A W-band auto-focus holographic imaging system for security screening

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Abstract: Millimeter-wave Holography is a promising technique for security screening to detect concealed weapons. However, a crucial disadvantage of this technique is that the close-range large-aperture operation result in a very short depth of focus. In this paper, a W-band auto-focus holographic imaging system is presented. By calculating and comparing the amplitude integral value of holographic imaging results reconstructed at different focusing distances, the algorithm can assess focusing quality of each imaging result, choose the optimal focusing distance, and extract the optimum viewing image from the imaging results. The scheme of imaging system is described in detail. Both simulation and experimental results are provided to demonstrate that the focusing performance of new auto-focus imaging system is much better than conventional holographic system.

Keywords: holography, auto-focus, millimeter-wave, imaging, security screening

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

1 Introduction

Holography theory was originally developed in optical devices by Gabor [1, 2] in 1948, thereafter the technique was extended to long-wavelength implementations such as microwave holography and acoustic holography [3, 4, 5]. Generally, holographic imaging operates by sampling the amplitude and phase of a wavefront which is scattered from a target object. In order to form the image of the target object, the sampled wavefront is then reconstructed either optically or by using Fourier-optics-based computer image-reconstruction algorithms [6, 7, 8]. Holography has been widely used in many fields including photography, medical examinations and security screenings.

Millimeter-wave holographic imaging for concealed weapon detection was proposed by Farhat and Guard [9] and substantially improved by Collins [10]. Millimeter-wave can penetrate common clothing barriers and be reflected off the person and any concealed items. Millimeter-wave holographic imaging utilizes the phase and amplitude information recorded over a two-dimensional aperture to produce high-quality imagery of the targets’ reflectivity. The resolution can be very high due to the relatively short wavelength. However, despite its high-resolution benefits, a crucial disadvantage of this technique is that the close-range large-aperture operation result in a very short depth of focus. In order to reconstruct the image in complete focus, either the target must locate precisely at the focal plane or the focal plane must move to the target. This shortcoming is acceptable to medical examinations since the distance between the targets and the sensor aperture can be precisely controlled [11]. By adjusting the focusing distance in reconstruction algorithm, the medical holographic imager can focus on arbitrary planes, similar to adjusting the focus on a microscope. However, for security screenings, this disadvantage cannot be ignored. The distance from the person being checked to the aperture is subject to change and is easily affected by the pose, position and body shape of the personnel, making it difficult to anticipate the focusing distance. If the focusing distance is fixed, varying degrees of blur will occur in almost all imaging results. As an alternative, Collins manually adjusted the focusing distance for each scene in order to completely focus on the target to obtain the optimum viewing image [10], but this will enormously increase operation time of security screening.

Given the situations and problems above, to achieve a high-quality and efficient holographic image, a solution is needed that allows holography to auto-focus on the target. Some techniques have tried to utilize an extra device to measure the distance between the target and the aperture. However, this method is also with problems. In
addition to increasing the complexity of the system, the measured distance is point-to-point and it can’t be guaranteed that the measured point is on the main targets we are truly concerned about. Additionally, no target is completely planar and every target has significant depth. Thus there is no guarantee that the distance measured by the device is the optimal parameter to focus the entire targets. In essence, large portions of the target could still be blurry and the real threat targets could have the possibility of being ignored if this point-to-point distance is set as the focusing distance.

In this paper, a W-band auto-focus holographic imaging system is presented, which avoids the aforementioned problems. By calculating and comparing the amplitude integral value of holographic imaging results reconstructed at different focusing distances, the algorithm can assess the focusing quality of each imaging result, choose the optimal focusing distance, and extract the optimum viewing image from the imaging results. The optimum viewing image is the image in which the largest part of the main target is completely focused. The auto-focus method discussed here is also potentially suitable for all imaging implements that use Point Spread Function (PSF) analysis. The effectiveness and performance of W-band auto-focus holographic imaging system is proved by both simulation and experimental validation with several application examples.

