Pattern Design and Imaging Methods in 3-D Coded Aperture Techniques

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Abstract

We have conducted research on coded aperture patterns composed of cyclic difference set uniformly redundant arrays (URA) such that the system point-spread-function is a delta function and no spurious artifacts are introduced by the spatial multiplexing process. Such arrays have the property that the autocorrelation functions have a single peak and flat sidelobes. Although there are some analytical methods for designing some patterns with such a property, the theory is quite incomplete thus requires a different approach. We have searched a complete list of such patterns for a range of 1-D and 2-D dimensions, and have obtained some rules. The available results can be used as practical patterns, or as future research reference for coded aperture pattern design.

We also summarize the 3-D coded aperture imaging methods through a single-angle view (such as coded aperture laminography, moving object coded aperture imaging) and through multiple-angle views (such as modular coded aperture technology, coded aperture tomography), describe the image reconstruction and data processing algorithms, and discuss and compare the performance of different coded aperture imaging methods. Simulation and experimental results have been provided for verification.

I. INTRODUCTION

Since the coded aperture imaging idea was first proposed in the 1960's, various approaches have been made for the pattern design to minimize the sidelobes of the system point spread function (SPSF).

We have conducted research on coded aperture patterns composed of cyclic difference set uniformly redundant arrays such that the system point-spread-function is a delta function and no spurious artifacts are introduced by the spatial multiplexing process. Such arrays have the property that the autocorrelation function has a single peak and flat sidelobes. Although there are some analytical methods for designing some patterns with such a property, the theory is quite incomplete thus requires a different approach. We have searched a complete list of such patterns for a range of 1-D and 2-D dimensions, and have obtained some rules. The available results can be used as practical patterns or as future research reference for coded aperture pattern design.

Coded apertures have been mainly used for astronomy. We have studied the method for near field imaging. 3-D coded aperture imaging through a single view and multiple views can be used.

II. THEORY

Coded aperture imaging is a technique for producing images of radiation emitting objects by using a mask (coded aperture) with spatially varying opacity distributed according to some mathematical algorithm. A radiation source (such as a photon source) will cast a shadow onto a position sensitive detector, thus encoding the spatial information contained in the source. The resulting shadowgram can be deconvolved with a suitable decoding algorithm to reconstruct the original source distribution. The sensitivity improvement for coded aperture methods over a pin-hole camera, whose size is the same as the size of each individual coded aperture, is in principle proportional to the square root of the number of holes in the coded aperture pattern when the pattern open fraction is not greater than 50%. The choice of aperture patterns determines the spatial resolution as well as the system response function. We have used a cyclic difference set as the coded aperture pattern; the system point spread function is a delta function and thus no spurious sidelobes are introduced.

We have found that a cyclic difference set[1] can be used to form the coded aperture pattern; the system point spread function is a delta function and thus no spurious sidelobes are introduced. Through exhaustive search, we have obtained the complete list of such sets for a range of 1-D and 2-D dimensions.[4]

We have conducted study on near field 3-D coded aperture imaging through a single view (data collection from a single angle) and multiple views (data collection from multiple angles). Image reconstruction and data combination methods are explored. Simulations and experiments have been performed for verification.

There have been a handful of attempts for near field coded aperture imaging, and even fewer for 3-D imaging. We will describe our research on three-dimensional coded aperture techniques using Moving Object Coded Aperture Imaging (MOCAI), Coded Aperture Laminography (CAL), Modular Coded Aperture Technology (MCAT), and multiple-view Coded Aperture Tomography (CoAT).

Pattern Design

The concept of a cyclic difference set is from circulant and Hadamard matrix.[1] A URA pattern whose basic pattern is a cyclic difference set has the property that the SPSF via correlation is a delta function thus no artifacts are introduced in the spatial multiplexing process of coded aperture methods.

Through exhaustive searching, we have obtained the complete list of the satisfactory patterns, and found more possible patterns with the above desired property, which

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cannot be calculated from any existing equation and are previously unavailable.[4] No complete theory or equation can effectively give all possible patterns.

As an example, the following shows the complete list for 4 by 4 patterns, and does not include the shifted (or rotated), reflected, and complementary patterns, nor all 0 (or 1) and single 0 (or 1) patterns.

