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(71) Applicant(s):
Qinetiq Limited
(Incorporated in the United Kingdom)
85 Buckingham Gate, London, SW1 6TD,
United Kingdom

(72) Inventor(s):
Geoffrey Derek De Villiers
Christopher William Slinger
Douglas Alan Payne

(74) Agent and/or Address for Service:
QinetiQ Limited
IP Formalities, A4 Building, Room G016,
Cody Technology Park, Ively Road,
FARNBOROUGH, Hants, GU14 0LX,
United Kingdom

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EP 1627526 A **WO 1996/024032 A1**
Coded aperture imaging with multiple measurements; Busboom, A. et al, J Opt. Soc. Am., Vol. 14, No. 5, May 1997.

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(54) Abstract Title: **Coded aperture imaging apparatus performing image enhancement**

(57) A method of processing data acquired from a coded aperture imaging apparatus comprises processing the data to form a first image and subsequently performing at least one image enhancement step. The image forming step may use a Tikhonov regularisation technique, Weiner filter technique or a Landweber iteration. Image enhancement may involve dividing the image into regions over which a point spread function is relatively invariant and processing each image area separately; processing may be sequential. The inverse problem may be solved over each small image region, with values of the solution at the region centres being retained as solutions; this may use Tikhonov regularisation using Fourier methods or truncated singular function translation. Prior to image forming and enhancement, the constraint that the true image is non negative may be used. Data from plural, combined images can be used, and image enhancement may comprise a 'track before detect' algorithm or super resolution curve fitting.

Figure 1

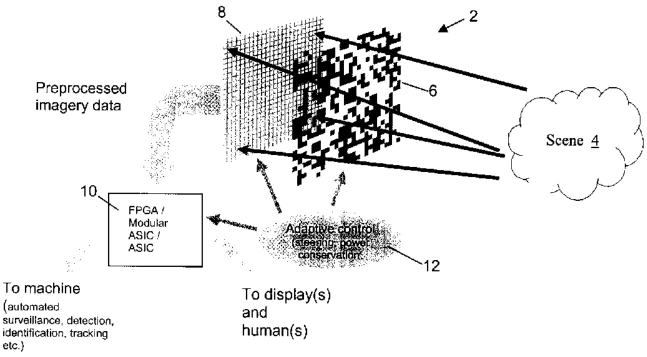

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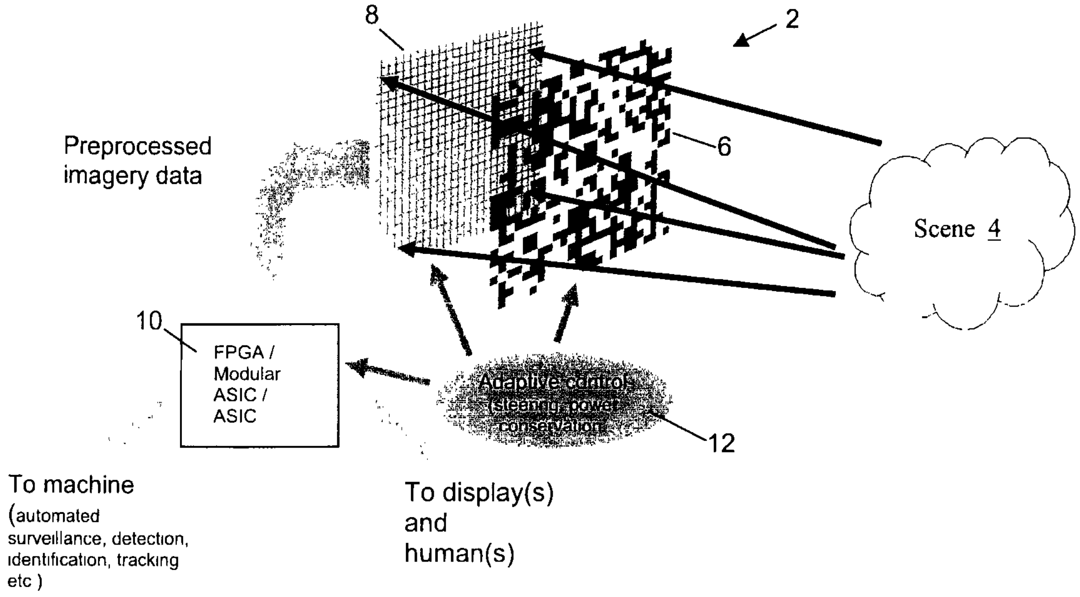
Figure 1


