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DISTANCE ESTIMATION OF CONCEALED OBJECTS WITH STEREOSCOPIC PASSIVE MILLIMETER-WAVE IMAGING

S. Yeom, D.-S. Lee, H. Lee, J.-Y. Son, and V. P. Guschin

Division of Computer and Communication Engineering
Daegu University
Gyeongsan, Gyeongbuk 712714, Korea

Abstract—Millimeter waves can be used to detect concealed objects because they can penetrate clothing. Therefore, millimeter wave imaging draws increasing attention in security applications for the detection of objects under clothing. In such applications, it is critical to estimate the distances from objects concealed in open spaces. In this paper, we develop a segmentation-based stereo-matching method based on passive millimeter wave imaging to estimate the longitudinal distance from a concealed object. In this method, the concealed object area is segmented and extracted by a k-means algorithm with splitting initialization, which provides an iterative solution for unsupervised learning. The distance from a concealed object is estimated on the basis of discrepancy between corresponding centers of the segmented objects in the image pair. The conventional stereo-matching equation is modified according to the scanning properties of the passive millimeter wave imaging system. We experimentally demonstrate that the proposed method can accurately estimate distances from concealed objects.

1. INTRODUCTION

Millimeter wave (MMW) technology is very useful for wireless communication, radio astronomy, remote sensing, and imaging under low visibility conditions [1, 2]. MMW can penetrate clothing and fabrics, and thus MMW imaging can be used to detect metallic or man-made objects concealed under clothing [3, 4]. Moreover, passive MMW generates interpretable images even under low-visibility conditions

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Corresponding author: Seokwon Yeom (yeom@daegu.ac.kr).

such as rain, fog, smoke, and dust [5, 6]. Therefore, MMW imaging has the advantage of capturing objects that are undetectable in the infrared or visible wavebands.

The passive MMW imaging system can be built as a stand-off type sensor that scans people with hiding dangerous objects [5–8]; in such applications, it is crucial to estimate the distances from any approaching concealed objects. Therefore, three-dimensional (3D) information of the object location must be estimated in order to eliminate the threat effectively. However, the passive MMW image quality is often deteriorated by system noise and the low level signals generated by the blackbody radiation of objects [9, 10]. Moreover, the limited aperture size causes low resolutions, thus difficulty in obtaining high-quality images. Previous researches have attempted to estimate the range from remote objects using stereoscopic passive MMW imaging [11]. However, distance estimations of hidden objects have rarely been reported in the literature. Such a method was first proposed in [12], but the experiment was not based on a realistic scenario since the image systems were assumed to be located within a distance less than their aperture size.

In this paper, we discuss the distance estimation of concealed objects based on segmentation-based stereo-matching of a passive MMW image pair. The distance estimation process comprises two stages: segmentation of concealed objects and stereo-matching with the corresponding pixels. The concealed objects are segmented by clustering pixels using a k-means algorithm equipped with splitting initialization [13]. This clustering method provides a reliable iterative solution for unsupervised learning. During stereo-matching, the centers of the segmented objects in the image pair correspond to each other. Pixel discrepancy is the binocular disparity which refers to the difference in coordinates of corresponding features of two stereo images. The discrepancy between these corresponding feature positions enables us to estimate the distance of the concealed object. Our passive MMW imaging system operates in the 3 mm wavelength region. In the experiments, the objects are located 2.5 m away from the imaging system. The experiment confirms that distance information can be extracted with suitable algorithms in the presence of the coordinate difference of the point between two stereo images. We demonstrate that the proposed method can accurately estimate the object distance. The longitudinal distance resolution is analyzed using the modified stereo-matching equation, which has the compatibility with the scanning imaging system. The distance estimation error is also analyzed in terms of the variance of the location estimated during segmentation.

This paper is organized as follows. In Section 2, we briefly describe a passive MMW imaging system. The distance estimation of the concealed object as well as the segmentation processes are discussed in Section 3. In Section 4, the experimental results are presented. Conclusions follow in Section 5.

