

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

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1. AGENCY USE ONLY (Leave Blank) 2. REPORT DATE
12 December 2003 3. REPORT TYPE AND DATES COVERED
Final 9/18/2000 -11/17/03

4. TITLE AND SUBTITLE
Electronic Imaging: Propagation, Retrieval, Recognition 5. FUNDING NUMBERS
DAAD19-00-1-0551
~~41230PH~~

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Institute of Optics
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REPORT NUMBER
309/00-03

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211 10. SPONSORING / MONITORING
AGENCY REPORT NUMBER
~~DAAD19-00-1-0551~~
~~41230PH~~
41230.1-PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
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13. ABSTRACT (Maximum 200 words)

This is the final report for a balanced program of theoretical and experimental research that has been conducted in order to discover and demonstrate novel emerging electronic imaging systems. Electronic imaging systems combine optical image acquisition and photosensor arrays with digital computers and displays. This combination leads to systems which are capable of remarkable performance, hence the designation smart cameras. Smart cameras are systems that see and think. During this program, we have made excellent progress on several projects and graduated two doctoral scholars. Papers were published on GRIN array imaging, holography of nonrigid objects, holographic interference filters for infrared communications, and extended depth of field by tenfold using our novel logarithmic asphere lens. Important image science publications include an extension to the Whitaker-Shannon sampling theory. Three patents were filed or granted: Imaging through turbulence, wide angle uniform diffusing screens, and the logarithmic asphere lens.

14. SUBJECT TERMS
image science, holography, depth of field, automatic recognition, image quality 15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT
UNCLASSIFIED 18. SECURITY CLASSIFICATION ON THIS PAGE
UNCLASSIFIED 19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED 20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. Z39-18
298-102

20040112 006

Enclosure 1

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Electronic imaging: Propagation, Retrieval, Recognition
FINAL PROGRESS REPORT
18 September 2000 to 17 November 2003

(4) Statement of the problem studied:

Emerging Electronic Imaging Systems

In electronic imaging an integrated consideration of image acquisition and image processing is leading to important new devices --- systems that see and think. In our research the topics group broadly into (1) Image Science, e.g., diffraction theory, image processing, and statistical optics, (2) Emerging Systems, (3) Information Processing, e.g., Holography, and (4) Automatic Recognition. This classification is often a matter of judgment and taste since there is considerable overlap in these groupings. For example, the discovery and demonstration of a new emerging imaging system certainly requires a generous application of Image Science.

(5) Summary of important results

Let us describe the more important results in chronological order. The discussion will follow the listing of publications in peer-reviewed journals that are contained in Section c (6)(a) below.

Automatic Recognition (1) In a paper by Berfanger and George [1] carried over from the prior ARO contract, there were several important findings to be described below. The paper has a blending across the areas (1) Image Science, (2) Emerging Systems, and (4) Automatic Recognition. Here are the important results:

1. Image quality assessment is shown by this paper to be a subset of automatic pattern recognition. The NIIRS rating community will find it interesting and important.
2. A system known as the ring-wedge-detector, invented by the PI, has been converted from an analog laser optical system to an all-digital form. Major innovations in digital processing and neural networks are carefully described.
3. Image quality assessments are shown to be possible in a manner that is widely independent of scene content (scenery, human subjects, technical photos, etc.). Accuracies of 95% are obtained without knowledge of the original and these rise to 98% when the reference scene is known.
4. The ring-wedge measurement system provides results that are highly superior to what one obtains with an ad hoc assortment of the "classical metrics" and a neural network.

Emerging Systems (2) (5) (9) The logarithmic asphere lens is described in this first publication by a doctoral scholar Wanli Chi and N. George. The significance and wide applicability of this result is just now becoming evident. While the cubic phase mask of Cathey and Dowski was first, it does appear that the log-asphere may be superior -- only time will tell. The log-asphere is a radially symmetric lens with a focal length that varies radially. As we described in the literature there are two important advantages inherent in this concept:

1. The log-lens can provide diffraction-limited resolution with a tenfold improvement over the "textbook version" of depth of field.
2. The radial (circular) symmetry makes it relatively easy to manufacture.