8
2
Preprocessed imagery data
6
Scene 4
10
FPGA / Modular ASIC / ASIC
Adaptive controls (steering, power conservation)
12
To machine (automated surveillance, detection, identification, tracking etc)
To display(s) and human(s)

Processing Methods for Coded Aperture Imaging

This invention relates to methods for processing image data acquired in a coded imaging system.

Coded aperture imaging is a known imaging technique which is primarily used in high energy imaging such as X-ray or γ-ray imaging where suitable lens materials do not generally exist, see for instance E. Fenimore and T.M. Cannon, "Coded aperture imaging with uniformly redundant arrays", Applied Optics, Vol. 17, No. 3, pages 337 – 347, 1 February 1978. It has also been proposed for three dimensional imaging, see for instance "Tomographical imaging using uniformly redundant arrays" Cannon TM, Fenimore EE, Applied Optics **18**, no.7, p. 1052-1057 (1979)

Coded aperture imaging exploits the same principles as a pinhole camera but instead of having a single small aperture uses a coded aperture mask having an array of apertures. The small size of the apertures results in a high angular resolution but increasing the number of apertures increases the radiation arriving at the detector thus increasing the signal to noise ratio. Each aperture passes an image of the scene to the detector array and so the pattern at the detector array is an overlapping series of images and is not recognisable as the scene. Processing is needed to reconstruct the original scene image from the recorded data.

The reconstruction process requires knowledge of the aperture array used and system configuration and the aperture array chosen is often coded to allow subsequent good quality image reconstruction. The processing is performed using a mathematical model of the particular array at a set location.

Coded aperture imaging can be thought of as a geometric imaging technique and for the applications it is usually used for, e.g. astronomy, diffraction is negligible.

Recently, see our co-pending UK patent application GB0510470.8, the present inventors have proposed using a reconfigurable coded aperture imager having a reconfigurable coded aperture mask means. The use of a reconfigurable coded aperture mask means allows different coded aperture masks to be displayed at different times. This allows, for example, the direction and FOV of the imaging system to be altered without requiring any moving parts. Further the resolution of the imaging system can also be altered by changing the coded aperture mask displayed on the coded aperture mask means.

The pattern displayed on the coded aperture mask means is a coded aperture mask and at least part of the coded aperture mask is a coded aperture array. That is either the whole pattern displayed on the mask means is a coded aperture array or only part of the pattern is a coded aperture array. For the avoidance of doubt the term aperture used herein does not imply a physical hole in the mask means but merely an area of the pattern which allows radiation to reach the detector.

As mentioned the reconfigurable mask means can display a variety of coded aperture masks having a variety of coded aperture arrays in different positions on the mask means. The field of view of the imaging system can be altered by changing the position of the coded aperture mask on the array relative to the detector and the resolution can be altered by changing the size of the coded aperture array. Knowledge of the particular array displayed and its location is used in reconstructing the scene image in the same way as for a fixed coded aperture.

GB0510470.8 teaches a versatile and lightweight imaging system that can be rapidly configured to have different fields of view or resolution without any moving parts. It eliminates the need for conventional optics, gives conformal imaging capability, can have an infinite depth of field and gives inherent power free encryption since decoding of the image requires knowledge of the coded aperture array used. The imaging apparatus described therein is particularly suitably for several imaging and surveillance applications in the visible, infrared or ultraviolet wavebands.

