# Stationary LIDAR Sensors for Indoor Quadcopter Localization

Marcell Rausch, Gabor Feher
Department of Telecommunication and Media Informatics
Budapest University of Technology and Economics, Budapest, Hungary

***Abstract*—Mobile robots need autonomous navigation, which cannot be fulfilled without proper localization. Today, there are various techniques for map creation and localization. However, most of them are not adequate for smaller devices, like quadcopters. In this paper, lightweight, small, and efficient stationary lidar sensors are proposed for localization. Through measurements and simulations, different sensor setups are investigated in the view of map creation quality and localization accuracy. Finally, the optimal sensor setup is presented with a minimal set of sensors, while the performance is still adequate.**

## I. INTRODUCTION

A prerequisite for future expansion of mobile robots is the ability to navigate autonomously and safely in their ever-changing environment without collisions. Simultaneous Localization And Mapping (SLAM) algorithms discover the surroundings, create a map, and localize the robot in the map with the help of ranging or visual sensors. In an indoor scenario, this sensor is often the Light Detection and Ranging (LIDAR) sensor.

Many papers can be found about SLAM and LIDAR sensors capable of building highly accurate maps of building-interiors or even outdoors [1] [2] [3]. However, they are using precise, long range rotating planner scanners, which can be carried by large an industrial-grade hexacopter or octocopter only, and due to their weight, they are not suitable for smaller quadcopters. Another frequent choice for drones is multiple cameras and image processing. The issue here is the rather intense computation demand, which is hard to satisfy on a small quadcopter with limited power supply.

In this paper, the evaluation of a SLAM system is introduced that uses stationary VL53L1X LIDAR sensors to scan the drone's environment and uses Cartographer SLAM to construct maps. This solution might provide lightweight, cheap, and computationally light alternative to currently used planar scanners.

Each setup is evaluated based on data collected from Gazebo simulator [4], and LIDAR sensors are simulated with parameters determined by measurements with VL53L1X sensors. On the collected data, multiple sensors layouts and settings were evaluated to find the optimal number of sensors and achieve a balance between accuracy and simplicity.

## II. RANGING SENSOR-BASED SLAM

Cameras are cheap, popular but they demand high processing capabilities. In contrast, ranging sensor-based approaches produce a lower amount of data and thus, they are less resource-intensive. Ultrasonic sensors have been used for distance measurements for many years, but they suffer from significant measurement noise. LIDAR sensors, on the other hand, use light to measure distance, offer more accurate measurements, typically lower form factor, higher resolution, and update rates. Planar scanners for 2D or 3D scanning typically use a rotating LIDAR sensor that makes evenly distributed measurements.

Stationary LIDAR sensor-based modules can be found for collision avoidance. TeraBee offers an off-the-shelf system with 8 selectable LIDAR sensors. The company offers long-range and fast-ranging versions, that can range up to 60m or 600Hz.

Bitcraze has developed a Multi-ranger deck for their mini drone that weighs only 27g. This deck carries 5 VL53L1X lidar sensors, 4 horizontally, and 1 vertically. The company website has a SLAM demo but provided no information of the SLAM algorithm in use.

## III. THE VL53L1X LIDAR SENSOR

VL53L1X is described as a long-distance ranging Time-of-Flight sensor by STMicroelectronics [5]. The size of the module is 4.9x2.5x1.56mm, it emits 940nm invisible laser and uses a single-photon avalanche diode (SPAD) receiving array with a field-of-view(FOV) of 27 degrees. The module runs all the digital signal processing on a built-in low power microcontroller that frees up the host processor from these tasks. According to the datasheet, the sensor is capable of 50Hz ranging frequency and up to 400cm distance measurements. The size of the laser receiving array can be programmatically changed by setting the region-of-interest(ROI) size.

The most relevant settings of the sensor are the timing budget, distance preset, and the resolution. The timing budget sets the maximum time available for the sensor to complete ranging. It can be adjusted between 18.5ms to 1s. Distance preset sets the expected range distance, and by moving the ROI across the whole field-of-view, higher scan resolution can be achieved. Using this method, the resolution can be extended to 4x4 without overlapping segments.

To simulate the VL53L1X sensor accurately, a series of measurements were conducted on distances from 0.5m to 4m in 0.5m steps with selected sensor settings. On each distance, the average measured distance, standard deviation, sampling rate, and typical range status were measured with the selected settings. Measurements were done with sensor resolutions 1x1,

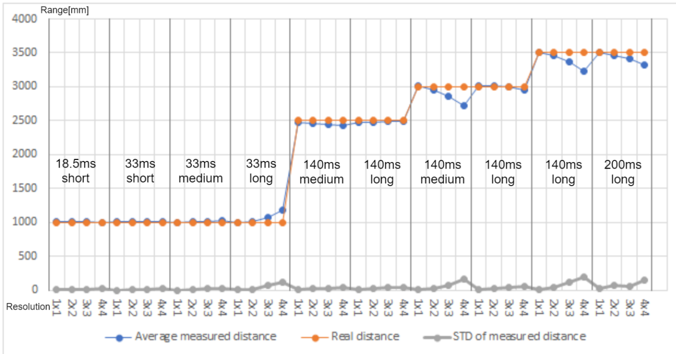


Fig. 1. VL53L1X measurements.

