Improving the Streaming Image Quality with LiDAR*

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Abstract

LiDARs, which scan the space and measure the distance to each point, do not always produce the required quality images. Therefore, the image quality improvement is ruther actual. The aim of this work is to develop a method for the image quality LiDAR generated improvement. The paper describes a study using an Intel RealSense L515 LiDAR, Intel RealSense Viewer v.2.53.1.

When a surface is scanned by a LiDAR, the part of it that is placed between two consecutive pixels is not displayed, which can lead to a deterioration in image quality and detail loss. A method of improving the image quality is proposed, which consists in moving (horizontal rotation) of the LiDAR camera around the axis or optical center, which will give the possibility to scan the areas between two consecutive pixels. An algorithm for the practical implementation of the method has been developed, consisting of two interrelated parts, the first controlling the LiDAR operation, and the second - the software that generates the surface image. The suggested method will enable us to obtain better quality images. In the case of a video stream, this increase in resolution will lead to a decrease in frame rate. This method implementation possibility has been confirmed by the experimental study results.

Keywords

LiDAR, image quality, streaming image, scanning

1. Introduction

LiDARs are widely used for scanning space and forming its three-dimensional image in various human activity fields. LiDARs are also used to create digital terrain models. Their use is especially relevant for area and environments mapping that change over time, including beaches and dunes [1], river and sea coastlines [2], the forest structure and spatial transformation, agricultural and urban ecosystems [3], changes in road conditions for self-driving vehicles [4], archaeological research [5], territory mapping [6], snow depth measurements [10], etc. In most previously mentioned works and other sources, considerable attention is paid to the accuracy of the image obtained, in particular, the distance to the scanning surface points [6]. Modern LiDARs have undergone a number of improvements as a result of scientific and technological progress and are now widely used for precision measurements in various systems: mapping, autonomous navigation, vegetation analysis, emergency management, and military support [22].

Many tasks that are solved with the LiDAR help require not only accurate distance measurement but also high-quality images (to the nearest centimeter), in particular in real-time systems that work with surfaces with unequal reflectivity and obstacle presence [7]. In general, in the odometry process, the image formation and analysis speed does not provide an opportunity for the image quality increase. In such cases, two algorithms are used simultaneously: low accuracy and high frequency for motion estimation, and high accuracy but an order of magnitude lower frequency for generating a high-quality image [8]. To improve the quality in the concurrent localization and mapping process, a method proposed [11], is based on effective local mapping and

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hierarchical optimization. 3D laser scanner measurements are aggregated into local maps at different resolutions by surface-based registration applying graph theory. Practical LiDAR implementation requires not only image improvement but also evaluation of the last. A number of works are devoted to this problem. In particular, [18] reviewed the relevant technologies, provided a formula for image quality assessment and proposed methods for their improvement. In [19], a strategy is presented, aimed to optimize such images using iterations and statistical methods. In [20], the image intensity correction was performed by adjusting the geometric parameters of the scan with a single-beam or multi-beam LiDAR. Evaluation was conducted via geometric/morphological and profound/portable teaching methods with intensity correction/normalization. These and similar image evaluation and enhancement methods are complex, not always effective in implementation, and require powerful computing resources.

In some cases, the LiDARs images are combined with other spatial data: traffic density maps [9], which help to perform a deeper analysis of the image and increase the laser scanning method functionality. There is a concurrent localization complexity as well as a display in the process of autonomous navigation and positioning of unmanned systems that use multisensory fusion [12, 23]. The effectiveness of this type of localization and mapping systems depends on the algorithms used for navigation and fusion.

The problem of processing streaming video images is relevant not only for LiDARs, but also for optical devices operating in conditions of low visibility. In [25] a neural network was used to analyze moving objects in a video stream.

The principles and technologies of LiDARs practical application are described in detail in [13]. LiDARs for automatic vehicle control systems, their structure and functioning are described in [14]. To carry out topographic work, LiDARs are placed on board aircraft, including unmanned ones. Appropriate technologies for their application are given in [15]. In addition to traditional LiDARs, single-photon LiDARs have become widespread, which send only one pulse to the object and measure the individual photons flight time [16].

