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High Sparse Single-frequency Millimeter Wave (MMW) Imaging for Human Safety Inspection

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Abstract
Millimeter wave (MMW) imaging technology has been widely applied in the field of human security inspection for its penetrability and nonionizing character.However,it needs sampling large number of spatial information to ensure image high resolution.Which means great burden for data collection and process,at the same time,it has to sacrifice the complexity and cost of hardware to improve image quality.The theory of compressed sensing is proposed able to reconstruct image with high resolution while the signal is collected as less as possible.In this paper,we adopt a CS-based method for MMW image and mainly researched the application of CS in 2D MMW image based on single frequency.We set several different under-sampling rate to make a comparison,experiments achieved high quality image reconstructed with far less than Nyquist data acquisition.It provides a promising method to reduce system cost and work of data processing for MMW security inspection.

Keywords
MMW, Human Security Detection, Compressed Sensing(CS), Single Frequency, Signal Acquisition

I. Introduction
In recent years, the threat of society security problems have draw people's high attentions and what in urgent is there needs an efficient human security inspection instrument to detect various hidden dangerous items without harming people's privacy and health.Millimeter wave (MMW) imaging techniques provided a promising method for this urgency and it has a great development in these years[1].Millimeter wave is electromagnetic wave with the frequency at 30GHz ~300GHz that corresponding wavelength is at the range of 1 ~ 10mm, electromagnetic wave can pierce through lot of things like clothing and the performance of short length makes it possible to capture more details of image to ensure very high image resolution,which makes it is attractable for so many imaging field such as communication, Radar,clinical medicine[2,3]. On the other hand, the nonionizing property of millimeter wave means it is more suitable for human testing. At present,the most common tools of security check are metal detectors and X-ray systems,however,the metal detectors are limited because it can only detect metal objects,other hazardous article like lighters and ceramic knives are beyond the ability of it.On the other hand, the X-ray systems is well known for the harmless to body that can not applied in the humanity detection. So,the MMW system is seemed as the method that is most able to efficiently replace or cooperate with other security tools.

Although there are so many advantages of MMW hologram imaging technology,the system is applied a wide band radar that based on a two-dimensional plane or cylindrical antenna array to collect a large amount of spatial data to guarantee the image resolution.However,there is a trouble that the data can show the whole body is very huge,whose transmission and procession is under great burden.in addition,the system complexity will also be increased.In engineering application there will be very glad to get a method that can ensure image resolution and at the same time decrease the acquisition rate.Compressed sensing (CS) can exactly resolve this problem like those[4-6].CS has gotten a big development since it was proposed in several years ago.According to the CS theory,it can accurately recover the signal even at a high sparse collection.It has been widely researched in the imaging files such as synthetic aperture imaging (SAR)[7], magnetic resonance imaging (MRI)[8],and terahertz imaging[9] to solve the problems of signal acquisition.

In our work,we main studied the CS based reconstructed for single-frequency millimeter wave imaging.By uniformly abandoning a part of full data to simulate undersampling pattern,to use the missing data to recover image.Different sampling rate was set to obverse the recovery results to verify the method we proposed.The paper is organized as follows:section-2 main introduced the conventional millimeter wave hologram imaging algorithm.Section-3 briefly described the theory of compressed sensing and main introduced total variation for CS based millimeter wave hologram imaging algorithm.Section-4 set up a lot of experiments and simulations to recover the image and made a series of undersampling to check the results.Section-5 main made some analysis about the CS based method according to the reconstruction.

II. Millimeter Wave Hologram Imaging Algorithm
Hologram imaging technology operated by collecting a set of coherent wave data generated on a two dimensional aperture to imaging for target.The coherent scattering wave source like electromagnetic waves or sound waves is used to illuminate the target,reflection or echo signal received by receiver,then a focused image can be reconstructed from the received data by the reflection function.The imaging system is shown in figure1.

