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Range image smoothing and completion utilizing laser intensity

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In this paper, we propose new denoising techniques for a deteriorated range image taken by a laser scanner. Laser scanner acquires a range value from the scanner to the target by measuring the round-trip time of the emitted laser pulse. At the same time, they can obtain the strength of the reflected light as a side product of the range value. Focusing on the laser intensity, we propose two denoising techniques for a deteriorated range image utilizing the intensity image: smoothing by extended bilateral filter, and completion by belief propagation. The extended bilateral filter makes use of laser intensity in addition to the spatial and range information in order that we can smooth a range image corrupted by noises while the geometric features such as jump and roof edges are preserved. The range image completion technique with belief propagation restores a deteriorated range image using the adjacent range values and the corresponding intensity values simultaneously. We conduct simulations and experiments using synthesized images and actual range images taken by a laser scanner and verify that the proposed techniques suppress noise while preserving jump and roof edges and repair deteriorated range images.

Keywords: laser scanner; range image; intensity image; extended bilateral filter; belief propagation

1. Introduction

In recent years, low-cost, real-time time-of-flight (RT-TOF) laser sensors have been released, including SwissRanger SR4100 (MESA Imaging AG), D-imager (Panasonic), and Canesta Vision (Canesta, Inc.).[1] These sensors capture range images of approximately 150–200 pixels by 150–200 pixels (20–40 thousand pixels) at 20–50 Hz and are applicable to various applications, such as robot navigation, vehicle control, and intuitive human interfaces. However, range data acquired by RT-TOF sensors contain large errors in distance measurement, and the spatial resolution is also insufficient compared with modern digital cameras.

On the other hand, high-precision three-dimensional (3D) laser scanners, such as RIEGL VZ-400 (RIEGL GmbH), Leica Scan Station 2 (Leica Geosystems AG), and TOPCON GLS-1500 (TOPCON) have been widely used for landscape surveying or digital 3D modeling. In addition, low-cost, high-resolution laser measurement systems using two-dimensional laser scanners (SICK LMS151 (SICK AG) and HOKUYO TOP-URG (HOKUYO)) and a rotary table have been proposed for 3D environmental map building for mobile robot navigation.[2] These LIDAR (light detection and ranging) sensors acquire high resolution and precise range images. However, range images often suffer from noise due to the reflectance property of objects’ surfaces or electrical and mechanical disturbances. For example, one sigma accuracy of RIEGL VZ-400 is 3 mm per 100 meters, thus, a flat surface is measured as a slightly uneven plate. Metal surface with a strong specular reflection or black color cannot be measured by standard laser scanners. Therefore, denoising techniques for range images taken by laser scanners still remain as a critical problem.

Several approaches can be used to denoise the range images captured by range sensors:

(1) Averaging a series of range images of the same scene (temporal smoothing).

(2) Applying spatial smoothing filters such as a Gaussian filter (spatial smoothing).[3–7]

(3) Combining range data with other information such as texture or brightness.[8–11]

Temporal smoothing is an intuitive and fundamental technique for denoising a range image and is widely used in high-precision laser scanners. However, this process must be performed for each measured point (pixel) during the measurement and the processing time is proportional to the number of images for averaging.

On the other hand, spatial smoothing can be applied off-line and is applicable to not only measured points but also structured meshes. In this technique, the range
values of adjacent points (pixels in a range image or vertices in structured meshes) are spatially convolved by applying a spatial convolution filter such as a median filter or a Gaussian filter.

In the present paper, we propose two denoising techniques which can be categorized into the third category mentioned above by focusing on the laser intensity.[12] When we measure range data by laser scanners, the intensity, which indicates the strength of the reflected light, can be obtained as a by-product of range data. Note that all pixels in the range image have corresponding intensity values. In other words, the range image and the intensity image are precisely and fundamentally aligned.

