Auto-focused Imaging of a Moving Target Using an Ultra-wideband Array Radar

T. Sakamoto[1], **T. Sato**[2], **P. Aubry**[3] **and A. Yarovoy**[3]

[1]University of Hyogo, Japan
[2]Kyoto University, Japan
[3]Delft University of Technology, the Netherlands

Abstract— The authors have developed a target speed estimation method for an ultra-wideband radar imaging system. The method is able to generate a focused image even if the target is moving at an unknown speed during the measurement, where many other techniques produce blurred images. Our technique uses the cross-range blurriness as a metric to measure the image focusing, and select the best-focused image among many generated for various candidate speeds. The target speed is estimated by finding the minimum cross-range blurriness, and the method compensates for the estimated speed to generate a focused three-dimensional image automatically. By exploiting the fact that the head size differs relatively little among individuals, we detected the head position in a radar image, and calculated the blurriness around the region to evaluate the focuse of the image. The speed estimation method is applied to the measurement of a mannequin on a moving stage, and it is shown that the target speed is estimated with an accuracy of 5%. Application results show that the developed technique can estimate target speeds accurately, and produce an image with sufficient resolution for the intended application.

1. INTRODUCTION

Because of possible terrorist attacks on public transport systems such as airports, microwave body scanners are considered an important measure of ensuring public safety. Microwaves can penetrate most clothing, and such body scanners are therefore capable of detecting weapons concealed under clothes by forming an image using radar echoes from the targets. Microwave-based imaging techniques have been intensively studied to improve their resolution, accuracy and computational speed, leading to various effective technologies and commercial products [1,2].

Recently, a new type of microwave imaging technique, revised range point migration (RRPM), has been attracting attention. The technique is faster than many existing techniques and can generate numerous images within a short time. This allows auto-focusing imaging of a moving target traveling at an unknown speed, by selecting the most focused image among many generated assuming various candidate speeds. In this paper, we review such techniques and present application results using measurement data to demonstrate the performance of the techniques. Some preliminary results have been reported at a previous conference [3], and details will be presented in an article [4] that is now under review.

2. SYSTEM MODEL

We assume a measurement system consisting of a transmitter and a receiver positioned in the $z = 0$ plane in the direction of the x axis at a fixed separation given by $2d$. The midpoint between the transmitter and receiver is labeled $(X, Y, 0)$, which means the transmitting and receiving antennas are located at $(X - d, Y, 0)$ and$(X + d, Y, 0)$, respectively. The transmitter-receiver pair scans at discrete intervals across a region of the $z = 0$ plane. Given the antenna midpoint $(X, Y, 0)$, the signal received is labeled $s(X, Y, Z)$, where $Z = ct/2$. Here, c is the speed of the electromagnetic wave and t is the time interval between transmission and reception. A schematic of the system model is shown in Figure 1.

3. IMAGING METHOD

We employ a fast imaging algorithm using the bistatic inverse boundary transform (IBST), which is a reversible transform between radar signals and radar images. The first step in imaging using the bistatic IBST is the extraction of signal peaks that exceeds a threshold T_s. These peaks are indexed as (X_i, Y_i, Z_i) for $(i = 1, 2, \cdots, N)$. The corresponding amplitudes of these peaks are denoted $s_i = s(X_i, Y_i, Z_i)$. Let us assume that these points are easily connected sequentially to form multiple curved surfaces $Z(X, Y)$. This function and its derivative are used in imaging with the bistatic IBST. To obtain stable derivatives Z_X and Z_Y, we use the RRPM algorithm [4], which is known to be fast and robust even for complicated shapes in a noisy scenario. The RRPM method estimates a derivative $Z_X = \tan(\theta_i)$, where θ_i is the inclination of the peak distribution and calculated as a weighted average over multiple peak points around the point of interest. Using multiple peak points, we can make the resultant derivative stable, leading to high-resolution imaging with in a short time.

4. TARGET SPEED ESTIMATION

The image obtained with a correctly assumed speed is well focused, where the focus can be evaluated using the image blurriness metric [3]. The proposed methodology produces multiple images corresponding to various assumed speeds, from which the optimum metric gives an estimate of the speed. It is essential to use the fast imaging technique with the bistatic IBST and RRPM in calculating these metrics because the imaging is repeated many times for various assumed speeds; this process can be impractically time consuming if conventional methods are used instead.

We introduce a metric to measure the cross-range blurriness of a radar image. Assuming that the method is applied to a human target, this metric uses only the part of a radar image that is likely to contain a head if the target is a human. First, we estimate the head position in an image by taking the largest peak of the vertical profile of the RRPM image. Because we do not yet know the exact target speed, we assume a stationary target to produce a reference image in this process. From this reference image, we estimate the head position where a strong reflection is observed. Next, the image sharpness is evaluated using the cross-range blurriness of the image at the estimated head position. If the image is focused, the blurriness is reduced; the actual target speed minimizes the value. More details on this method are found in [4].