However, high resolution imaging requires small aperture sizes and a longer optical path from the detector to the mask, which increases the effects of diffraction. Diffraction causes a blurring of the pattern formed by the mask on the detector array, reducing the coding and having a corresponding detrimental effect on decoded image quality.

It is therefore an object of the invention to provide a method of processing image data from a coded aperture imaging system which recovers good image quality.

Thus according to the present invention there is provided a method of processing data acquired from a coded aperture imaging apparatus comprising the step of processing the data to form a first image and subsequently performing at least one image enhancement step.

Thus the method of the present invention works in stages. In a first stage the intensity pattern on the detector array is processed to form an image.

The skilled person will appreciate that, in the diffraction free case, the signal recorded at the detector array of a coded aperture imaging system can be described as a convolution of the scene intensity with the aperture function of the coded aperture array plus some noise. The object of all decoding algorithms is therefore to recover the scene image by using knowledge of the mask pattern, for instance by performing a deconvolution or cross correlation.

Where diffraction effects are significant however the intensity pattern at the detector array no longer corresponds directly to the aperture function. Instead the diffraction pattern formed at the detector array is in effect a blurred version of the mask pattern. Thus a decoding algorithm based on the aperture function of the coded aperture array will result in a blurred image.

The present invention therefore forms a first image of the scene. This first image will be blurred due to any diffraction effects. The method of the present invention therefore applies at least one image enhancement step to improve image quality.

The step of forming the first image may use any of the processing techniques known for conventional coded aperture array. Preferably however, as image decovolution is an ill posed inverse problem various techniques applicable to the solution of ill posed inverse problems may be applied. In one preferred embodiment a Tikhonov regularisation technique may is applied in producing the first image. Tikhonov regularisation is a known technique in the solution of inverse problems, see for example page 108 of "Introduction to Inverse Problems in Imaging, M. Bertero & P. Boccacci, Institute of Physics Publishing, 1998, ISBN 0750304359 (hereinafter referred to as Bertero & Boccacci). Alternatively a Weiner filter technique could be applied. An iterative technique such as the Landweber iteration could also be used, see page 291 of Bertero & Boccacci.

The first step of the method of the present invention therefore produces an image which is a blurred version of the true image. In order to improve image quality at least one image enhancement step if performed. The blurred image can be seen as the true image convolved with a point spread function. The step of image enhancement is then to recover the true image.

Preferably the at least one image enhancement step therefore involves the step of dividing the first image into a series of image regions over which the point spread function is relatively invariant and processing these sub-images to improve quality. Dividing the image into a plurality of small image areas not only ensures that the point spread function is spatially invariant for that area but it also eases the computation as compared with attempting to process the entire image. Preferably the inverse problem is solved over each small image region and the values of the solution at the centre of the region are retained as the solution. The region is then moved by a number of pixels and the process repeated.

Preferably solving the inverse problem for each image region is Tikhonov regularisation which may be accomplished using Fourier methods. Alternatively a truncated singular function expansion could be used as proposed in "Scanning singular-value decomposition method for restoration of images with space-variant blur", D A Fish, J Grochmalicki and E R Pike, J.Opt.Soc.Am A, 13, no. 3 1996, pp464- 469. This is a more computationally intense method that Tikhonov regularisation. This method requires calculation of the singular value decomposition (SVD) associated with the point-spread function. However if the point-spread function is spatially invariant then the SVD just needs to be calculated once for treating the entire image.

Since coded aperture imaging involves incoherent imaging the true image has to be non-negative. This prior information can be included in the solution of the inverse problem (see, for example, G D de Villiers, E R Pike and B McNally - Positive solutions to linear inverse problems. Inverse Problems 15, 1999 pp. 615-635.).