Using the intensity image, we first propose a new smoothing technique using the extended bilateral filter and intensity as a denoising technique of an image. In the proposed method, the extended bilateral filter is applied for not only the range image but also the corresponding intensity image. By taking account of the properties of range and intensity images, the proposed method can smooth range images, while preserving geometric features such as jump and roof edges. Adelsberger et al. [13] proposed a similar technique for low-resolution infrared TOF sensors (SwissRanger, MESA-Imaging). However, the detailed discussion for denoising performance has not been presented.

Next, we propose a new inpainting technique of a range image using an intensity image and belief propagation. In this method, the deteriorated range values in a range image are recovered using not only the adjacent range values but also the continuity of the intensity image.

In Section 2, an overview of the previous approaches will be presented. In Sections 3 and 4, we will propose two new denoising techniques for range images using intensity images, that is, range image smoothing by the extended bilateral filter and range image inpainting by belief propagation. In Section 5, simulations and experiments using a laser scanner will be reported for the purpose of verifying the performance of the proposed techniques.

2. Related research

Smoothing techniques for range images are classified into two categories: pixel-based or point-based techniques,[7,8,14,15,10,11] and mesh-based techniques. [4–6,9] Raw range data acquired by range sensors is composed of a group of 3D points called a point-cloud. Pixel or point-based methods denoise the range image or the point cloud directly without taking the continuity of pixels into account explicitly. On the other hand, mesh-based methods are applied to structured meshes such as triangular patches by considering the continuity of the vertexes in the structured meshes.

For the case in which a high-resolution gray-scale image and a low-resolution range image are simultaneously captured from a range sensor, Diebel et al. [8] proposed a technique for estimating high-resolution range images by considering the Markov Random Field in high- and low-resolution range images and adjusting smoothing parameters according to the gradient of the high-resolution gray-scale image. Crabb et al. [16] and Chan et al. [14] also proposed upsampling techniques using the joint bilateral filter.[17] Bohme et al. [9] proposed the denoising technique for a range image using the shape-from-shading technique.[18] They introduced an energy function consisting of the difference of the observed laser intensity and its estimation based on the Lambertian reflectance model and the continuity of the range image and intensity image. Then, the energy function is minimized by the nonlinear conjugate gradient method so that the noise in the range image is suppressed. Using the range information from a range scanner and the information of normal directions from photometric stereo, Nehab et al. [10] and Okatani et al. [11] proposed denoising techniques for reconstructing a 3D geometric model precisely. Nehab et al. [10] refines the bias in the measured normal direction at first, and then optimizes the 3D model so that the estimated normal direction fits the 3D model. Okatani et al. [11] estimates the shape of the object by integrating the surface normal and 3D data based on probabilistic framework.

On the other hand, several techniques based on the bilateral filter,[19] which was developed as an edge-preserving filter for gray-scale images, have been proposed.[5–7,20] Fleishman et al. [6] proposed a 3D edge-preserving filter by applying the bilateral filter for the distance from a point to its adjacent points projected on a tangential plane (tangential component) and the distance from the adjacent points to the tangential plane (normal component). Jones et al. [5] proposed a similar technique using triangular meshes instead of tangential planes. However, these smoothing techniques are applied after converting from the point cloud to the meshes and it is difficult to obtain the normal vectors stably from meshes that contain a great deal of noise. Moreover, in some cases, the construction of structured meshes from a noisy point cloud is not a simple and trivial problem.

Miropolsky [7] proposed the geometric bilateral filter which used the distances from the adjacent points and the difference of normal directions for each point in the point cloud. However, a stable solution of normal vectors from a noisy point cloud has not yet been found.

While these methods can be considered as a simple extension of the bilateral filter for a gray-scale image to a range image, the technique proposed herein uses a intensity image that corresponds one-to-one to the range image for smoothing the range image. Note that although we assume that the range and intensity images have the
3. Smoothing range image using the extended bilateral filter

In this section, we propose a new technique for smoothing a range image using the extended bilateral filter and an intensity image.

As mentioned above, the conventional smoothing techniques for range data are mainly applied for a range image directly. On the other hand, we focus on an intensity image that is acquired as a by-product of the range image for most of the range sensors. By taking the properties of both the range and intensity images into account, the proposed technique can suppress noise in a range image while preserving geometric features such as jump and roof edges.