5. MEASUREMENT SETUP

We applied the speed estimation method using the cross-range blurriness to measurements obtained for the metal-coated mannequin shown in Fig. 2. The target was placed on a moving platform. We employed frequencies from 5.0 to 25.0 GHz for the measurement. The antennas were spaced at 5.5 cm and scanned at 1.0-cm intervals over an area 75.0 × 75.0 cm in the $x - y$ plane. While the antennas scanned from left to right, the target moved in the $-z$ direction over a distance of 38.0 cm, corresponding to a target speed of 1.0 m/s, assuming a total measurement time of 0.38 s. The RRPM method extracted 15 peaks for each antenna position. We set $\sigma_X = \sigma_Y = 0.8$cm, $\sigma_Z = 0.3$cm and $\sigma_\theta = \pi/100$. The i-th target image point (x_i, y_i, z_i) was weighted with amplitude $|si|$ to generate a three-dimensional image.

6. APPLICATION OF THE PROPOSED METHOD

To investigate the performance of speed estimation, we apply the target speed estimation explained above. Figure 3 shows the conventional MB sharpness metric [5] and cross-range blurriness for the mannequin target. The MB sharpness metric and cross-range blurriness are respectively plotted as dashed black and red solid lines and give the estimates of target speed. The target speeds estimated using the MB sharpness metric and cross-range blurriness are respectively 0.89 and 0.95 m/s, giving errors of 11% and 5%. Our cross-range blurriness gives a better estimate, because a mannequin is difficult to approximate as a point target, where the conventional MB sharpness metric assumes that the target is a set of point targets. In contrast, the cross-range blurriness maintains its accuracy within an acceptable range. Figure 4 shows the 3-D images generated for the speed estimated using the cross-range blurriness. It is confirmed that the shape of the target is clearly imaged, and the resolution is considered to be sufficient for many applications. The next step in this series of studies is quantitative analysis of the image resolution under various conditions such as different target motion patterns, which will reveal the applicability and limitations of the developed technique.

7. CONCLUSION

We presented a target speed estimation technique and imaging method, and provided an application result. The method produces multiple images assuming various candidate speeds, among which we select the best-focused image and its corresponding speed as an estimate of the target motion.

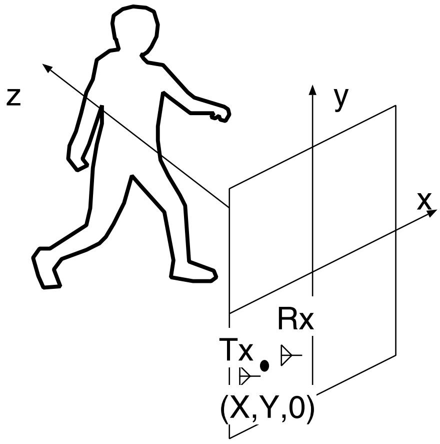

Figure 1: System model of antenna array-based radar for detecting concealed weapons worn by a person in motion.

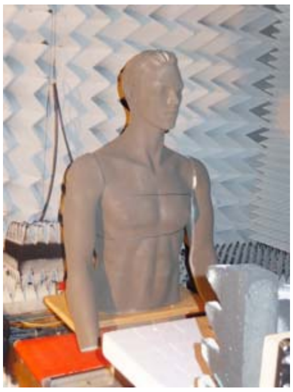

Figure 2: Metal-coated mannequin on a moving platform used in our radar measurement.

Because this approach requires the production of numerous images assuming different candidate speeds, we employed a fast imaging method, RRPM, to realize fast processing sufficient for many security systems. By exploiting the fact that the head size differs relatively little among individuals, we detected the head position in a radar image, and calculated the blurriness around the region to evaluate the focusing of the image. The method was applied to measurement data for a moving mannequin, and it was shown that the target speed was estimated with an accuracy of 5%. Our developed techniques were demonstrated to be effective in estimating the speed accurately and producing a focused image.

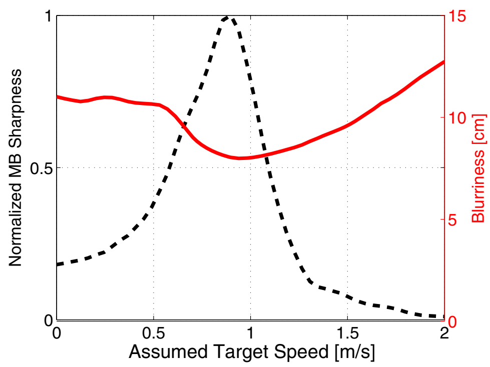

Figure 3: MB sharpness metric (black) and cross-range blurriness (red) for a mannequin. Actual speed is 1.0 m/s.

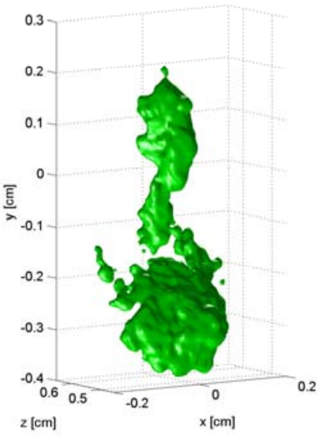

Figure 4: Focused image of the mannequin generated using the blurriness metric proposed by the authors.

ACKNOWLEDGMENT

This research was partially supported by the Supporting Program for Interaction-based Initiative Team Studies (SPIRITS) under Japan–Netherlands joint development of sleep monitoring technology using ultra-wideband radar, the Center of Innovation Program (COI) under The Last 5X Innovation R&D Center for a Smart, Happy, and Resilient Society, JSPS KAKENHI under grant numbers 25249057 and 15K18077, and the R&D project for expansion of radio spectrum resources for more efficient use of frequency resources for the future supported by The Ministry of Internal Affairs and Communications, Japan.

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