4 by 4 (6 patterns; no half-occupied patterns)

0110	1110	0111
0101	0001	0100
0011	0001	0010
0000	0001	0001
1011	1110	0010
0001	0100	0001
0100	0100	1101
0001	0001	0001

Single-Angle View Imaging

CAL (single angle one-shot imaging)

Coded Aperture Laminography is a focusing technique to image different layers of an object using coded aperture methods. Photon sources at different distances to the coded aperture plane cast scaled coded aperture patterns on the detector array. When a particular scaling factor is used in decoding, only the corresponding layer is focused, and other layers are blurred out. The advantage for this method is simplicity, and the disadvantage is limited capability for the range of depth it can image, i.e. the depth of focus (DOF). An illustration of the concept is shown in Figure 1.

The detector array needs to hold and discriminate at least a basic pattern of the mosaicked URA coded aperture pattern, thus when the layer being imaged is closer to the coded aperture plane, the required detector area is larger; when the layer being imaged is farther away from the coded aperture plane, the required size for the detector resolution elements is smaller in order to discriminate apertures in the pattern. This is in contrast to the MOCAI method described in next section. In MOCAI, the requirement for detector is constant, the detector usage is maximum and optimal, and the system performance is more uniform than that of CAL.

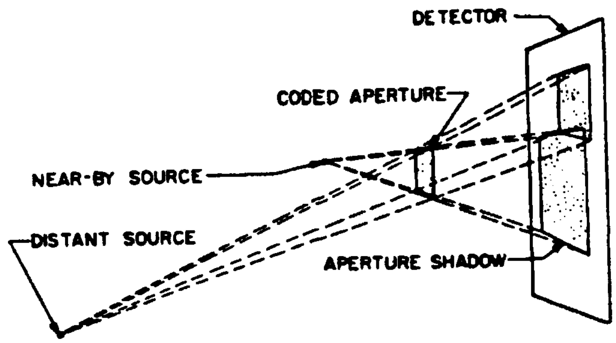


Figure 1. Diagram of Coded Aperture Laminography (CAL).
This figure illustrates the concept for coded aperture laminography, which is a scaling method for 3-D coded aperture imaging with a single view.

MOCAI (single angle multiple-shot imaging)

The moving object 3-D coded aperture imaging method that we have used is illustrated in Figure 2. The object layer being imaged is indicated in the figure. The distance between the coded aperture plane and the detector system is the same as (as illustrated in the figure) or different than that between the coded aperture plane and the object plane being imaged. The object is being moved continuously or step-by-step toward the imaging system through a transportation belt under the object. The imaging system works in a continuous or "step-and-shot" whole object 3-D imaging mode, respectively. Mechanical mechanism will transfer the imaged objects away from the imaging system. In Figure 2, photon imaging is assumed, where photons can be from any X-ray or gamma-ray emitters or other photon emitters within the object being imaged, for example, photon emission due to neutron analysis, gamma-ray resonance analysis, gamma-ray emission, or Compton scattering. (Sources of neutrons and high energy charged particles such as electrons within the object can also be imaged by this method if proper detectors and coding mask are used.) In the geometry setup in Figure 2, in order to collect the complete information about the object plane being imaged, the detector system should be able to image and discriminate the URA basic pattern.

For CAL, the object being imaged is considered static and has different layers with different distances to the coding mask plane. Different layers of the object cast scaled versions of the coding mask pattern to the position-sensitive detector system. The detector system must be physically large enough to hold a basic pattern projected from the nearest plane in the object, and has enough detector pixels such that the elements of the projected coding mask pattern from the farthest object plane can be distinguished. This requires more detector pixels than a basic pattern in the coding mask.