In the following sections, we introduce the conventional bilateral filter and the intensity image captured by range sensors. The extended bilateral filter using intensity image is then described in detail.

3.1. Intensity image

Optical range sensors, such as a laser scanner, obtain range data by measuring the round-trip time of a laser pulse reflected by an object. Figure 2(a) shows an example of a range image acquired by a 3D laser scanner (Figure 1[2]). On the other hand, most optical range sensors can measure the strength of the reflected laser pulse (laser intensity).

Laser intensity value indicates an intensity on the surface point of the target under a single-frequency light source. Based on the dichromatic reflection model, the intensity value consists of a diffuse and specular reflection. Assuming that the specular component can be ignored and Lambertian reflection is used as a model for diffuse reflection, the intensity value is expressed as follows [9]:

\[
I = k_d \frac{I_g}{r^2 \cos \alpha}
\]

where \(k_d\) is the diffuse reflection coefficient, \(I_g\) is the power of the light source, \(r\) is the distance of the light source toward the target, and \(\alpha\) is the incident angle against the surface normal. Figure 2(b) shows an intensity image that depicts intensity values as a gray-scale image. As mentioned above, a unique intensity value is determined for each pixel in the range image. In other words, the range image and the intensity image are precisely and fundamentally aligned.

3.2. Extension of the bilateral filter to a range image

The bilateral filter [19] is an edge-preserving smoothing filter that extends the Gaussian filter so that not only the spatial relation but also the variation of the pixel intensity is considered. Let us apply the bilateral filter for a gray-scale image to a range image. The bilateral filter for a range image can be defined as follows:

\[
g_i = \frac{\sum_j w_i(x_i, x_j)w_f(f_i, f_j)f_j}{\sum_j w_i(x_i, x_j)w_f(f_i, f_j)}
\]

\[
w_i(x_i, x_j) = \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{|x_i - x_j|^2}{2\sigma_i^2}}
\]
where \( g_i \) and \( f_i \) are new and original range values at pixel \( i \), and \( w_x(x_i, x_j) \) and \( w_f(f_i, f_j) \) are Gaussian functions for two-dimensional spatial and range information with variances of \( \sigma_x^2 \) and \( \sigma_f^2 \), respectively.

### 3.3. Extended bilateral filter with an intensity image

The method mentioned above is a straightforward extension of the bilateral filter to a range image. However, as shown in Figure 2(a), although abrupt changes of range values such as a jump edge are easily detected in a range image, moderate changes such as a roof edge are quite difficult to detect. Miropolsky [7] introduced the directional variation of normal vectors in order to emphasize these moderate changes in the range image. However, if we observe the intensity image shown in Figure 2(b), it is easy to see that these moderate changes are clearly detected in the intensity image.

Based on the above consideration, we propose a new filter that uses intensity and range images simultaneously for smoothing a range image as follows:

\[
g_i = \frac{\sum_j w_x(x_i, x_j) w_f(f_i, f_j) w_d(d_i, d_j) f_i}{\sum_j w_x(x_i, x_j) w_f(f_i, f_j) w_d(d_i, d_j)}
\]  

\[
w_x(x_i, x_j) = \frac{1}{\sqrt{2\pi\sigma_x^2}} e^{-\frac{(x_i - x_j)^2}{2\sigma_x^2}}
\]  

\[
w_f(f_i, f_j) = \frac{1}{\sqrt{2\pi\sigma_f^2}} e^{-\frac{(f_i - f_j)^2}{2\sigma_f^2}}
\]  

\[
w_d(d_i, d_j) = \frac{1}{\sqrt{2\pi\sigma_d^2}} e^{-\frac{(d_i - d_j)^2}{2\sigma_d^2}}
\]
The filter given by Equation (5) takes into account three kinds of information in range and intensity images for smoothing a range image. In other words, it is an extension of the bilateral filter for images so that it takes the variation of the laser intensity into consideration for range image smoothing. Thanks to a variety of properties in range and intensity information, the proposed extended bilateral filter enables not only jump edges but also roof edges to be preserved in a range image, and the extended bilateral filter is expected to have higher performance for edge preservation than the simple expansion of the bilateral filter given by Equation (2).