Image Science (3) (6) (7) (11) Several interesting papers have been published during this contract. These results will appear in a thesis by Kedar Khare later (2004). Herein, we would like to showcase two major findings. In the paper (3) "Direct sampling and demodulation of carrier-frequency signals," an important

extension of the famous Whittaker-Shannon sampling theory has been found. It has been shown (as well) that direct sampling of carrier-frequency fringes can be used as an alternative to photomixing with a saving of a factor of 5 times in the number of samples needed. Another important aspect of this work that can be important in phase retrieval systems is the recovery of the phase of an optical wave, demonstrated experimentally (6,7). This basic finding should be useful to the data processing community for the lossless compression of carrier frequency data, such as SAR, that may be collected in a satellite.

For the second finding in sampling theory that we would like to highlight, we include the Abstract of paper (11) for a concise statement:

Sampling theory approach to prolate spheroidal wavefunctions (11)

Kedar Khare and Nicholas George

J. Phys. A: Math. Gen. 36 (2003) 1011-1021

We use the Whittaker-Shannon sampling theorem to show that the eigenvalue problem for the sinc-kernel is equivalent to a discrete eigenvalue problem. The well-known eigenfunctions, namely, the prolate spheroidal wavefunctions, their corresponding eigenvalues and the orthogonality and completeness properties are determined without invoking the prolate spheroidal differential equation. This analysis based on the sampling theorem may be used for calculating the eigenvalues and eigenfunctions of bandlimited kernels in general as we illustrate with an additional example of the sinc²-kernel.

Image Science (10) An important topic in diffraction theory was to develop a better understanding of gradient-index array imaging. These arrays are typically used in commercial printers for 1:1 image transfer over a short distance. They are used in the millions of units per year worldwide. The ABCD matrix generalization of Fresnel zone propagation was used in our Fourier optical analysis. Our analysis included aperture effects and emphasized imaging using incoherent illumination. This research is continuing so that one may better understand a wider application of these arrays including extended depth of field and color as well as greater lengths.

Information Processing (4) During the contract period, we completed a major study of the feasibility of using photopolymer material to fabricate holographic multilayer optical filters. In the publication we described a chain-matrix computation which we call thin multilayer decomposition (TMD) that is useful for modeling a multilayer film having an arbitrary index profile $n(z)$. Also using a DuPont photopolymer sensitive in the visible, we describe an optical configuration so that filter passbands can be obtained in the infrared range 1300 to 1600nm. More theoretical modeling is planned on this topic of an arbitrary $n(z)$.

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2. Requirement (ARO Form 18 / July 2003)

c(6)(a). Papers submitted and peer-reviewed and published

1. "All digital ring-wedge detector applied to automatic image quality assessment," Appl. Opt. 39, pp.4080-4097, 2000, D. M. Berfanger and Nicholas George. (Carryover from previous grant)
2. "Electronic imaging using the logarithmic asphere," Opt. Lett. 26, No. 12, pp875-877, 2001, Wanli Chi and Nicholas George.
3. "Direct sampling and demodulation of carrier-frequency signals," Opt. Comm. 211, pp85-94, 2002, Kedar Khare and Nicholas George.
4. "Holographic interference filters for infrared communications," Appl. Opt. 42, No. 7, pp.1203-1210, 2002, Damon W. Diehl and Nicholas George.
5. "Extended depth of field with the logarithmic asphere," Opt. & Photonics News, Dec. 2002, Wanli Chi and Nicholas George.
6. "Sampling, demodulation and phase retrieval," Opt. & Photonics News, Dec. 2002, Kedar Khare and Nicholas George.
7. "Direct coarse sampling of electronic holograms," Opt. Lett. 28, No. 12, pp 1004-1006, 2003, Kedar Khare and Nicholas George.
8. "The exponential of $\sqrt{\Delta^2}$ and the wave equation," Am. J. Phys. 71 (9), pp995-996, 2003, Kedar Khare.
9. "Extended depth of field using the logarithmic asphere," J. Optics A, Special Issue: Optics for the Quality of Life, 2003, Nicholas George and Wanli Chi.
10. "Fourier optical analysis of GRIN array imaging," Appl. Opt. 42, No. 42, pp 4434-4444, 2003, Xi Chen and Nicholas George.
11. "Sampling theory approach to prolate spheroidal wavefunctions," Journal of Physics A, 36, pp 10011-10021, September 2003, Kedar Khare and Nicholas George.

c. (6)(b)

Papers/Abstracts in conference proceedings

OSA Annual Meeting 2000

1. Extended depth of field smart camera, Wanli Chi and Nicholas George.
2. Holographic filters for infrared communications, Damon Diehl and Nicholas George.

