Millimeter-Wave Single-Pixel Imaging Using Liquid Crystal Mask Cell with Matrix Electrode Structure

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ABSTRACT

A millimeter-wave single-pixel imaging (MMW-SPI) system was developed using a liquid crystal mask electrically switched based on a simple operation method. The proposed MMW-SPI system can detect a concealed small metal piece placed under an opaque paper sheet.

1 Introduction

Millimeter-wave (MMW) imaging technology is used for various practical applications, such as nondestructive inspections, security gates, material analyses, and remote sensing. Nevertheless, image acquisitions typically require processing steps because low-cost, high-performance, and convenient MMW cameras, such as the visible-light digital camera, have not been developed extensively. The two main image reconstruction methods are raster scanning using a sensing probe and computer-assisted reconstruction. The latter method comprises MMW holography, computerized topography, and computational imaging. Recent advancements in computer processing ability and a detailed understanding of computational imaging technology have led to MMW single-pixel imaging (SPI) development [1].

Generally, the SPI system comprises at least three components: an MMW source, a detector, and a switchable mask. This simple architecture is an attractive aspect of SPI. In the visible-region SPI, the switchable mask is substituted with digital mirror devices or liquid crystal (LC) spatial light modulators. However, these electro-optic devices must be redesigned to maximize the controllability of the MMW based on the physical characteristics of the MMW. The LC mask used in the MMW single-pixel imaging (MMW-SPI) system is customized to modulate the MMW amplitude dynamically. The developed LC device is incorporated with a matrix electrode structure similar to ordinary passive matrix LC devices. Nevertheless, requirements such as the steep transmittance-voltage characteristics and the limited number of electrodes are neglected, enabling the production of a device structure for optimum MMW-controlling capability.

In this paper, the constructed MMW-SPI system and its working principle are briefly introduced. Next, the effect of the measurement error on the reconstructed image is discussed. Finally, a simple demonstration of concealed, tiny metal piece detection is presented.

2 MMW-SPI system

Figure 1 shows the proposed MMW-SPI system developed using an LC mask cell with a matrix electrode structure. The MMW was generated using a Gunn oscillator (70 GHz) and then directed to a horn antenna. The emitted MMW was incident on a test object, and the transmittance was nonuniform. The transmitted MMW was further spatially modulated by passing it through the LC mask. The MMW polarization direction coincided with the orientation direction of the LC, which was identical to the rubbing direction. Finally, all MMW bundles were collected using a second horn antenna. The integrated MMW intensity was measured using a detector.

It is known that LC materials typically exhibit strong anisotropy during MMW absorption; for example, $\alpha_{\parallel}$ = 0.019 mm^{-1} and $\alpha_{\perp}$ = 0.036 mm^{-1} for 5CB [2]. Hence, the MMW transmittance can be switched in response to the change in the orientation direction of the LC, which is flipped by an applied voltage. The voltage applied across each pixel is controlled by the crossed slit electrode configuration (Fig. 2). In our MMW-SPI system, the conventional passive matrix driving method was not employed. A more convenient method was adopted; that is, a constant voltage was applied between the selected slit electrodes. The column and row electrodes were chosen individually during the operation. In this driving method, multiple pixels were turned on simultaneously. Some researchers might be concerned about the so-called cross-talk issue, widely encountered in passive matrix LC devices. However, in ordinary SPI systems, the multiple pixel operation is no longer recognized as a problem because the coded mask pattern consists of multiple on-state pixels. Furthermore, the proposed LC mask cell provides other advantages; thus, a steep transmittance–voltage property is unnecessary, allowing for an unlimited number of electrodes.

In the MMW-SPI system, a linear relationship between the measured data $\mathbf{y}$ and estimated data (reconstructed image) $\mathbf{x}$ was assumed; that is, $\mathbf{y} = \mathbf{Ax}$, where $\mathbf{A}$ is the measurement matrix. The image can be restored using $\mathbf{x} = \mathbf{A}^{\dagger}\mathbf{y}$, where $\mathbf{A}^{\dagger}$ is a pseudoinverse of $\mathbf{A}$. $\mathbf{A}^{\dagger}$ is equal to a matrix inverse $\mathbf{A}^{-1}$ only when $\mathbf{A}$ is regular. The measurement matrix was generated based on the combination of the selected row and column electrodes.

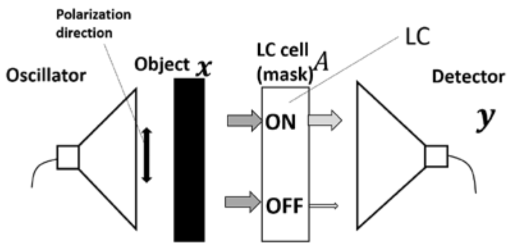

Fig. 1 Proposed MMW-SPI system.