2x2, 3x3, 4x4, and all distance presets: short, medium, long. It is unnecessary to test the sensor with all possible timing budget values, so 4 values have been selected. 18.5 ms provides the highest sampling rate of 50Hz, but can only be used with short-distance preset. 33ms is the lowest timing that can be used with long-distance preset. Based on the datasheet, 140ms is the lowest budget that can provide ranges up to 400cm, and lastly, 200ms is expected to provide less noisy measurements. The last three values are also used in the VL53L1X datasheet[5] to demonstrate ranging accuracy.

Based on the completed measurements, it can be seen that sampling time is independent of the distance preset and is directly proportional to the resolution and the timing budget. In each tested scenario, the most accurate measurements were always with resolution 1x1. By increasing the resolution, therefore lowering the receiver SPAD array size, the measured distance starts to deviate from the real distance, and standard deviation increases. This can be seen at 2.5m distance with medium preset. Long-distance preset, however produces more accurate measurements even on 3m, so it is preferred over medium preset. Measurements with long-distance preset and 140ms timing budget follow the real distances even on 3 meters but start to deviate at 3.5 meters with 2x2-resolution and above. Raising the timing budget to 200ms reduces the error and standard deviation, but the error is still significant.

18.5ms timing budget with short distance preset can produce the fastest ranging measurements up to 1.6m according to the datasheet. The short preset also has the best ambient light immunity, a favorable quality. Surprisingly, in the tests, the sensor with these settings was able to measure up to 2m with only 7mm standard deviation only. Above 2m no ranges were successful. Compared to other presets, the sampling time for each resolution decreased significantly. In the case of 4x4-resolution, the sampling time has decreased from 390ms to 265ms, and the maximum distance decreased from 2.5m to about 1m. The increase in the update rate might be beneficial for the SLAM algorithm.

## IV. 2D SLAM EVALUATION

To be able to compare the performance of the SLAM algorithm with each sensor setup, the same dataset is used. The collected data contains LIDAR measurements of the surroundings of the vehicle in 3D. In the Gazebo simulator, LIDAR scanners are placed on the top and bottom of the quadcopter to evenly scan the top- and bottom hemispheres. The drone was flown around inside a simulated building, that was designed to have rooms that only have distances under the maximum distance of the ranging sensor and bigger rooms so that ranges some scans can be saturated. The building contains no furniture but has doors and windows. All sensor and control messages are recorded. The LIDAR measurements update at 30Hz, while IMU is published at 50Hz.

The recorded data is filtered to simulate the VL53L1X sensors in a specific layout, all with the same settings. Sensor parameters are determined using the measurements with the actual sensor. These simulation parameters are the sampling rate and maximum distance.

The filtered data is played back for Cartographer SLAM, that is tuned to have the best possible performance with the current setup. Tuning requires a good understanding of the parameters, and the procedure is unique for each setup. At first, the algorithm is tuned to build stable and consistent submaps, then for global SLAM and loop closures.

To have an absolute measure besides visual inspection, the RMS error is calculated of the SLAM trajectory of each setup. The ground-truth trajectory is provided by Gazebo.

The LIDAR parameters are introduced incrementally, starting from unfiltered range data, that is expected to result in the best possible map and trajectory using this dataset. Sensor resolution, sampling rate and maximum distance limit are introduced after each other to see their effects individually. 13 sensors are used in even layout on the horizontal plane for the evaluation process. Finally, the number of sensors is reduced until the SLAM algorithm is still capable of consistent and reliable mapping.

### A. *Effects of LIDAR resolution*

First, unfiltered data ranges with maximum rate and distance were used, without additional noise. Even without global SLAM, a decent quality map could be built. The extracted trajectory closely followed the ground-truth trajectory. The RMS error on the x- was 6.3cm and a bit less 6.5cm on the y-axis, resulting in a cumulated 9.05cm RMS error. The lowered resolution introduces an artifact, that is referred to as transition point. These points appear when the ROI is partly covered by a close object and the rest is by a far object, so the reported distance is in between the two obstacles. For example, this causes corners to be curved on lower resolutions.

4x4 and 3x3 resolutions provide a high number of points per scan, which makes scan matching more effective. Mapping accuracy and map building reliability are decent for both cases, but 3x3 produced slightly lower RMS error. This might be because of more efficient tuning.