Positivity may also be incorporated into the solution using a variant of the Landweber iteration and this is potentially easier to implement (see Bertero and Boccacci, page 291). Note that the Richardson-Lucy method (also known as the Expectation Maximization method) has similar performance to the projected Landweber method though it is computationally more intensive (Bertero and Boccacci, page 179).

Where one has prior knowledge that the image has a small number of point targets the image enhancement step may additionally or alternatively may use of super-resolution methods involving curve-fitting.

If the coded aperture imager is to be used for tracking then high-resolution patches may only be needed where tracking is being carried out. This would cut the computational load significantly. Therefore the method may involve the step of performing image enhancement only at parts of interest of the image, i.e. moving parts of the scene or areas of possible or confirmed targets.

The image enhancement step may also involve combining data from a plurality of images of the scene. By taking several images of the scene using different coded aperture masks it is possible to generate additional information about the scene. In essence on can impose some statistical structure on the data.

Specifically where the coded aperture imager is used for target tracking information from more than one image can be combined. Preferably a track-before-detect scheme is used. Track Before Detect algorithms have been previously used in the radar and sonar fields and use data from several acquisitions of data from the sensor together to improve target identification. A similar approach could be used to different images from a coded aperture imaging system.

The present invention may therefore employ a three stage process. In the first stage a first image of the scene is produced. This will be a blurred image of the scene due to diffraction effects. In a second stage the image may be divided into image regions and each processed to improve image quality. Finally in a third stage data from other images may be combined to further improve the image quality of at least part of the image.

The present invention will now be described by way of example only with respect to the following drawing of which;

Figure 1 shows schematically a coded imaging system of the present invention.

Coded aperture imaging (CAI) is based on the same principles as a pinhole camera. In a pinhole camera, images free from chromatic aberration are formed at all distances away from the pinhole, allowing the prospect of more compact imaging systems, with a much larger depth of field. However, the major penalty is the poor intensity throughput, which results from the small light gathering characteristics of the pinhole. Nevertheless, the camera is still able to produce images with a resolution determined by the diameter of the pinhole, although diffraction effects have to be considered. The light throughput of the system can be increased by several orders of magnitude, while preserving angular resolution, by using an array of pinholes. Each detector element sees the result of the summation of contributions from the various pinholes, corresponding to each viewpoint of the scene.

Another way of understanding the operating principle of conventional CAI is to observe that this is a purely geometric imaging technique. Light from every point in a scene within the field of regard (FOR) of the system casts a shadow of the coded aperture onto the detector array. The detector measures the intensity sum of these shadows. The coded aperture is specially designed such that its autocorrelation function is sharp with very low sidelobes. Typically pseudorandom or uniformly redundant arrays (URA) (such as described in E. Fenimore and T.M. Cannon, “Coded aperture imaging with uniformly redundant arrays”, Applied Optics, Vol. 17, No. 3, pages 337 – 347, 1 February 1978) are used where a deconvolution or decorrelation of the detector intensity pattern can yield a good approximation to the point distribution in the scene.

Previous CAI systems have generally been employed in application where diffraction effects are minimal. For instance coded aperture imaging has often been used in astronomical imaging. However, for some applications of coded aperture imaging techniques, it is necessary to improve the angular resolution significantly. This can be especially true when operating in the visible, infrared or ultraviolet wavebands say, or in other wavebands requiring high resolution imagery. Assuming that the detector pixels are smaller than the feature size of the coded aperture array, p, the angular resolution is determined by $\tan^{-1}(p/s)$ where s is the optical distance between the mask and the detector array. Therefore increasing the resolution of the imager requires either decreasing the size of the apertures or increasing the mask to detector distance or both. With relatively small apertures and/or large mask to detector distances, diffractive effects start to become significant. The blurring effects of diffraction mean that the pattern projected onto the detector array is effectively smeared, reducing image quality.