Consequently, the proposed smoothing technique for a range image is summarized as follows.

1. Acquire range and intensity information by a TOF range sensor.

2. Create range and intensity images in which the values of each pixel in range and intensity images are proportional to the range and intensity values.

3. Apply the extended bilateral filter given by Equation (5) using range and intensity images and obtain a smoothed range image.

4. Construct a 3D model consisting of meshes from the smoothed range image.

4. Range image inpainting by belief propagation

In the previous section, we proposed a range image smoothing technique using the extended bilateral filter and intensity image. Although this method is effective for range images that are corrupted by noise, a deteriorated range image that is missing part of the original image due to specular reflection or weak reflectivity of the laser pulse is difficult to repair. For recovering a range image that is missing part of the original image, this section proposes an image inpainting technique using belief propagation and intensity image.

4.1. Loopy belief propagation

Let us consider a graph $P$ consisting of multiple nodes connected by multiple arcs. We assign label $f_p$ to node $p$ so that the following energy function is minimized.
where $D_p(f_p)$ is a cost term for assigning label $f_p$ to node $p$, and $W(f_p,f_q)$ is a penalty term if labels $f_p$ and $f_q$ are assigned to nodes $p$ and $q$, respectively. Here, $N$ indicates the neighbor nodes of node $p$.

In the framework of belief propagation, the following messages are repeatedly exchanged between the adjacent nodes in order to determine the optimum label $f_p$ that minimizes the energy function:

$$m_{p\rightarrow q}(f_q) = \min_{f_p} \left( D_p(f_p) + W(f_p,f_q) + \sum_{s \in N(p)\setminus q} m_{s\rightarrow p}^{-1}(f_p) \right)$$

After $T$ iterations, optimum label $f_q^*$ is determined so as to minimize the following cost function:

$$b_q(f_q) = D_q(f_q) + \sum_{p \in N(q)} m_{p\rightarrow q}^{-1}(f_q)$$

### 4.2. Range image inpainting using an intensity image

We apply belief propagation to a deteriorated range image and repair the image using the intensity image. When we measure range data using a laser scanner, it often occurs that part of the range image is lost due to the saturation of reflectivity by specular reflection or a weak laser pulse reflected on a black surface. In most cases, not only the range information but also the intensity information in this region is lost. The proposed inpainting technique for the range image consists of two steps. First, we repair the intensity image by belief propagation in Section 4.1 because the intensity image clearly contains roof and jump edges, and the restoration of the intensity image is easier than the restoration of the range image. Then, we apply belief propagation to the range image using the repaired intensity image. In Section 5, this two-step algorithm is demonstrated to be able to inpaint the range image more precisely than directly applying belief propagation to the range image.

Since belief propagation requires a huge memory and large calculation cost, the range and intensity images are first converted into a 256-level gray-scale image. Therefore, the number of labels to be assigned is 256, as expressed by integers from 0 to 255.

We define the cost term $D_p(f_p)$ for assigning label $f_p$ to pixel $p$ as

$$D_p(f_p) = 0$$

for lost regions and

$$D_p(f_p) = |f_p - L_p|$$

### Table 1. RMS error.

<table>
<thead>
<tr>
<th></th>
<th>RMS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original image</td>
<td>45.8</td>
</tr>
<tr>
<td>Gaussian filter</td>
<td>17.8</td>
</tr>
<tr>
<td>Bilateral filter</td>
<td>14.1</td>
</tr>
<tr>
<td>Extended bilateral filter (proposed)</td>
<td>11.7</td>
</tr>
</tbody>
</table>

Figure 5. Experimental setup.