The structure of modern LiDARs is based on a variety of principles. These are usually four image scanning mechanisms [21]: optical-mechanical, electromechanical, micro-electromechanical systems (MEMS) and solid-state scanning systems. Electromechanical scanning is the most common, but MEMS is a more advanced technology than other existing ones. Solid-state scanning has prospects for development, since it has high reliability, a large field of vision and scanning speed, but today it is technologically difficult to manufacture.

Improving the LiDAR image quality can be achieved not only by mathematical methods and algorithms. This problem successful solution example based on physical principles is given in [24]. Based on the Schaempflug method LiDAR, scans at an angle with correction, increasing the clarity of the entire image. In general, the quality of the LiDAR in practice should be at a high level, and its improvement is an urgent scientific and technical task.

2. Proposed methodology

The aim of the work is to develop a method for improving the image quality obtained by the LiDAR.

The method is based on mechanical movement of the camera at a small angle, which allows scanning the space between neighboring pixels and detecting image details.

Experimental studies using Intel RealSense L515 LiDAR [17], and Intel RealSense Viewer v.2.53.1 software have confirmed the possibility of its implementation.

A step-by-step algorithm for implementing the proposed method has been developed, the probably issues of its implementation and ways to solve them have been analyzed.

3. LiDAR formed image quality

Digital images formed by various devices, including LiDARs, must be of appropriate quality for practical usage, dictated by relevant requirements. Image quality indicators include the resolution – the number of pixels horizontally and vertically – as well as the color sampling range of each pixel in bits. However, to achieve high-quality images, it is necessary to ensure the correct properties reproduction of the real object being depicted. The image quality generated by optical devices can be influenced by the lens optical properties. In the case of a LiDAR, the quality of the raw image is determined by the scanning mechanisms precision and distance measurements.

3.1. LiDAR image formation and its improvement

This section examines how Intel RealSense L515 LiDAR creates images, designed for indoor environments at short ranges. The LiDAR scans a space section enclosed by pyramid sides, presenting the distance field as a pixel frame. Micro-electromechanical systems (MEMS) technology controls the laser beam, which operates in pulsed mode. Scanning begins along the top horizontal line, then the beam descends to the next line, continuing the process down to the lowest line. The laser beam is focused sufficiently and forms a narrow solid angle (Figure 1). Reflected light from the laser-illuminated surface reaches the photodiode, enabling measurement of the distance to the area, and that distance is shown in the pixel, possibly through a certain colour. However, between neighboring laser-illuminated sections on the surface within the field, some sections remain unlit by the laser. As distance increases, the size of these unlit sections grows, leading to a loss in detecting small objects or parts, especially at longer distances, which reduces clarity and image quality.

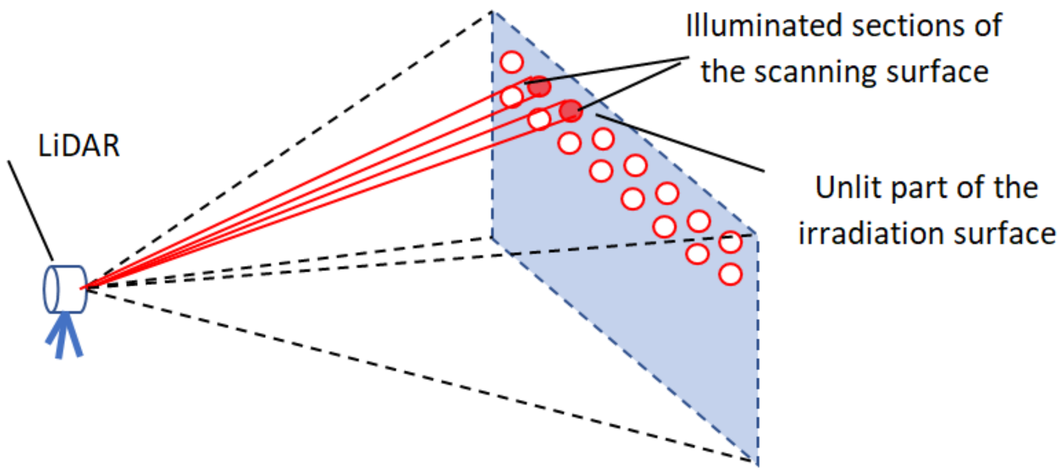

Figure 1: LiDAR space scanning.

It should be noted separately that improving the video image quality is more complex and involves not only processing a single frame but also that of a consecutive frame series.