2. PASSIVE MILLIMETER WAVE IMAGING SYSTEM

The passive MMW imaging system has a Cassegrain dish antenna of 50 cm diameter (D) as illustrated in Fig. 1 [7]. A feed horn antenna is installed at the focal plane of the dish antenna, receiving the regime of 3 mm wavelength (λ). The receiver connected to the feed horn antenna is composed of a Dicke modulator, a dielectric wave guide, three monolithic microwave integrated circuit (MMIC) amplifiers, and a Schottky diode detector. The scanning mechanism rotates both the antenna and the receiver in both horizontal and vertical directions with a constant scanning step. The angular resolution is around 0.42° according to the Rayleigh criterion when λ is 3 mm and D is 0.5 m. Two identical imaging systems are placed parallel on the stereoscopic baseline to capture a stereoscopic image pair.

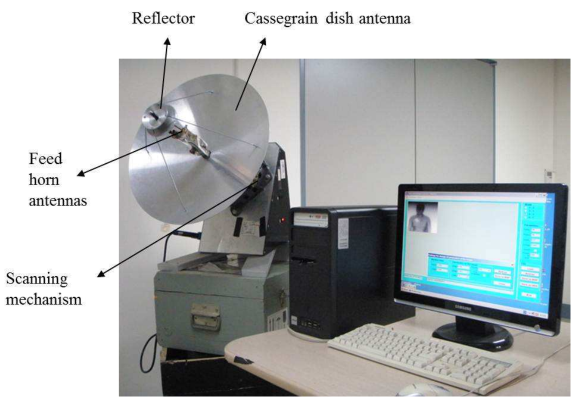


Figure 1. A passive MMW imaging system.

3. OBJECT SEGMENTATION AND DISTANCE ESTIMATION

The distance estimation procedure comprises segmentation using the k-means algorithm and distance estimation by a modified stereo-matching of the object centers.

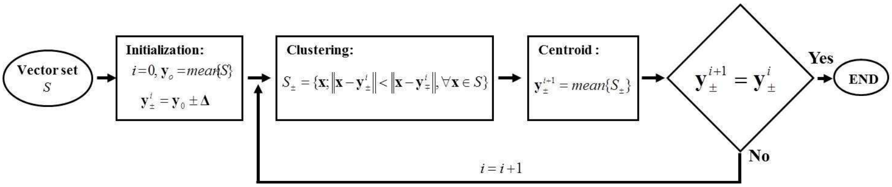


Figure 2. Block diagram of k-means algorithm.

3.1. Object Segmentation

The k-means algorithm with splitting initialization is adopted to extract the concealed object area. Figure 2 shows the k-means algorithm for generating two clusters S_+ and S_- from a set $S = \{\mathbf{x}_1, \ldots, \mathbf{x}_{n_p}\}$. Each element in the set S corresponds to each pixel. The initial value $\mathbf{y}_0$ is the mean of an input set S; $\mathbf{\Delta}$, a splitting value; and n_p, the number of pixels in the image. The sets S_+ and S_- are the two final clusters generated to obtain a binary image. One cluster represents the body area, while the other represents the hidden object and the background area. If more than two clusters are required to obtain, this process can repeat in each cluster.

3.2. Distance Estimation

The configuration of stereoscopic passive MMW imaging is similar to that of the conventional stereoscopic matching system as illustrated in Fig. 3. Two identical imaging systems are placed on the stereoscopic baseline. Fig. 4 shows the pixel formation via the scanning process. Although the feed antennas are scanned on the convex trail, the imaging plane can be approximated to be nearly flat when the longitudinal distance is considerably larger than the image size in the x direction. Therefore, the following equation is hold:

$$\Delta_x = l \cdot \alpha \cdot \Delta_p, \tag{1}$$

where l is the distance to the imaging plane; α is the scanning step; $\Delta_x = x_{c,l} - x_{c,r}$, where $x_{c,l}$ and $x_{c,r}$ are the centers of the concealed object in the left and right images in the x directions, respectively; and $p_{c,l}$ and $p_{c,r}$ are identical centers in a pixel unit, which correspond to $x_{c,l}$ and $x_{c,r}$, respectively. In consequence, the distance d is derived as

$$d = \frac{l \cdot b}{\Delta_x} = \frac{b}{\alpha \cdot \Delta_p}, \tag{2}$$

where b is the baseline distance.