Figure 6. Range image and intensity image.
for other regions where \( L_p \) is the original label of pixel p. In addition, we consider the four-neighbor q of pixel p and define the cost function for assigning labels \( f_p \) and \( f_q \) as

\[
W(f_p, f_q) = g(r_p, r_q)(f_p - f_q)^2 \tag{14}
\]

where \( r_p \) and \( r_q \) are the values of pixels p and q in the intensity image and \( g(r_p, r_q) \) is a gain term that indicates the effect of the intensity image.

\[
g(r_p, r_q) = ae^{-rac{\|r_p - r_q\|^2}{2\sigma_d^2}} \tag{15}
\]

Equation (14) indicates that the neighboring pixel which has a similar intensity value is preferentially selected to repair a lost pixel in the deteriorated range image. In contrast, a pixel having an intensity value that is changed discontinuously affects the repair of the range image only slightly.

5. Experiment

This section introduces the results of the preliminary experiments for image smoothing using the extended bilateral filter and image inpainting by belief propagation using simulated and actual range images. We conducted experiments with various parameters selected manually and determined parameters used for the following experiments.

5.1. Range image smoothing by the extended bilateral filter

5.1.1. Simulation using a synthesized image

First, we performed the simulation experiments using the synthesized image shown in Figure 3, which is a scene of a square box having sides of one meter in a room. A gray-scale image (Figure 3(a)) is used instead of intensity image, and we added a random noise of 1% of the range value to the range image.

Figure 4 shows the results obtained using the Gaussian filter, bilateral filter, and extended bilateral filter, respectively. Table 1 shows the RMS errors of the range images after applying these filters. In the experiment, the kernel size of each filter is \( 9 \times 9 \) pixels, and the ranges of the range data and the intensity data are 13,293–17,128 mm and 0–255, respectively. The variances are set as \( \sigma_v = 4.0 \), \( \sigma_f = 0.4 \), and \( \sigma_d = 6 \).

As shown in Table 1, the RMS error of the proposed extended bilateral filter is the smallest and the proposed extended bilateral filter is verified to have high performance for range image smoothing and edge preservation.

5.1.2. Experiments with LIDAR

Next, we performed the experiments using the 3D laser measurement robot CPS-V shown in Figure 1.[2] The robot enables the surrounding range data to be captured by rotating the laser scanner (SICK, LMS151) by means of a rotary table. The image size is \( 760 \times 1133 \) pixels.
Figure 5 shows the experimental condition: a stone monument with a Kanji inscription. Figure 6 shows the range image and intensity image of the scene captured by the measurement robot.

The results for the scene (Figure 5) are shown in Figure 7. In this experiment, we set the kernel size of the filters to $9 \times 9$ pixels, and the ranges of the range data and the intensity data are $443$–$49,726$ mm and $0$–$255$, respectively. The variances are $\sigma_x = 3$, $\sigma_f = 0.3$, and $\sigma_d = 13$ for the normalized range image. As shown in Figure 7(b), the bilateral filter blurs the edges of the characters, while smoothing the surfaces of the stone monument. Figure 7(c) shows the result after applying Bohme’s technique [9] that estimates a Lambertian reflection coefficient and a normal direction on each part of the surface simultaneously by minimizing the energy.

![Image of range images and intensity images](image-url)
function. Since this technique utilizes the difference between intensity and a normal direction in each pixel and their averages of its neighbor pixels as a smoothing term, the obtained range image also fails to conserve the detailed geometric features as is the case with the mean filter and Gaussian filter. On the other hand, the extended bilateral filter preserves the geometric features successfully suppressing noises in the range image as shown in Figure 7(d).

5.2. Range image inpainting by belief propagation

5.2.1. Simulation using a synthesized image

We performed the simulation for range image inpainting by belief propagation as described in Section 4. In the experiment, we prepared deteriorated intensity and range images which have a small missing region. The size of the image is $320 \times 240$ pixels and the size of the missing part is $20 \times 20$ pixels. In this experiment, we use $\alpha = 0.75$ and $\beta = 1.0$.