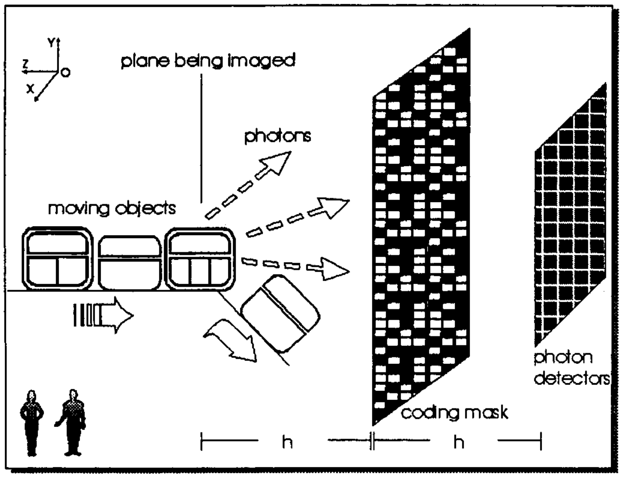


Figure 2. Illustration of Moving Object 3-D Coded Aperture Imaging (MOCAI). This figure illustrates the concept of moving object 3-D coded aperture imaging. The objects (photon emitter) being imaged are moving (step-by-step or continuously) toward the coded aperture imaging system, and the system reconstructs an image of the object plane being focused (labeled in the figure) after each data collection. This figure shows an equal-distance imaging geometry, i.e., the scaling factor is 2. In actual cases, we can use a larger scaling factor to improve spatial resolution.

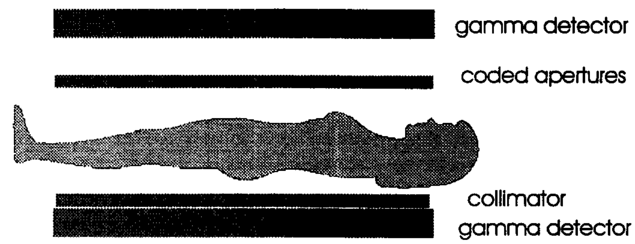


Figure 3. Diagram of Modular Coded Aperture Technology (MCAT). This figure illustrates the concept for MCAT: A coded image and a conventional image using a parallel-hole collimator are produced simultaneously on a dual detector imaging system. The decoded image is then "merged" with the conventional image to produce the final representation of the object.

The final results can be as satisfactory as other tomography methods because data sampling is performed from many different angles thus all spatial frequencies have been sampled and the obtained information is intact. Figure 4 illustrates the idea for CoAT. [2] The illustration shows a dual-angle view CoAT system, and those two views are orthogonal. This is the simplest CoAT system. When multiple views are employed, finer data sampling in the spatial domain is performed, and it will yield better reconstructed images.

Multiple-Angle View Imaging

MCAT (dual-view one-shot imaging)

The Modular Coded Aperture Technology (MCAT™) is a method that combines coded apertures with collimators. Currently, it has been used for 2-D radiography and 3-D SPECT to enhance system resolution and sensitivity. Park Medical Systems has used this technique to achieve an MCAT planar spatial resolution of 5.4 mm (FWHM), and MCAT SPECT spatial resolution of 6 mm (FWHM).

The principle of MCAT imaging is that a coded image and a conventional image using a parallel-hole collimator are produced simultaneously on a dual detector ISOCAM II imaging system. The decoded image is then "merged" with the conventional image to produce the final representation of the object. Intuitively speaking, the coded acquisition is providing counts and resolution, the conventional image is providing information on the background and on the general structure of the object. Although the "merging" method used by the company is unknown, some empirical methods can be used to combine the data from coded apertures and the data from collimators, for example, treating the collimator image as a weighting factor, or using the collimator data as part of the feedback in iterative reconstruction algorithms.

CoAT (multiple view one-shot imaging)

Coded Aperture Tomography (CoAT) presented here is a multiple-angle view 3-D coded aperture imaging technique, and is not a combination of coded aperture method with some other imaging modality such as SPECT. The CoAT is different from other tomography techniques using backprojection, such as X-ray CT and emission tomography, but use some data combination methods for data from multiple views.

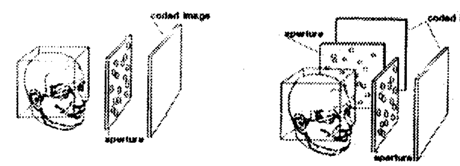


Figure 4. Diagram of Coded Aperture Tomography (CoAT).
This figure illustrates the concept for CoAT. The drawing on the left shows a single-angle view imager; the drawing on the right shows an orthogonal-view imager, which illustrates the idea for multiple-angle view coded aperture imaging. [2]

The data combination methods used in CoAT include the following:

1. Point-to-Point Product (or Element-wise Multiplication) method: In each view (or angle), after data collection, performing 3-D image reconstructions using CAL. The reconstructed 3-D images are then interpolated into a standard dimension such as 256 x 256 x 256. Balanced decoding is used in the process. The resulting 3-D images from all views are then combined via point-to-point product (or element-wise multiplication). The signal in voxels containing sources will be greatly enhanced, and the noise will be balanced.