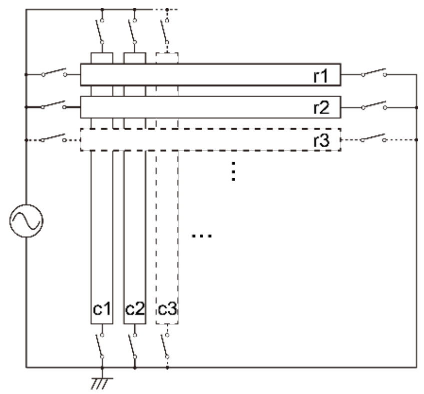

Fig. 2 Electrode configuration of LC mask.

3 Demonstration of MMW-SPI

The measurement matrix exhibited a pronounced influence on the quality of the reconstructed image. We investigated the effect of the measurement error (noise) on the estimated data. The measured data were expressed as a summation of the signal and noise components ($\mathbf{y} = \mathbf{y}_s + \mathbf{\Delta y}$). The deviation of the estimated data was calculated as $\mathbf{\Delta x} = \mathbf{A}^{\dagger}\mathbf{\Delta y}$. Figure 3 shows the calculated values of the mean square error (MSE) of $\mathbf{\Delta x}$ for three different measurement matrices (the Hadamard, identity, and proposed matrices) in the proposed one-by-one electrode selection method. The Hadamard matrix is widely used for general SPI systems. The identity matrix was used for the raster scan.

The added Gaussian noise $\mathbf{\Delta y}$ for each examination was randomly generated, and the $\mathbf{\Delta x}$ evaluation was repeated 100 times. The standard deviation of the introduced noise was 1% of the signal component of the raster scan, and the same noise was introduced equally to the measured data for all matrices. It should be noted that the signal-to-noise ratios (SNRs) for the three measurement matrices were different because the absolute value of the signal components were different. The highest SNR was obtained for the Hadamard matrix, indicating “bright measurement.”

The average standard deviation of $\mathbf{\Delta x}$ was 1% for the raster scan because $\mathbf{\Delta x} = \mathbf{\Delta y}$; accordingly, the average MSE (variance) was 1.0×10^{-4}, consistent with Fig. 3(a). The Hadamard matrix is generally suitable as the measurement matrix because the noise exhibits a minimal effect (Fig. 3(a)); the MSE was as low as 8.0×10^{-6}. For the proposed measurement matrix, the average MSE was 2.0×10^{-5}, which was 2.5 times higher than that of the Hadamard matrix; however, it was significantly lower than that of the identity matrix. We expect that the optimal combination of the operating row and column electrodes decreases the MSE for the proposed measurement matrix.

Finally, a demonstrative experiment was conducted. A rectangular copper piece attached to the back of a paper sheet was inserted into the system. The width and length of the metal patch were 5 and 10 mm, respectively. The specimen was obliquely directed to the system and invisible by the naked eye. The dark area (indicated by the dotted-border rectangle in Fig. 3(b)) was easily recognized. The features of the dark area, such as the size, position, and direction, were similar to those of the test metal patch, proving that the proposed MMW-SPI system can detect concealed metal objects. However, the blurred images obtained in this study should be improved. Optimizing the measurement matrix and pixel size will lead to low-noise and high-resolution images.

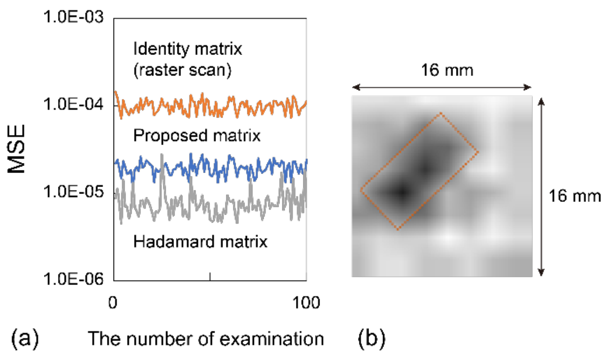

Fig. 3 (a) MSE of estimated data in presence of Gaussian noise during measurements. (b) Reconstructed image of metal patch (8 x 8 pixels) concealed under paper sheet.

4 Conclusion

In this study, an MMW-SPI system was developed using an LC mask cell with a matrix electrode structure. We confirmed the possibility of practical nondestructive inspections through a demonstrative experiment for detecting a concealed tiny metal piece.

References

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