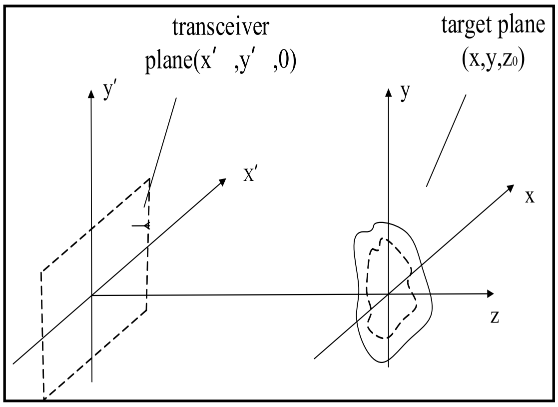


Fig.1:The hologram imaging system

We assumed the receiver is at the point $(x', y', 0)$,a point on the target plane is (x, y, z_0) , $f(x, y, z)$ is the reflection function of target plane.Thus,the scattered field of the transceiver plane can be approximated seem as the superposition of reflection wave, those waves are reflected on each point on target plane.So the echoed signal can be expressed as:

$$s(x', y') = \int f(x, y, z) e^{-j2k\sqrt{(x-x')^2+(y-y')^2+z_0^2}} d_x d_y \quad (1)$$

Where k is the wavenumber,the exponential term can be seem as a spherical wave which is the superposition of plane waves. It expressed as:

$$e^{-j2k\sqrt{(x-x')^2+(y-y')^2+z^2}} = \iint e^{jk_x'(x'-x)+jk_y'(y'-y)+jk_z'z_0} dk_{x'} dk_{y'} \quad (2)$$

The Fourier transform form for equation (1) is written as:

$$s(x,y) = \iint F(k_x, k_y) e^{jk_z z_0} e^{j(k_x x + k_y y + k_z z_0)} dk_x dk_y \quad (3)$$

The finally imaging algorithm is

$$f(x,y) = FT_{2D}^{-1}[FT_{2D}[s(x,y)] e^{-j\sqrt{4k^2-k_x^2-k_y^2}z_0}] \quad (4)$$

The focused image of target can be gotten by calculate the equation (4),where FT_{2D}^{-1} and FT_{2D} are the operator of two-dimensional back and former Fourier transform.

II. The Imaging Method Based On Compressed Sensing

Conventional sampling is based on the Nyquist theory to guarantee the image out of distortion.So,the collected data is a huge amount,while most part of those date is redundant and just a small portion of them take significance responsibility for imaging reconstruction.Thus,full sampling means waste and great burden for sampling,storage and transaction.Compressed sensing can exact resolve the problems.

1. Compressed Sensing

The bases of CS theory expresses as: Assuming a signal $X \in R^n$ is compressible in a transform domain and it can be expressed as $\Theta = \Psi^T X$ in the sparse domain.There need a $M \times N$ matrix Φ ,to obverse the transformation ratio Θ ,where M is (much) lower than N ,So we get the part of signal we need $Y = \Phi\Theta = \Phi\Psi^T X$. This can also be seemed as that X be observed by a matrix $A^{cs} : Y = A^{CS} X$ .Finally,by solving a l_0 -norm optimization problem to get a accurate or approximate value of X .The mathematical expression is:

$$min\|\Psi^T X\|_0 \quad s.t \quad A^{CS} X = \Phi\Psi^T X = Y \quad (5)$$

It always be solved as the Lagrangian form:

$$min\|Y - \Phi\Psi^T X\|_2 + \lambda\|\Psi^T X\|_0 \quad (6)$$

Where λ is the regularization parameter that take the function of control the trade-off between sparsity and closeness of the image.The most important of compressed sensing theory can be categorized into the following three points: sparsity, projection matrix and signal reconstruction.A key point of the reconstruction quality is the sparsity of signal,the signal more sparse in a transform domain [10],the more precise of reconstructed signal. Most common three sparsity bases are wavelet,curvelet and total variation (TV),there also consider some joint sparse. Another critical factor is the correlation between sparse matrix and projection matrix,it is called as restricted isometry property (RIP).The more uncorrelated,it has more possibility to recover sparsity K.

As a new coming sampling theory,compressed sensing has been studied in a lot of fields,such as channel estimation,magnetic resonance imaging (MRI), radar imaging,information sampling. For the huge potential of decreasing information collection,there will must be a great application of CS in so many territories.