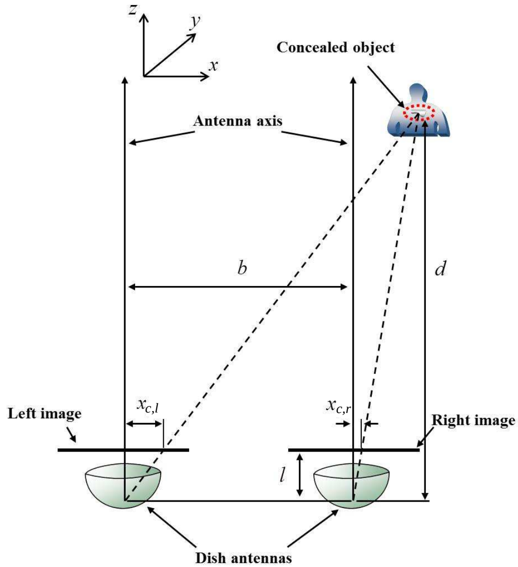


Figure 3. Configuration of stereoscopic passive MMW imaging.

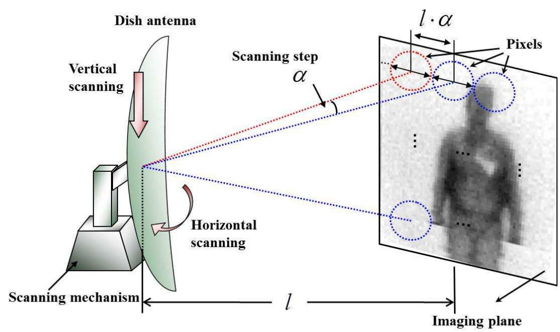


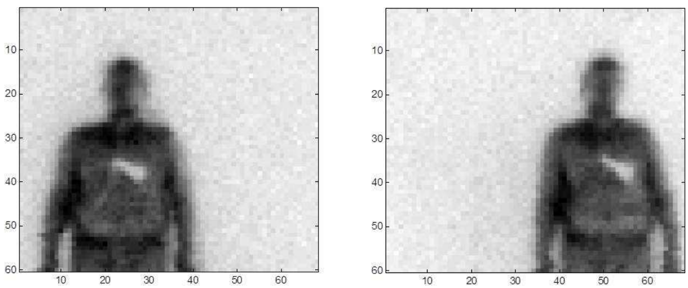
Figure 4. Image formation via scanning process.

4. EXPERIMENTAL ANS SIMULATION RESULTS

A metal axe is concealed under the clothing of a human subject. The distance between the human subject and the imaging system is set to 2.5 m. The baseline distance between two identical imaging systems is set to 50 cm. In the experiments, the concealed object is captured twice using the same single imaging system. The scanning step is set to 0.4° ($\approx$ 0.007 rad). Fig. 5(a) shows the visual image of a human subject hiding the object, and Fig. 5(b) shows the actual metal axe concealed

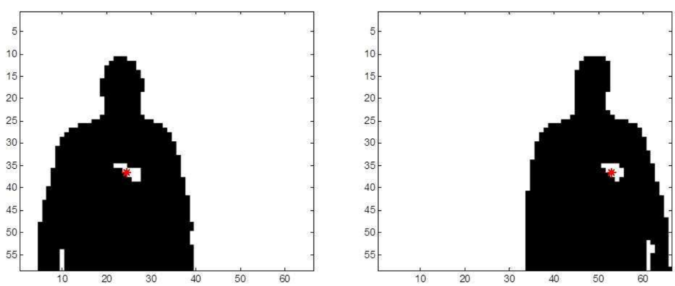
(a) (b)

Figure 5. Visual images of (a) human subject, (b) metal axe.



(a) (b)

Figure 6. Stereoscopic image pair, (a) left image, (b) right image.



(a) (b)

Figure 7. Segmentation results and center of objects in, (a) left image, (b) right image.

under the clothing. Figs. 6(a) and 6(b) are the passive MMW image pair (left and right images); the size of each image is 69×60 pixels.