2x2 and 1x1 resolutions have significantly fewer points per scan that makes tuning of Cartographer significantly harder. 1x1 proved to be unreliable, and the algorithm was unable to

TABLE I
RMS ERROR OF DIFFERENT RESOLUTIONS

| | 4x4 | 3x3 | 2x2 | 1x1 |
|---|---|---|---|---|
| x [cm] | 8.12 | 4.04 | 7.95 | - |
| y [cm] | 10.48 | 7.3 | 14.17 | - |
| sum [cm] | 13.26 | 8.34 | 16.25 | - |

match scans to build submaps. The map built using 2x2 resolution resulted in curved corners and blurry edges. Lowered grid resolution resulted in higher accuracy and stability.

### B. *Effects of sampling rate*

For the 4x4-resolution 400ms sampling time was chosen, based on the real sensor measurements. The dropped sampling rate from 30Hz to 2.5Hz was significant and made the tuning much harder. Two different grid resolutions were tested as well. The quality of the map was decent in both cases, and no major flaws were visible. The global SLAM had to compensate rotation drifts, that occurred when the drone quickly turned around in the big room, where some ranges became saturated. Low grid resolution produced a smoother path, while on the high-resolution grid, there were jumps and sharper turns.

The cumulated RMS error on a high grid resolution was 16.49cm. On low grid resolution, it was higher: 18.95cm. Higher grid-resolution results in greater accuracy in position estimates, but its stability is lower in comparison to a lower resolution.

As for the 3x3-resolution, the same sensor settings were chosen, but this setup has a better sampling time of 220ms compared to the previous 400ms. This results in an 80% increase in update rate to 4.5Hz, which also means almost twice more often pose updates. Lowering the grid resolution was necessary here as well. The map quality was adequate, and global SLAM almost has not done any corrections. The cumulated RMS error was 10.4cm, 6.4cm on the x-axis, and 8.2 on the y-axis. Because of stability and accuracy, 3x3-resolution seems like a better resolution for Cartographer SLAM.

### C. *Effects of maximum distance*

The VL53L1X sensor measurements showed that each setup works accurately until 2.5m and each has about 25cm drift at a distance of 3m, so 2.75m as the maximum distance was chosen for the tests. The lowered maximum distance had a positive effect that the number of transition points has been reduced because on the shorter distance, the field of view could not open as wide as it could before. The downside of the limited range is that the algorithm loses track in the open spaces. This caused more flaws, and a small tilt can be observed in the map. The trajectory using sensors with 3x3-resolution has a significant offset on the y-axis, which was picked up due to the reduced reference points. Similar scans were pulled together, resulting for example in a shortened corridor. The trajectory using 4x4-resolution sensors has a smaller offset. It seems like with more points per scan, the SLAM algorithm was able to pick up small details and better track the movement of the drone even on a mostly even corridor. On the other hand, it failed in a big room with significantly greater distances than 2.75m.

The cumulated RMS error for 3x3-resolution is 38.16cm and 35.12cm for 4x4. This also showed that a mostly constant offset with otherwise correct shape results in a smaller error, than the pose estimation that follows ground-truth closely but failed in shape at a relatively small area.

### D. *Reduced set of evenly distributed LIDAR sensors*

In this test, the goal was to find the minimum number of LIDAR sensors, with which the SLAM algorithm still works reliably and can produce a coherent map. The sensors were set to 4x4 and 3x3-resolution, 400ms update rate, and 2.75m as maximum distance. The tuning of the algorithm proved to be significantly harder this time. 8 sensors proved to be the lowest, using 7 already caused the submaps to fall apart. The RMS cumulated error was 34.1cm for 4x4, while mapping has failed using 3x3-resolution.

## V. CONCLUSION

Indoor quadcopters require lightweight localization systems for navigation. An option for this task could be the application of stationary LIDAR sensors. The performance evaluation presented in this paper has shown that it is possible indeed to perform adequate localization using such sensors. In addition to the measurement and simulation analysis of different sensor setups, an optimal sensor configuration was presented. In this setup, there should be 8 stationary LIDAR sensors, as fewer sensors make the localization to fail.

## REFERENCES

[1] J. Engel, T. Schöps, and D. Cremers, “Lsd-slam: Large-scale direct monocular slam,” in *European conference on computer vision*. Springer, 2014, pp. 834–849.

[2] R. Mur-Artal, J. M. M. Montiel, and J. D. Tardos, “Orb-slam: a versatile and accurate monocular slam system,” *IEEE transactions on robotics*, vol. 31, no. 5, pp. 1147–1163, 2015.

[3] J. Engel, J. Stückler, and D. Cremers, “Large-scale direct slam with stereo cameras,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 1935–1942.

[4] G. Simulator, “Website,” www.gazebosim.org, accessed: 2019-11-28.

[5] VL53L1X, “Datasheet,” www.st.com/resource/en/datasheet/vl53l1x.pdf, accessed: 2019-11-30.