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Letter

Elimination of Artifacts on Aperture Synthesis Images Using Ultrasonic Sensor's Directivity and the Ratio of Intensity

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Aperture synthesis images using a small number of ultrasonic sensors contain circular or elliptic artifacts. In this letter, to generate clear images less affected by artifacts with the same number of sensors, we propose a method that eliminates these artifacts using sensor's directivity and the ratio of its intensity. The experiments of detecting a plate were performed in terms of estimation of the edge point and the inclination of the plate. Results show that the proposed method can achieve smaller errors than the conventional method. © 2013 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: ultrasonic sensor, aperture synthesis, directivity, ratio of intensity

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1. Introduction

Recently, ultrasonic sensory systems have been widely applied for the detection of objects (e.g., mobile robots [1]) because these systems are of low cost. In order to exploit the advantage of ultrasonic sensors as much as possible and expand their application, it is required to obtain multidimensional images of sensing area only by ultrasonic sensors. In this case, the aperture synthesis method using multiple sensors is applied [2]. In principle, two sensors are required for two-dimensional images. Practically, images generated by a small number of sensors include circular or elliptic artifacts [3]. To overcome this, we have only to increase the number of sensors. However, this spoils the advantage at costs. In this letter, we propose a method that eliminates these artifacts using sensor's directivity and the ratio of its intensity. We perform experiments that detect the edge and inclination of the plate obstacles, assuming the mobile robots' routing.

2. Aperture Synthesis Method

Aperture synthesis method synthesizes multiple sensors' information to obtain objects' images in a multidimensional space. We assume that one object exists in a sensing area and the number of sensors is M. Let $\mathbf{x}_{\mathrm{t}}$, $\mathbf{x}_{\mathrm{r}}$, $\mathbf{x}_{\mathrm{o}}$, and c denote the positions of a transmitter, receiver, object, and the sound speed, respectively. When the signal is received by a receiver whose index is i $(1 \leq i \leq M)$, the elapsed time t_i after transmission equals the sum of both travel time from a transmitter to an object $|\mathbf{x}_{\mathrm{t}} - \mathbf{x}_{\mathrm{o}}|/c$ and that from an object to a receiver $|\mathbf{x}_{\mathrm{o}} - \mathbf{x}_{\mathrm{r}}|/c$. For one receiver, an infinite number of points satisfy this relation; therefore, we cannot determine the object position. For two and more receivers, t_i is different for each receiver; therefore, we can determine the object position by synthesizing all t_i. By scanning a sensing area, we add the intensity I_i at t_i to a pixel at each point $\mathbf{x}$ as $P(\mathbf{x}) = \sum_{i=1}^{M} I_i(t_i)$ to obtain an image.

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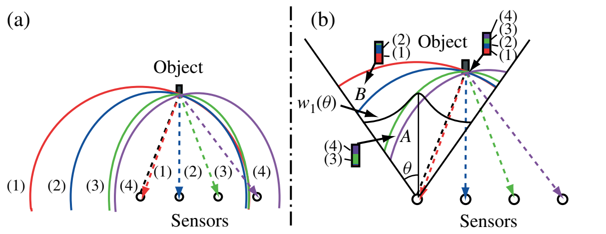

Fig. 1. (a) Reflected signal (dotted) and candidate of objects (solid line) and (b) eliminating artifacts using directivity and the ratio of intensity

Figure 1(a) shows the path of the transmitted and reflected signals and the candidate points of an object when the sensor in the left end is transmitting and all are receiving. When the transmitter is the same as the receiver (1 in the figure), candidates of objects are on a circle whose center is the location of the sensor, because the distance from the sensor ($2d_{\mathrm{to}}$) is constant. In the other cases (2–4), candidates of objects are on an ellipse whose foci are the transmitter and receiver, because the sum of d_{to} and d_{or} is constant. The former leads to circular artifacts and the latter to elliptic artifacts.

3. Eliminating Artifacts from Images

3.1. Using sensor's directivity

To exploit the directivity of sensor, we multiply the weight $w_1(\theta)$ as $P'(\mathbf{x}) = w_1(\theta)P(\mathbf{x})$, where θ [°] denotes the directivity angle and $w_1(\theta)$ is defined as $\exp(-\theta/\theta_t \log \epsilon)$ in Fig. 1(b). Using $w_1(\theta)$, we can reduce the pixel values of the artifacts except in front of a sensor array. In this letter, ϵ and θ_t are 0.1 and 30°, respectively.