2. CS method for single frequency MMW imaging

We have introduced the imaging algorithm in section-2,the equation (4) can be written as:

$$s(x, y) = FT_{2D}^{-1}[FT_{2D}[f(x, y)] e^{jk_z z_0}] \quad (7)$$

Where $k_z = \sqrt{4k^2 - k_x^2 - k_y^2}$,to be more convenient expressed,changing (7) into following:

$$\boldsymbol{S} = \boldsymbol{HF} \quad (8)$$

Where $\boldsymbol{S}$ is the function of $s(x, y)$,similarly, $\boldsymbol{F}$ is the function of $f(x, y)$,and $\boldsymbol{H}$ is a operator of all the transformation,where $\boldsymbol{H} = FT_{2D}^{-1}[FT_{2D}[\cdot] e^{jk_z z_0}]$ .The inverse transformation of equation (8) is

$$\boldsymbol{F} = \boldsymbol{H}' \boldsymbol{S} \quad (9)$$

$\boldsymbol{H}' = FT_{2D}^{-1}[FT_{2D}[\cdot] e^{-jk_z z_0}]$ .As we have reminded of that $\boldsymbol{S}$ is the echoed signal,on the other words,it is the signal that we should collect.So,according to CS theory,the signal could not full sampling,we simulated undersampling by uniformly leaving out a part of data.In mathematics,it is expressed by a mask $\boldsymbol{M}$ which is a matrix only contains 1 and 0,where 1 means sampling and 0 means abandoning.thus,the signal sampled can be expressed:

$$Y = M.*S = M * H \qquad (10)$$

In CS theory,one of the most important factors that influence constructed image quality is the sparsity or compressibility of signal,image compression usually adopts sparse transform [11,12] such as wavelet transform (WT) or discrete cosine transform (DCT). In this paper, it is necessary to take into account the recognition of the target image.Total variation (TV) [13,14] regularization has a better performance in keeping the image edge and smoothing noise,by introducing some constraints, the image restoration can be converted into a well-posed problem, and it can ensure the image restoration is exist and unique,which has the advantage of less noise interference[15].The discrete total variation model used in this paper can be expressed as:

$$TV(F) = \|\nabla_x F\|_1 + \|\nabla_y F\|_1 = \sum_{i,j} |F_{i+1,j} - F_{i,j}| + \sum_{i,j} |F_{i,j+1} - F_{i,j}| \qquad (11)$$

So the imaging model based on CS can be expressed as

$$\hat{F} = \arg\min_{F} \|M.*HF - Y\|_2 + \alpha TV(F) \qquad (12)$$

solving this equation will be able to get the recovered image. $\hat{F}$ is the result obtained by solving the equation based on sparse constraint.Where α is the regularization parameter that used to balance the sparse term and the fitting term to make the image is the best quality.

III. Experiments and Results

1. Experiments setting and simulations

The experimental data are derived from the echo data that scans a real gun.The sampling scene parameters are as follows:the distance between center of antenna array and target is Z_0,it's 0.33m, the antenna spacing is 0.001m,scanning bandwidth is 20GHz. According to the Nyquist sampling theory,the sampling points should be 200 x 200,the collected data will be imaged in MATLAB. The hologram image based on traditional RMA algorithm used Nyquist sampling data as shown in the figure 2.

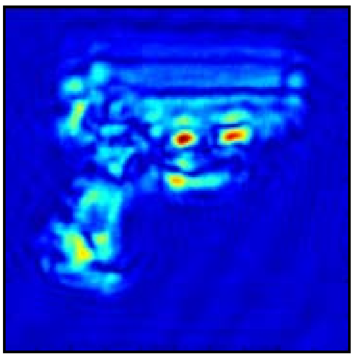
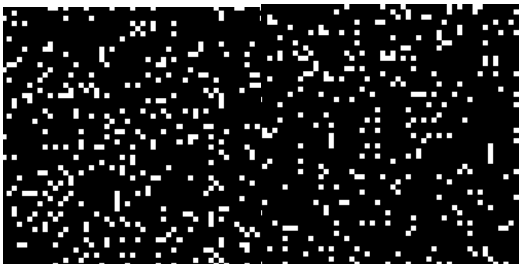


Fig. 2:The hologram image based on full data.