<table>
<thead>
<tr>
<th>Number of iteration</th>
<th>RMS (mm) Without intensity</th>
<th>RMS (mm) With intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>36.24</td>
<td>29.01</td>
</tr>
<tr>
<td>20</td>
<td>30.15</td>
<td>14.16</td>
</tr>
<tr>
<td>30</td>
<td>28.99</td>
<td>10.68</td>
</tr>
<tr>
<td>40</td>
<td>29.47</td>
<td>10.47</td>
</tr>
<tr>
<td>50</td>
<td>29.44</td>
<td>10.64</td>
</tr>
</tbody>
</table>

Table 2. RMS error for range image inpainting.

Figure 8(a) and (b) show the original and deteriorated range images and Figure 8(c) and (d) show the deteriorated and repaired intensity images. The inpainted range images after applying belief propagation 30 times are shown in Figure 8(e) and (f). These images are repaired with and without the intensity image, respectively. The RMS errors for these repaired images are compared in Table 2. From these results, the range image inpainting is successfully carried out using the two-step algorithm with belief propagation and intensity image.

5.2.2. Experiments with LIDAR

Next, we performed the experiments using actual range and intensity images taken by the laser scanner on the CPS-V robots (Figure 1). In this experiment, we use $\alpha = 0.75$ and $\beta = 0.5$. Figure 9 shows the 3D models restored by two techniques, that is, the simple belief propagation for range images and the proposed two-step algorithm using laser intensity. Missing parts are recovered appropriately by both techniques and there is no big difference in terms of the image quality. To emphasize the difference of the two techniques, we prepared deteriorated range and intensity images manually by cutting a part of a wall, and applied simple belief propagation and the proposed technique. Figure 9 shows the restored wall after applying these techniques and each RMS error is shown in Table 3.

As shown in Table 3, the RMS error of the proposed technique is the smallest, and the proposed technique is verified to fill-in a hole in the range image successfully.

Figure 9. Experimental results for the performance evaluation.
Finally, we performed the experiment to verify our denoising techniques using actual range and intensity images taken by the laser scanner (LMS511) on the CPS-V robots (Figure 1). In this experiment, we set the kernel size of the filters to $9 \times 9$ pixels and the variances are $\sigma_x = 3$, $\sigma_f = 0.3$, and $\sigma_d = 9$ for the extended bilateral filter. We also use $\alpha = 0.75$, $\beta = 2.0$, and $T = 100$ for our two-step algorithm. Figure 10(a) is a 3D model constructed from the original range image. Several unexpected bumps appear on the surfaces of the walls and objects due to the noise in the range image. In addition, several holes can be seen due to the occlusion or specular, or weak reflection. Figure 10(b) and (c) show the 3D model restored by the two-step inpainting algorithm and its smoothed 3D model by using the trilateral filter, respectively. The two-step algorithm repairs the missing region appropriately by taking the continuity of laser intensity into account. Moreover, the extended bilateral filter smooths the range image successfully, while preserving the geometric features such as jump and roof edges appropriately.

### 6. Conclusion

In the present paper, we proposed two denoising techniques of range images using laser intensity, namely, range image smoothing by the extended bilateral filter and range image inpainting by belief propagation. By taking into account the properties of range and intensity images, the proposed extended bilateral filter can suppress noises in range images, while preserving geometric features such as jump and roof edges. Belief-propagation-based range image inpainting was also proposed to recover deteriorated range images using not only the adjacent range values but also the continuity of the intensity image. We conducted experiments using a synthesized image and actual range images and verified that the proposed denoising techniques successfully suppress noises and repair deteriorated range images.

Since the intensity image is obtained as a by-product of range data, the proposed method has several advantages. For example, no additional measurements or instruments are required and, unlike conventional camera images, the intensity image is not affected by lighting conditions. In addition, a range image has the advantage of detecting jump edges, and the intensity image is suitable for detecting roof edges. Therefore, it is expected that the proposed technique has higher performance in edge preservation than the techniques that uses range or intensity information only.

In future, we will discuss the optimum parameters for the proposed technique and perform quantitative evaluation for a variety of scenes.
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References