In LiDAR, reduced clarity and image quality may result from low rate reflectivity on the illuminated surface and the detail presence between neighboring pixels. The first issue is tied to the physical properties of the surface and is therefore almost impossible to resolve. Only in specific cases, when low reflectivity rate arises not from material properties but from a large angle between the laser beam and the surface normal, it can be increased by changing the beam incidence angle. The second issue of reduced clarity, caused by insufficient resolution or distance measurement error, can be solved using methods similar to image enhancement techniques, such as software-based resolution enhancement through interpolation methods. It’s important to remember that each pixel corresponds not to colour, but to distance. However, as with conventional images, this method does not always accurately render intermediate details.

3.2. Software image quality improvement

Existing images can be software enhanced. The corresponding methods of digital image quality improvement are known and widely used in various fields related to image processing. Such methods are implemented by various algorithms that analyze the image and edit it. However, errors may occur while algorithm execution, which leads to certain image incorrect detailing. Note that in the LiDAR image enhancement case, the distances are actually refined. In this regard, the principles and approaches of images created by a LiDAR improvement differ significantly from those used to work with images captured by optical cameras. The cameras of this kind can cause the certain image fragments clarity loss since they go beyond the depth of field or due to insufficient resolution or sensitivity to the photosensitive matrix available light.

3.3. Software and hardware image quality enhancement

Enhanced quality can be achieved by compacting the beams during the scanning process. However, this method requires appropriate structural changes in the LiDAR. It is a challenging method when we use a ready-made device, given the maximum scanning density that has probably already been achieved by the developers. Therefore, if a certain LiDAR type is available and it is impossible to make changes to its structure, the image quality can be improved, without taking into account traditional software methods, by additional space scanning that is located between consecutive points that are irradiated by laser beams and for which distances are measured. This scanning should be done without interfering with the internal LiDAR structure.

Based on these considerations, we propose a method that, unlike the existing ones can solve the second problem and partially the first described above. The main point of this method is to mechanically move (rotate around the axis or optical centre) the LiDAR to the appropriate angle in order to scan the surface unlit parts, and then to process (compensate) the corresponding movement programmatically.

Experimental studies have been conducted in order to verify the method's feasibility in practice. In the absence of a LiDAR rotation mechanism, the LiDAR was placed on a horizontal surface in a motionless state, and the objects to be observed were moved.

The objects displayed by the LiDAR were a cylinder and a rectangular parallelepiped (Table 1).

Table 1
Size of objects

Number	Object	Height, mm	Diameter (width), mm
1	Cylinder	170	7
2	Rectangular parallelepiped	51	12
3	Rectangular parallelepiped	51	35

The objects were placed vertically (Figure 2).

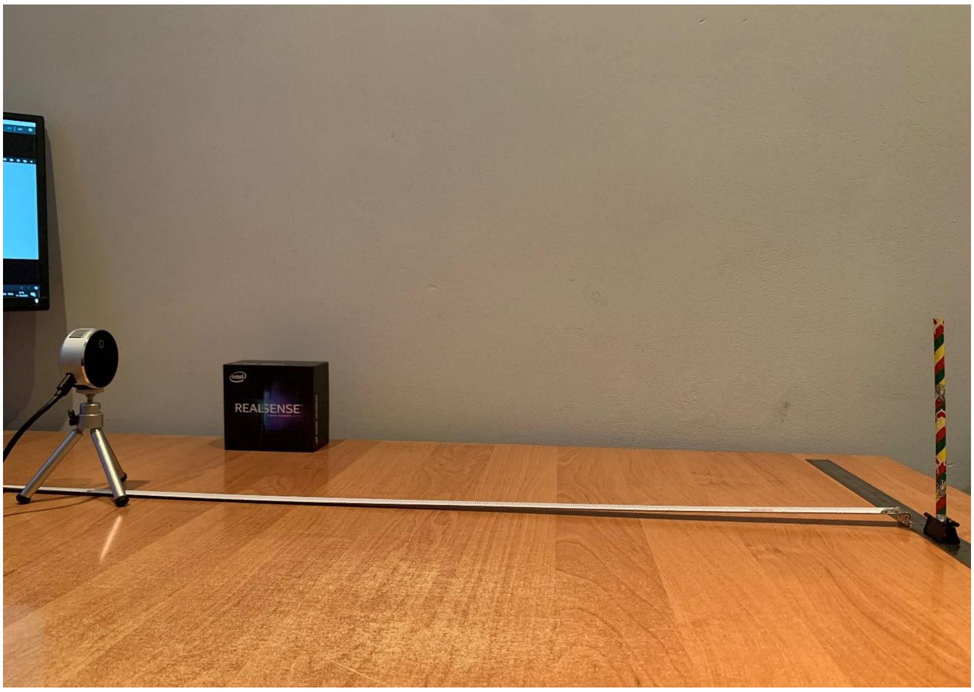

Figure 2: Experimental study of LiDAR image sensitivity and quality improvement.