3.2. Using sensor's ratio of intensity

Figure 1(b) shows the component ratios of each sensor's intensity $\mathbf{I} = (I_1(t_1), \ldots, I_M(t_M))$ to the pixel values $P'(\mathbf{x})$ at respective three points on the image. This shows that the component ratio of each sensor is nearly uniform at the point where the object exists, because the reflected signal from the object is propagated to each sensor. On the other hand, at points A or B in the

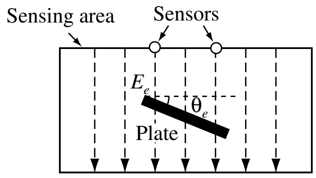

Fig. 2. Scanning for detecting the edge E_e and estimating the inclination θ_e

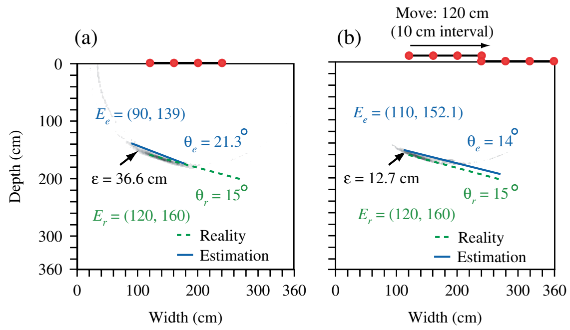

Fig. 3. (a) Conventional method's one-time image and (b) 10 times synchronously added image

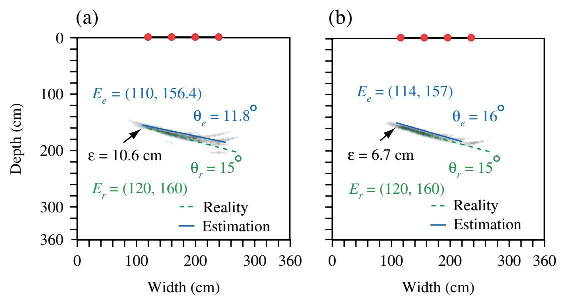

Fig. 4. (a) Proposed method's images using sensor's directivity and (b) using sensor's directivity and ratio of intensity

figure, the intensity of the sensors that mainly generate artifacts is greater than that of the other sensors. To calculate the difference from the uniformity, first we calculate the ratio of sensor intensity at each point and normalize it as $\mathbf{u} = \frac{\mathbf{I}}{|\mathbf{I}|}$. Second, we take an inner product $\sigma(\mathbf{u}) = \mathbf{u} \cdot \mathbf{u}_0$ $(\frac{1}{\sqrt{M}} \leq \sigma \leq 1)$, where $\mathbf{u}_0$ is a unit vector when the ratio of intensity is uniform as $\mathbf{u}_0 = \frac{1}{\sqrt{M}}(1, 1, \ldots, 1)$. Third, we convert $\sigma(\mathbf{u})$ into the weight $w_2(\mathbf{u})$ as $w_2(\mathbf{u}) = \left(1 - \frac{1}{\sqrt{M}}\right)(1 - \epsilon)\left(\sigma(\mathbf{u}) - 1\right) + 1$. Using $w_2(\mathbf{u})$, we can reduce the pixel values at the points where the intensity of each sensor differs significantly. Finally, pixel values P'' are calculated as $P''(\mathbf{x}) = w_2(\mathbf{u})P'(\mathbf{x}) = w_1(\theta)w_2(\mathbf{u})P(\mathbf{x})$.

4. Experiments

We detected an inclined (15°) plate (180 × 90 cm^2) using four piezoelectric transducer (PZT) (58 kHz) sensors, whose height and interval were 65 and 40 cm, respectively. The nearest edge was 160 cm away from the sensor. One sensor transmitted and all received the signal. We obtained four images by changing a transmitter and added them synchronously to one.

We estimated a plate's edge E_e and inclination θ_e: First, by scanning the area laterally as in Fig. 2, we counted the number of pixels whose value was over a threshold. Second, after smoothing, we determined a reliable area where the number of detected pixels was over the threshold. Finally, we considered the edge of the reliable area E_e and calculated θ_e using a linear regression.

5. Results and Discussions

Figure 3(a) shows image obtained using the conventional method. The dotted line, solid line, and circles indicate an actual plate, a detected plate, and sensors, respectively, where $E_{r,e}$ and $\theta_{r,e}$ are the real and estimated edge's coordinate and inclination of a plate. The contour corresponds to the pixel values P, P', or P''. The error ϵ is the distance between E_r and E_e. Figure 3(b) shows the image with 10 times synchronous addition by moving the sensor positions. The errors (ϵ, $|\theta_r - \theta_e|$) decrease from (36.6 cm, 6.3°) to (12.7 cm, 1°).

Figure 4(a) shows the image by using a sensor's directivity. This shows that artifacts on the left side are eliminated and the edge is clearly detected. The errors decrease from (12.7 cm, 6.3°) to (10.6 cm, 3.2°). Figure 4(b) shows the image by using both the sensor's directivity and the ratio of intensity. This shows that the artifacts near the center decrease and that both the edge error and the inclination error are reduced. This error (6.7 cm, 1°) is smaller than in the case of the conventional synchronous addition. Apparently, the length of a plate is more accurate in Fig. 4(a) than in Fig. 4(b), however, there are more artifacts around the right edge in Fig. 4(a), which led to the inclination error. To detect the nearest edge precisely is more important for a mobile robots' routing than to detect both ambiguously because by moving toward the right edge, it can be detected.

6. Conclusions

We proposed a method that eliminates artifacts using sensor's directivity and the ratio of intensity. The experiments showed that the proposed method achieved smaller errors than the conventional method.

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