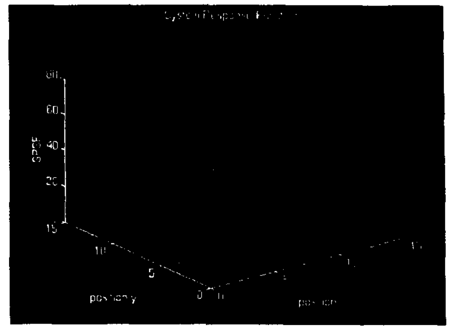
2. Summing method: Reconstructing 3-D images using CAL and interpolating them into a standard dimension as above. The resulting 3-D images from all views are then combined via summing, then the signal in the voxels containing sources will be greatly enhanced, and the noise will be balanced. This is a "softer" (less dynamic) method than the above one.

III. EXPERIMENTS

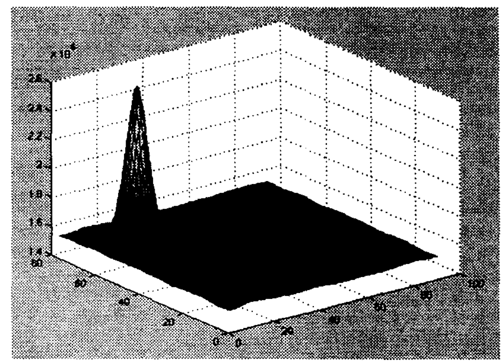
In simulations, we simulated typical situations in different coded aperture imaging methods.

In experimentation, we have conducted coded aperture imaging with a 11 by 13 pattern and a 41 by 43 pattern for phantoms simulating photon sources from 1-D to 3-D, and have compared the results with collimator systems. Experiments have been conducted using Siemens E.CAM and MULTISPECT 2 gamma/SPECT cameras. The above experiments are for technitium-99m (140 keV gamma rays) and fluorine-18 (511 keV gamma rays) radiopharmaceuticals used routinely in nuclear medicine.

Figure 5 shows the SPSF of our coded aperture patterns. (a) is from error-free theoretical analysis, i.e. the ideal SPSF for an 11 x 13 cyclic difference set URA pattern. (b) is from experimental measurement and reconstructions, i.e. the experimental results for the SPSF of such a pattern (for 140 keV gamma rays).



(a)



(b)

Figure 5. System point spread function (SPSF) of coded apertures using a cyclic difference set URA. (a) SPSF of a cyclic difference set URA: error-free theoretical performance. (b) Reconstructed image of a point gamma-ray source (technetium-99m, 140 keV gamma) using coded apertures: experimental SPSF, the system point spread function measured experimentally.

IV. RESULTS AND DISCUSSION

Results from simulations and experiments we have performed show significantly improved sensitivity for a coded aperture imaging system over pin-hole cameras and collimator systems, and show that the system point spread function (SPSF) has a single peak and flat sidelobes.

From Figure 5, we can see the delta-function-like SPSF in both error-free theoretical analysis and the actual experimental measurement and reconstruction. Single-angle view coded aperture imaging is an easy way to achieve near field 3-D imaging capability with high sensitivity. Multiple-angle view coded aperture imaging can produce reconstructed images with fewer artifacts because of more spatial sampling. The possible artifacts from 3-D coded aperture imaging methods are from defocused object planes.

V. CONCLUSIONS

A coded aperture imaging system using a cyclic difference set uniformly redundant array can achieve very high sensitivity while retaining spatial resolution. The sensitivity is proportional to the total open area in the coded aperture plane if the pattern open fraction is not more than 50%. The system spatial resolution depends on the aperture size, imaging geometry, and detector spatial resolution. Single-angle view imaging such as CAL and MOCAI can be used to achieve 3-D imaging and suppress noise from defocused object planes; multiple-angle view imaging such as CoAT can be used to achieve better images and balance noise from defocused object planes. A combination of coded apertures and collimators as well as iterative postprocessing algorithms can be used to achieve reconstructed images of better-quality.

VI. ACKNOWLEDGMENTS

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