Figure 1 shows schematically an example of a coded aperture imaging system, generally indicated 2. Rays of light from points in the scene 4 fall onto a particular coded aperture array 6. The coded aperture array acts as a shadow mask and therefore a series of overlapping coded images are produced on the detector array 8. At each pixel on the detector array, the intensities from the overlapping, coded images are summed. The output from the detector array 8 is passed to a processor 10 where image of the scene can be subsequently decoded from the detector signals using a variety of digital signal processing techniques.

Recently GB0510470.8 has proposed using a reconfigurable mask means 6 to provide reconfigurable coded aperture array. The coded aperture mask means 6 is controlled by a controller 12 which controls the reconfigurable mask means to display different coded aperture masks. If only part of the coded aperture mask means displays a coded aperture array, the rest of the mask preventing radiation from reaching the detector, then the field of view of the apparatus is determined by the location and size of the coded aperture array relative to the detector, changing its position or size changes the field of view and/or resolution of the imager.

CAI therefore offers the ability to provide a compact and lightweight imaging apparatus which has a large depth of field and has a changeable field of view without requiring any moving parts.

As mentioned above the intensity pattern formed at the detector array 8 is a series of overlapping images of the scene created by the various apertures. This intensity pattern requires decoding to construct a recognisable image of the scene.

Since the Fraunhofer pattern for a multiple aperture system only becomes observable at a range commensurate with the size of the large aperture (rather than the individual apertures) it will not be possible to observe this pattern using a coded aperture imager without a large mask to detector spacing. For practical implementation of coded aperture imaging there may be a limit on the possible mask to detector spacing and hence the imager will operate somewhere between the Fresnel regime and the Fraunhofer one. In this region the mask pattern will still be visible, though very blurred.

The Fresnel diffraction pattern is a blurred version of the mask. There will be energy in the regions corresponding to closed pixels (see, for example, P V Avizonis, J S Fender and R R Butts – Interference of diffracted multiple wavefronts in the geometric shadow of the Fresnel region. Applied Optics, 28, no. 1 1989, pp.163-172). However, vestiges of the mask pattern are still visible in the Fresnel pattern.

The Fresnel diffraction pattern of the mask will have the same number of peaks as there are open pixels in the mask. In order to discuss resolution issues it is advantageous to start with a blurred image which consists of the true image convolved with a point-spread function which has one narrow main lobe and low sidelobes.

This suggests a multi stage procedure – firstly correlate with the Fresnel image of the mask pattern. As a result of the correlation one will end up with a blurred version of the true image. Since before correlation the image was linearly related to the true image it will remain so after correlation, since correlation is a linear operation. The resulting point-spread function (the autocorrelation function of the diffraction pattern of the mask) is smooth and relatively localised and the processing is then that associated with linear inverse problems with smooth kernels.

For this first stage it is important that the mask is designed in such a way that the autocorrelation function of the Fresnel diffraction pattern associated with the mask has a narrow main lobe and low sidelobes, though there will inevitably be a trade-off between these two properties.

Note that since it is envisaged that the mask will be larger than the detector, for off-axis sources a different part of the diffraction pattern of the mask will be required for cross-correlation purposes. Hence the field of view will need to be divided into portions over which a given pattern will be used for correlation purposes. This could lead to a point-spread function which is not spatially invariant.

The image is therefore divided into small regions over which the point-spread function is relatively invariant. The inverse problem is solved over each small region and the values of the solution in the centre of the region are retained as the solution. The region is then moved by a number of pixels and the process is repeated. This combination of scanning and only using the values of the solution in the centre of the region guarantees that the "blockiness" often associated with image deblurring methods which divide the image into sub-images does not occur.

In what follows the inverse problem will be taken to mean that associated with one of these sub-images.

One option for solving the inverse problem is Tikhonov regularisation (see Bertero and Boccacci, page 108). This may be accomplished using Fourier methods.