We simulate the under-sampling pattern by uniformly abandon a part of data.So,we can random setting the percent of acquisition to observe the reconstructed effect to examine the algorithm based on CS.In this paper,the sampling rate was set at a low level,as the result shows,the CS method has a great effect to recover the high undersampling images.We set the collection rat are 50%,33%,25%,20%,12.5% and 10%,all of sampling are uniform and random,as the figure 3 shows the sampling mask.

(a) (b)

(c) (d)



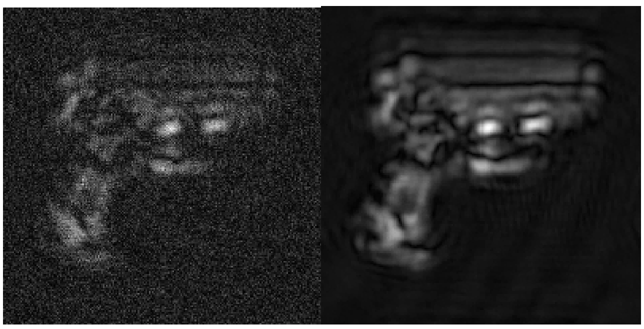
(e) (f)

Fig.3:(a) (b) (c) (d) (e) (f) are sampling mask with the sampling rate at 50%,33%,25%,20%,12.5% and 10%.

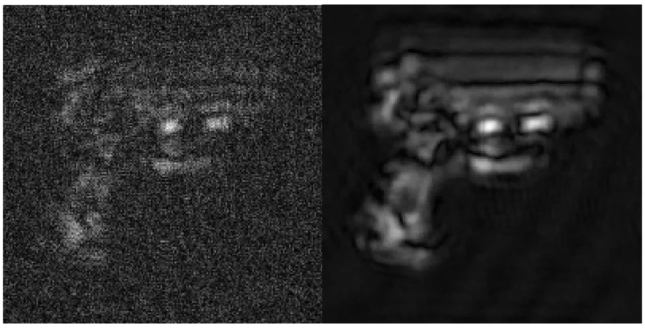
The white points in the figure is the palace where we sampled, for randomly sampling,they are uniformly distributed.Based on those pattern,we use CS method to recover the image.

2. Results and analysis

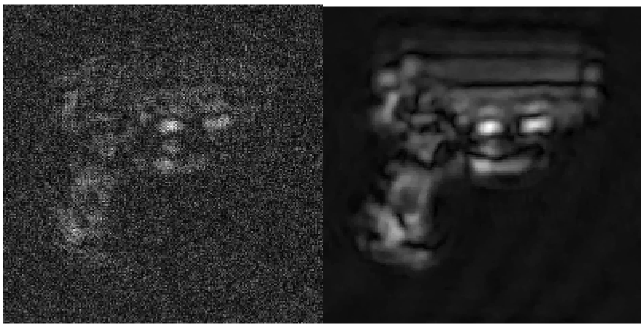
In order to be better prove the great effect of CS method,we contrast the images based traditional algorithm and CS method at the different sampling rate,the images show in figure 4.



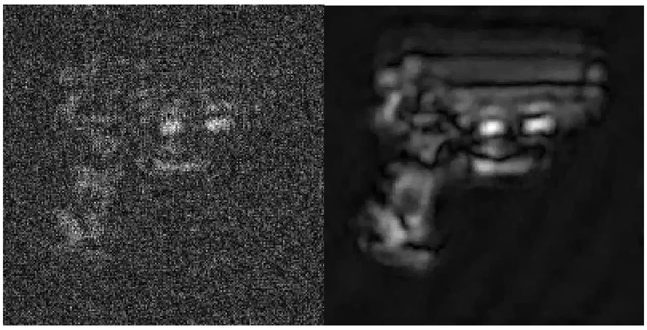
(a)