2 Millimeter-wave holographic imaging

The configuration of holographic imaging system is illustrated in Fig. 1. The sensor aperture is on the left side and the target locates near the origin of coordinate. The sensor is a single-tone coherent millimeter-wave transceiver. The dots on the sensor aperture are sampling positions. At each sampling position, the transceiver transmits single-tone continuous wave, and both amplitude and phase of the reflected signal are recorded coherently. The data can then be mathematically reconstructed to form a focused image of the target’s reflectivity function.

The transceiver is assumed on the planar aperture at the position \((x', y', Z_1)\), where \(Z_1\) is constant. A general point on the target is at the position \((x, y, z)\). The target can be characterized by a reflectivity function \(f(x, y, z)\), which is simply the ratio of the reflected field to the incident field.

![Fig. 1. Holographic imaging system configuration](image-url)
The response at the transceiver will be the superposition of each point on the target multiplied by the roundtrip phase to each sampling position. The target is assumed to be flat at constant $z_0$ and parallel to the scan plane, the echo signal can be written as:

$$s(x', y') = \iiint f(x, y, z_0) e^{-j2k\sqrt{(x-x')^2 + (y-y')^2 + (z_0-z)^2}} \, dx \, dy$$  \hspace{1cm} (1)$$

The wavenumber is denoted by $k = \omega/c$, where $\omega$ is the angular frequency and $c$ is the speed of the light.

Using 2-D spatial Fourier transformation, function (1) is transformed by means of POSP (Principle of Stationary Phase). The variables of sampling position are $x'$ and $y'$.

$$S(k_x, k_y) = \iiint f(x, y, z_0) e^{-jk_x x} e^{-jk_y y} e^{j\sqrt{4k^2 - k_x^2 - k_y^2(Z_1-z_0)}} \, dx \, dy$$  \hspace{1cm} (2)$$

Note that the exponential term $e^{j\sqrt{4k^2 - k_x^2 - k_y^2(Z_1-z_0)}}$ can be regarded as the frequency character of matched filter, and it is related to the distance between the target and the sensor aperture. Once the parameter $Z_1 - z_0$ is chosen as $Z_{\text{ref}}$, function (2) yields the inversion for the image.

$$f(x, y, z_0) = \text{IFFT}_{2D}[S(k_x, k_y) e^{-j\sqrt{4k^2 - k_x^2 - k_y^2Z_{\text{ref}}}}]$$  \hspace{1cm} (3)$$

In addition to showing that the ultimate result is a 2D image, function (3) also indicates that for holographic imaging system, only the target that locates at $Z_{\text{ref}}$ can get the best focusing performance due to the parameter of the matched filter. For the targets not on the reference plane, their imaging result is defocused.

For focused imaging result, the lateral resolution can be calculated as:

$$\delta x = \delta y = \frac{\lambda}{4 \sin \left(\frac{\theta}{2}\right)}$$  \hspace{1cm} (4)$$

$\theta$ is the lesser of the full beamwidth of the antenna or the angle subtended by the aperture, and the $\lambda$ is wavelength.

### 3 Auto-focus holographic imaging

Reference distance $Z_1 - z_0$ is the key factor for obtaining a focused image, because it is the primary parameter of the matched filter. Due to the relatively short wavelength and close-range large-aperture operation, the depth of focus is very short. Once the reference distance is inaccurate, the imaging result is easy to be blurred. In this new holography algorithm, instead of manually adjusting the reference distance, an auto-focus method is used to choose the accurate reference distance, and then to focus on the target to form a high resolution image.

Simulations have been done to demonstrate the effectiveness of auto-focus scheme. A single point is set as the target at the origin of coordinate, and generates reflected signal. Using the holographic imaging algorithm mentioned in Section II, a focused imaging result is reconstructed and illustrated in blue in Fig. 2. A defocused imaging result is also reconstructed by intentionally choosing an inaccurate reference distance as the parameter of the matched filter, and the result
is illustrated in red in Fig. 2. The abscissa represents azimuth range, and the ordinate shows normalized amplitude.

