oscillating-mount, vertically- or diagonally-aligned LIDAR sensors. See paragraph XI.I.