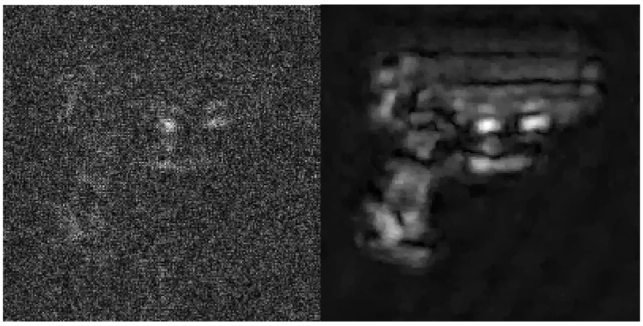
(b)



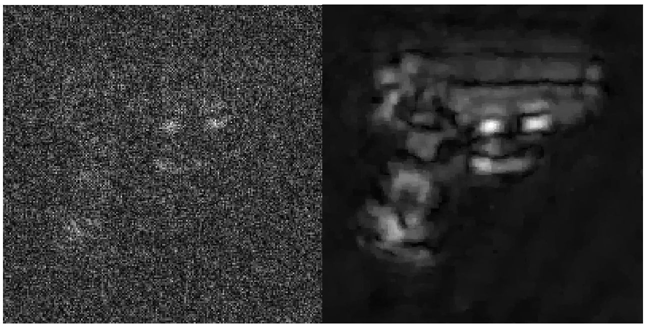
(c)



(d)



(e)



(f)

Fig.4:(a) (b) (c) (d) (e) (f) are the recoveries based on traditional imaging algorithm and CS algorithm with the sampling rate at 50%,33%,25%,20%,12.5%,10%.

The images can show the recover effect at the visual,it's a qualitative comparison,to be more concrete,we set the value of relative error to get a quantitative analysis,the comparisons are shown in figure5.

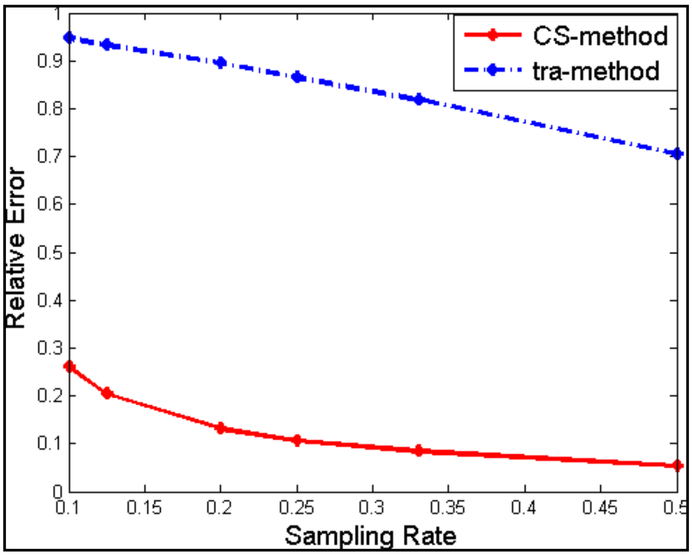


Fig.5: Relative errors of traditional method and CS method.

The recovered images and the comparison of relative error show that CS has a great effect to reconstructed the high sparse image on the condition that great lack of data.When the data is 50% of full data,the relative error is just 5.56% compare with the full data image,in the visual,it is almost has not distortion.Even when the data is 10%,the basic outline of a gun is clear,while the traditional method recover the image can not distinguish even a point,and the image is full of noise.In addition,due to the characteristics of total variation, the image noise and artifact reduction.

IV. Conclusion

Based on the algorithm of CS that it can recovery signal on the condition of just sampling a part of full data as long as the original signal is sparse.We applied this theory in single-frequency millimeter wave imaging,we have found that even sampling rate is only 10% of the original data, the image is still very good recovery;when the sampling rate is 50%, the relative error is very small,compared with original image the recovered image is almost the same resolution as the original image.So,based on CS method can greatly reduce the collection of data and the image can be smoothed the noise.In summery CS applied in the millimeter wave hologram imaging can reduce the cost of hardware at the same time guarantee the image quality,it is a promising method.

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