For the focused imaging result, only linear phase is remained in wave-number domain after matched filter. According to the Point Spread Function (PSF) analysis, the imaging result approximates sinc function. On the contrast, the defocused imaging result’s wave-number domain has non-linear phase portion, which results in decreased peak, extended main lobe and increased side lobes. A considerable difference between the two curves is the peak value, but it is not a stable criterion to judge the focusing quality, because it is easily influenced by noise and blur pattern from defocused targets. The judgement criterion should be statistical characteristic of reconstructed image. Ultimately, the amplitude integral value is chosen to judge the focusing quality of the image. Advantages of this criterion include: 1) sensitive to inaccurate reference distance, 2) insensitive to noise, 3) can be easily calculated.

There are four steps to accomplish auto-focus, 1) choose a certain range in which the target locates; 2) discretize the range and reconstruct the image at each discrete distance; 3) calculate the amplitude integral value of each imaging result; 4) extract the image with the best focusing performance. According to the simulation, the amplitude integral value will increase when the reference distance is away from the accurate focused distance. The variation of amplitude integral value with respect to the distance deviation is illustrated in Fig. 3. The minimum
amplitude integral value corresponds to the optimal reference distance. By finding the minimum amplitude integral value, the auto-focus is realized reliably.

4 Imaging system compositions

An imaging prototype, utilizing a 92 GHz millimeter-wave transceiver and a programmable planar scanner, has been used to gather data to validate the performance of algorithm and W-band imaging system.

A block diagram of the imaging system is shown in Fig. 4. The transmitted RF signal is launched using a small conical horn antenna. The antenna and the transceiver are mounted on a fast large programmable mechanical scanner. The scan velocity is settable. While scanning, the scanner is emitting 3000 pulses in one second. By counting the pulses, the computer, which is connected with the scanner, calculates the position, and controls the transceiver to launch and receive the RF signal through antenna at the sampling position, as well as controls the A/D converter to digitize the signal and store in the hard disk. In order to sample on a 2-D aperture, the computer will control the scanner to move to a new initial scan position, and start another linear scan. The 2-D aperture data is then formed as the input of the image reconstruction algorithm $s(x', y')$. The data processing module, typically a fast speed digital signal processor, will process the data. Finally, the image will display on the terminal UI.

A photograph of the scanning system and a photograph of the antennas and transceiver are shown in Fig. 5. The system is quasi-monostatic, which means the transmitting and receiving antenna are separate, but in approximately the same location and may be assumed to be coincident at the midpoint between the two antennas. The receiving antenna usually has the same size and type as the transmitting antenna and is placed immediately adjacent to the transmitting antenna. In this way, the pair of antennas simulates a single antenna, but with significantly higher transmit-receive isolation.

A simplified schematic of the transceiver is shown in Fig. 6. A 140 MHz single frequency signal is generated as the intermediate frequency (IF) using the Direct Digital Synthesizer (DDS) to ensure the coherent characteristic. The first local
The oscillator operates at 4.5 GHz. The second local oscillator operates at 10.92 GHz. After passing the octupler and mixer, the signal transmits through the antenna. Regarding receiving channel, after down-converting with two oscillators, a 140 MHz intermediate signal is received.

5 Experiment result

Experiment has been done to verify the performance of auto-focus scheme. The W-band transceiver, which operates at 92 GHz, is used as the sensor. This single-tone coherent millimeter-wave transceiver and antennas are mounted on a programmable mechanical scanner to achieve aperture scanning. The beamwidth of both transmitting antenna and receiving antenna are 38°. The aperture of the imaging system is 66 cm × 66 cm, and the distance to the target is approximately 1 m. The data are discretely sampled with typical dimensions of 220 \( x \) samples and 220 \( y \) samples with spatial intervals of 3 mm (\( \Delta x \)), 3 mm (\( \Delta y \)), respectively. Based on
equation (4), the theoretical lateral resolution is approximately 3 mm. Which means the sampling interval satisfies Nyquist sampling criterion.

To reconstruct the auto-focus holographic image, the distance deviation range is chosen as $[-0.3 \text{ m}, 0.3 \text{ m}]$. In another words, the reference distance is from 0.7 m to 1.3 m, which makes sure that the target is absolutely within this range. The discrete interval is 0.01 m, so there are totally 61 reconstructed holographic imaging results. Then the amplitude integral value of each image is calculated to judge the focusing quality of the image, and find the minimum to extract the optimal result.