The images were analysed by moving the objects horizontally along the surface (Figure 3).

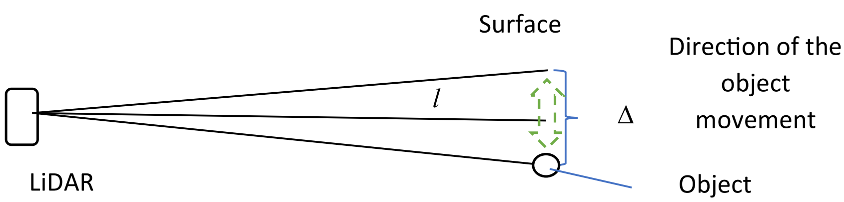

Figure 3: Experimental study of sensitivity and image quality improvement from LIiDAR (top view scheme).

The maximum distances to the objects l_i, i=1, 2, 3 were experimentally determined, so they are detected by the LiDAR (Table 2).

When objects have been moving in a direction perpendicular to the LiDAR direction, they appeared and disappeared in the image sequentially. To more accurately determine the required displacement dimensions at which the objects disappeared and reappeared, we moved to a distance where the objects image disappeared and reappeared 10 times, and divided the resulting distance by 10. The values of the shifts Δ_i were obtained (Table 2). Using the trigonometric formula

$$\sin\frac{\alpha_i}{2}=\frac{\Delta_i}{2l_i}, \tag{1}$$

where l_i – is the distance to the surface along which object i moved, α_i – is the smallest angle of movement during which the object disappeared and reappeared, and Δ_i – is the length of movement, we obtained the angles for the objects. The results are shown in Table 2.

Table 2
Results obtained from experimental studies of sensitivity and image quality improvement from LiDAR

Number	The maximum distance l, mm	The smallest displacement value Δ, mm	The smallest angle of movement α_i, degrees
1	700 ± 5	3 ± 0.5	0.245
2	1100 ± 5	5 ± 0.5	0.260
3	2250 ± 5	10 ± 0.5	0.254

The conducted studies show the relevance of the proposed method of LiDAR image enhancement.

3.4. The method and the algorithm of LiDAR image enhancement

We propose the method for improving image quality and the algorithm for its implementation. This algorithm describes one of the possible variants of the method implementation in practice. To preserve the generality of the method, it is assumed that the distance to each point on the surface scanned by the LiDAR deviates slightly from the average value.

The distance matrix for frame p is

$$L^p = \begin{pmatrix} l_{11}^p & l_{1n}^p \\ l_{m1}^p & l_{mn}^p \end{pmatrix} \tag{2}$$

where l_{ij}^p is a distance from LiDAR to the inlit area on the surface corresponding the pixel in the column i and the row j. Depending on the distance to the surface, there is an interval between two adjacent inlit areas that can contain one or more areas whose dimensions are equal to the area irradiated by one pixel. The obtained capacity $r, r \in \mathbb{N}$ of the unirradiated interval determines the multiplicity $k = r + 1$, which will be the angular division factor. By turning the camera left (right) k times on an angle $\frac{\varphi}{k}$ where φ is the angle between two adjacent beams, we measure the distances and record them into a matrix $D = (d_{qj})$ of size $(kn + 1) \times m$, which we obtain by the formulas:

$$d_{1,j} = l_{1,j}^p, \tag{3}$$

$$d_{qj} = l_{ij}^{\tilde{p}}, \tag{4}$$

where $q = k(i-1) + s + 1, \tilde{p} = p + s, 1 \leqslant i \leqslant n, 1 \leqslant s \leqslant k, 1 \leqslant j \leqslant m, s \in \mathbb{N}$. The obtained matrix D described the high quality image frame. Next, we renumber the elements of the matrix D in reverse order by q, take $p + k$ instead of p, and using formulas (3), (4) we construct the next frame of a high-quality image.