Figure 7 shows the segmentation results and the object centers marked by a "$*$" symbol. These centers are located at 24.5 and 53

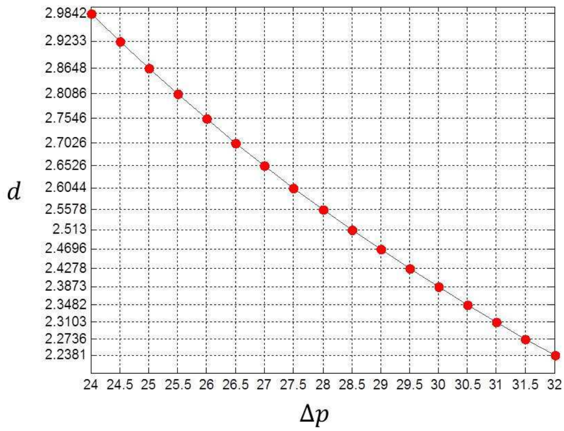


Figure 8. Discretet pixel discrepancy and distance resolution.

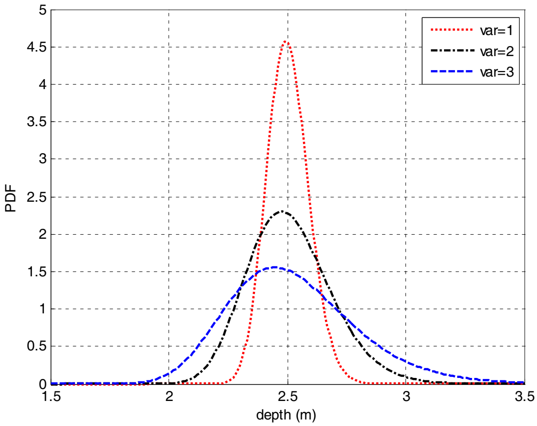


Figure 9. PDF's of distance estimation with different position error variances.

pixels in the left and right images, respectively, thus the discrepancy is 28.5 pixels while the resulting distance is 2.51 m. Fig. 8 shows the distance according to Eq. (2) with varying Δ_p. In the paper, the pixel discrepancy is discrete with a half-pixel resolution since the centers of two horizontal ends are adopted as the corresponding feature. The distance resolution increases with increasing pixel discrepancy between the image pair as illustrated in Fig. 8.

Let us assume that the vertical edge at the horizontal ends of the object is estimated with Gaussian error as $p = p_0 + e$ where p_0 is the true value of the edge position and $e \sim N(0, \sigma^2)$, which follows the Gaussian distribution with zero mean and variance σ^2. The center of the object becomes $p_c = \frac{1}{2}(p_l + p_r) = p_{c0} + e_c$, where p_l and p_r are the obtained left and right ends of the object, respectively, p_{c0} is the true value of the center, and $e_c \sim N(0, \frac{\sigma^2}{2})$. Thus, the pixel discrepancy which is equivalent with the horizontal shift of the centers in the stereo images becomes $\Delta_p = p_{c,l} - p_{c,r} = \Delta_{p0} + e_\Delta$, where $p_{c,l}$ and $p_{c,r}$ are the estimated centers of the objects in the left and right images, respectively, Δ_{p0} is the true value, and $e_\Delta \sim N(0, \sigma^2)$. In consequence, the distance estimation has the following probability density function (PDF): $f_p(d) = \frac{\kappa}{d^2} f_g(\frac{\kappa}{d})$, where $d = \frac{\kappa}{\Delta_p}$, $f_g(\Delta_p)$ is the Gaussian distribution with mean Δ_{p0} and variance σ^2, and $\kappa = \frac{b}{\alpha}$ in Eq. (2). Fig. 9 shows the PDF of d when $b = 0.5\,\text{m}$, $\alpha = 0.007\,\text{rad}$, and σ^2 is 1, 2, or 3 pixels.

5. CONCLUSION

It is important to estimate 3D locations of dangerous objects for security and defense purposes. In this paper, we proposed a method for the distance estimation of concealed objects using stereoscopic passive MMW images. In this method, the objects are segmented by the k-means algorithm and the centers of the segmented objects are employed as the corresponding points between the left and right images. The distances are estimated by employing a modified stereo-matching equation. Experimental results confirm that the effectiveness of the stereoscopic passive imaging system to localize hidden threats to perform 3D surveillance. This technique could be applied to 3D surveillance of targets under low visibility conditions as well as concealed objects.

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