A reconstructed holographic image of ten metal balls is shown in Fig. 7. In the image, the default reference distance is 1 m. Fig. 7(a) is the optical photo of ten metal balls which are embedded in foam plastic board and parallel to the scan plane. Fig. 7(b) is the conventional holographic imaging result which uses default reference distance as the parameter of matched filter. Fig. 7(c) shows the resolution of one metal ball in Fig. 7(b), the $-3\text{ dB}$ lateral resolution is 5.5 mm. Fig. 7(d) is

![Fig. 7.](image)

- (a) Optical photo
- (b) Conventional holographic imaging result
- (c) resolution of conventional result
- (d) Amplitude integral value with respect to the distance deviation
- (e) Auto-focus holographic imaging result
- (f) resolution of auto-focus result
the amplitude integral value with respect to the distance deviation. The abscissa represents distance deviation to default reference distance, and the ordinate shows amplitude integral value of imaging result at corresponding distance. According to the integral curve, the actual distance between scan plane and the target is 0.99 m, which is also the optimal parameter of matched filter. Fig. 7(e) is auto-focus imaging result which uses 0.99 m as the reference distance. Fig. 7(f) shows the resolution of one metal ball in Fig. 7(e), with better focusing quality, the $-3 \text{ dB}$ lateral resolution is 3.8 mm. The background shadow in Fig. 7(b) and Fig. 7(e) mainly comes from the reflection of the wall of laboratory, which is behind the foam plastic board.

A reconstructed holographic image of more complex target is shown in Fig. 8. A scissor and a knife are fixed by nails on a foam plastic board and parallel to the scan plane. Using the holographic imaging algorithm with default reference distance, the blur is obvious in Fig. 8(b). That means the reference distance is inaccurate and the target is out of the depth of focus. According to the integral curve in Fig. 8(c), the actual distance between scan plane and the target is 0.96 m. The auto-focus imaging result is shown in Fig. 8(d), the nails placed at both handle of the scissor and branch of the knife can be clearly seen due to the high resolution, so does the metal chain at the tail of the knife.

![Image](image_url)

**Fig. 8.** (a) Optical photo, (b) Conventional holographic imaging result, (c) Amplitude integral value with respect to the distance deviation, (d) Auto-focus holographic imaging result

Fig. 9 shows the photo and W-band holographic imaging result of a concealed knife covered by a cotton T-shirt. This experiment simulates a practical situation to test the detecting performance of the imaging system. Using default reference distance, Fig. 9(b) is reconstructed. The concealed knife can be identified in the
image. According to the integral curve in Fig. 9(c), the optimal reference distance is 1.04 m, and the auto-focus imaging result is shown in Fig. 9(d). Compared with Fig. 9(b), Fig. 9(d) has better focusing quality, fine details are apparent in the imaging result that we can clearly recognize the striation of the T-shirt and shape of knife. This experiment sufficiently demonstrates the detecting capability of the W-band auto-focus holographic imaging system.

Image-reconstruction time is another important factor to evaluate the performance of the algorithm. The raw data was processed in MATLAB. Depending on MATLAB timer, conventional holographic imaging takes 1.695 seconds, and auto-focus holographic imaging takes 1.811 seconds. The time consumption is acceptable.

6 Conclusion

This paper has demonstrated an auto-focus millimeter-wave holography for security screening. The imaging system uses a coherent 92 GHz single-tone transceiver to scan over a large aperture, both horizontally and vertically. Then the echoed complex signal is recorded coherently by the transceiver, digitized and stored in the computer to reconstruct a focused image. In order to achieve the best focusing performance, the algorithm forms a series of imaging result with different reference distance. By calculating and comparing the amplitude integral value of each imaging results, the algorithm can assess the focus quality of the images, choose the optimal focusing distance, and extract the optimum viewing image from series. Both simulation and experiment have provided strong validation that this auto-focus holography is effective and efficient to achieve the best focusing performance.