The algorithm for implementing the proposed method consists of two interrelated parts that operate in parallel. The first part concerns the LiDAR's function and its movement (rotation), while the second describes the high-quality image frame and its display on the screen:

I. Image formation by the LiDAR

1. As the beam moves within the pyramid field of view, the first frame of the image with a resolution of $n \times m$ pixels is obtained.
2. The average distance to the surface, the inlit areas at this distance diameter, and the distance between adjacent surfaces are determined, the angular division factor k is then calculated.
3. The next rotation direction (left or right) is selected.
4. The camera in the selected direction by an angle such that the angle between consecutive beams is a multiple of k is rotated, inabling it to illuminate the nearest part of the surface that wasn't inlit in the previous frame.
5. After the beam scans the LiDAR's field of view, the next frame is obtained.
6. We continue performing steps 2 and 3 until the newly obtained frame shifts by 1 pixel in the selected direction compared to the first frame.
7. The camera's movement direction is chaneged, the last frame is designated as the first, and than returned to step 2.

II. Image construction and display I. Image formation by the LiDAR

1. In the image processing software, a matrix of $(kn + 1) \times m$ size is formed.
2. The shift's direction (right or left, opposite to the initial rotation direction) is chosen and a base column (first on the left or right, depending on the shift direction) is set.
3. Using the LiDAR's first frame data, the matrix columns values are set starting with the base column, and each subsequent column with frame data is assigned into the matrix with an offset of $k - 1$ columns.
4. In the matrix, one column is moved in the shift direction and taken as the base column.
5. The next frame is taken as the current one.
6. Using data from the current LiDAR frame, the values of the columns in the matrix are set, starting from the current base, skipping $k - 1$ columns for each successive column.
7. Steps 4, 5, and 6 are continued until the final column in the matrix is filled.
8. The generated image on the screen is displayed based on the matrix data.
9. The direction is changed to the opposite, the last frame is considered to be the current frame, the last column is considered to be the base. After this one may go to step 4.

Thus, continuous LiDAR surface scanning will enhance the resulting image quality.

3.5. Discussion

The result of this method will be an image that will have a horizontal size of $kn + 1$ pixels. This will give the possibility to achive greater clarity. However, due to the use of $k + 1$ frames to build one frame of the enhanced image, this will lead to a lower frame rate and slower video. With a small multiplicity ($k = 2, 3$), there will be no special problems. With greater k values, this disadvantage can be compensated by the fact that in parallel with the formation of high-quality images, raw frames directly formed by the LiDAR can be additionally viewed. In the case of this view, another problem arises – the constant movement from left to right. Its solution can be achieved by software image stabilization, making a synchronous shift in the opposite direction and limiting the frame size on the left and right.

The proposed method can also be used to improve the quality and increase the vertical size of the image. In this case, the camera should be rotated around the horizontal axis that passes through the optical center. If there is a need to increase the image quality both horizontally and vertically, then the proposed method can be modified to obtain images of fragments with higher resolution both horizontally and vertically. In this case, the camera should be rotated in the horizontal and vertical directions so that the LiDAR beam would scan the corresponding unlit part of the surface sequentially. The number of consecutive frames required to create a high quality image will be significant, and therefore the real-time viewing will be difficult. However, for image analysis (object recognition), this quality improvement will be appropriate.

If the surface has a significant unevenness of heights, or if a part of the space is being scanned with objects located at different distances from the LiDAR, a problem may arise due to the fact that on the surfaces of objects located at close distances, a lower multiplicity should be selected compared to those located at a far distance. The solution to this problem can be in selecting the optimal multiplicity for both close and distant objects, or in selecting a fragment of an object at a certain distance and improving its quality by selecting the multiplicity k based on the average distance to it.

3.6. Conclusions

In order to improve the LiDAR image quality and display objects or fragments the size of which is smaller than the distance between two consecutive pixels at the corresponding distance from the LiDAR, a method is proposed that consists in turning the device from right to left by the angle between two consecutive rays in the rotation direction, scanning the space in the intermediate areas as well as performing a software generation of images with higher resolution in the direction of LiDAR rotation. The possibility of implementing such a method and displaying small objects that may not be included in the image formed by a fixed LiDAR has been proved by the experimental research. Possible problems that may arise when implementing the proposed method and ways to solve them are analyzed.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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