A more computationally-intensive method is the truncated singular function expansion (see Fish et al. 1996). In order to do this one needs to calculate the singular value decomposition (SVD) associated with the point-spread function. However if the point-spread function is spatially invariant then the SVD just needs to be calculated once for treating the entire image.

Positivity

Since the camera operation involves incoherent imaging the true image has to be non-negative. This prior information can be included in the solution of the inverse problem (see, for example, de Villiers et al., 1998).

Positivity may also be incorporated into the solution using a variant of the Landweber iteration and this is potentially easier to implement (see Bertero and Boccacci, page 291). Note that the Richardson-Lucy method (also known as the Expectation Maximization method) has similar performance to the projected Landweber method though it is computationally more intensive (Bertero and Boccacci, page 179).

High Resolution Methods

Super-resolution methods involving curve-fitting such as may be applicable to obtain very high resolution if one has the prior knowledge that the image consists of a small number of point targets and the signal to noise ratio is very high.

Examples of such methods are CLEAN in radio astronomy, approximate maximum likelihood, the IMP algorithm, iterative removal of sources (IROS) in coded-aperture imaging, the MUSIC algorithm in radar and sonar, and many other similar methods.

Tracking applications

If the camera is to be used for tracking then high-resolution patches may only be needed where tracking is being carried out. This would cut the computational load significantly.

Track before detect algorithms can be also be applied to improve resolution of targets in the scene.

Claims

1. A method of processing data acquired from a coded aperture imaging apparatus comprising the step of processing the data to form a first image and subsequently performing at least one image enhancement step.

2. A method as claimed in claim 1 wherein the step of forming a first image uses one of a Tikhonov regularisation technique, a Weiner filter technique and a Landweber iteration.

3. A method as claimed in claim 1 or claim 2 wherein the at least one image enhancement step therefore involves the step of dividing the first image into a series of image regions over which the point spread function is relatively invariant and separately processing each these image regions.

4. A method as claimed in claim 3 wherein the inverse problem is solved over each small image region and the values of the solution at the centre of the region are retained as the solution.

5. A method as claimed in claim 4 wherein each image region is processed sequentially.

6. A method as claimed in claim 4 or claim 5 wherein the step of solving the inverse problem for each image region is performed by Tikhonov regularisation using Fourier methods.

7. A method as claimed in claim 4 or claim 5 wherein the step of solving the inverse problem for each image region is performed using a truncated singular function expansion.

8. A method as claimed in any preceding claim wherein the constraint that the true image is non negative is included as prior information in the step of forming the first image and/or the image enhancement step.

9. A method as claimed in any preceding claim the image enhancement step uses super-resolution methods involving curve-fitting.

10. A method as claimed in any preceding claim wherein the method involves the step of performing image enhancement only at parts of interest of the image.

11. A method as claimed in any preceding claim wherein the image enhancement step may comprises combining data from a plurality of images of the scene.

12. A method as claimed in claim 11 wherein the image enhancement step comprises a track-before-detect algorithm.

The Patent Office
For Innovation

Application No:	GB0602386.5	**Examiner:**	Matthew Males
Claims searched:	1 - 12	**Date of search:**	27 April 2006

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 3, 8 at least	EP 1627526 A XCEED IMAGING - see abstract; page 30 onward; Figs 1, 4, 9 etc.
X	1 at least	WO 96/24032 A1 PINECONE IMAGING - see abstract; Figs 1 , 4A, 4B etc.
X	1 at least	Coded aperture imaging with multiple measurements; Busboom, A. et al, J Opt. Soc. Am., Vol. 14, No. 5, May 1997. See page 1062, para B: the "difference image" would seem to anticipate the "first image" of claim 1, and subsequent filtering is a form of "image enhancement".

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

H4F

Worldwide search of patent documents classified in the following areas of the IPC

G01T; H04N

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC, INSPEC, TXTUS0, TXTUS1, TXTUS2, TXTUS3, TXTEP1, TXTGB1, TXTWO1, TXTAU1