OSA Annual Meeting 2001

1. Fourier optical analysis of GRIN array imaging, Xi Chen and Nicholas George.
2. Color image recovery using the logarithmic asphere, Wanli Chi and Nicholas George.
3. Detection of small-amplitude, low frequency vibrations, William W. Cook and Nicholas George.

IS & T's PICS Conference, 55th annual Conference, Portland, Oregon 2002

1. Smart Camera using the logarithmic asphere, Nicholas George and Wanli Chi

ICO 19th meeting, Florence, Italy 2002

1. Extended depth of field using the logarithmic asphere, Nicholas George and Wanli Chi

OSA Annual Meeting 2002

1. Imaging with the logarithmic asphere, Wanli Chi and Nicholas George.
2. Sizing and recognition of moving particulates, Weizhen Yan and Nicholas George.
3. Sampling theory for phase retrieval, Kedar Khare and Nicholas George

OSA Annual Meeting 2003

1. Eigenfunction analysis of imaging systems, Kedar Khare and Nicholas George

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c(7) Participating Scientific Personnel

Dr. Nicholas George, Principal Investigator
Wilson Professor of Electronic Imaging and
Professor of Optics

Partial support for research by the following list of doctoral scholars

David Berfanger, Xi Chen, Wanli Chi, Wade Cook, Damon Diehl, Christopher Ditchman, Kedar Khare, Hema Roychowdhury, Weizhen Yan.

Graduated as of December 2003

Dr. William Wade Cook, West Point undergraduate
Veteran of Persian Gulf, Bosnia, Afghanistan
Two Bronze Stars

Dr. Damon Diehl, University of Chicago undergraduate

c(8) Innovations (by title only)

Patents granted resulting from ARO-support

System for Recovery of Degraded images, U.S. Pat. No. 6,459,818 B1
Nicholas George

Optical System for Diffusing light, U.S. Pat. No. 6,583,932 B1
Nicholas George and D. R. Schertler

Patent Application

Imaging Using a Multifocal Aspheric Lens to Obtain Extended Depth of Field, U.S. Pat. Appl. No. 10/324,255
Nicholas George and Wanli Chi

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4. Scientific Progress and Accomplishments

Electronic imaging using a logarithmic asphere: Transmission functions are derived valid in the non-paraxial case for a class of lenses which will image a continuum of points along the object-optical-axis to a single image point. This lens, which we call a logarithmic asphere, is then used in a digital camera. The resolution of the camera is limited by the pixel-size of the CCD, i.e., it is not diffraction limited. Digital processing is used to recover the image, and image plane processing is used for speed. We find a ten-fold increase in the depth-of-field over that for the diffraction limited case.

Digital sampling and demodulation of carrier-frequency signals: We show that a generalized carrier-frequency signal can be efficiently sampled based upon the notion of space-bandwidth product. Using an envelope function form, we can treat both amplitude-modulation and frequency-modulation cases simultaneously. We derive an exact formula for the sampled carrier-frequency signal; and from this, we show that it is possible to recover the envelope function also in a sampled form. This alternative to the conventional demodulation process is illustrated with numerical examples. Extension to the two-dimensional case is also included.

5. Technology Transfer

For the logarithmic asphere discovery, we have had major interactions with the Army-supported Center for Optical Manufacturing (H. Pollicove) and the ARO Program Manager (D. Skatrud). Additionally, this work is of interest and is being coupled to John Hall, NV-ARL, for his consideration as a means for providing better vision through a tank window. To American industry, we have made presentations both at Xerox Corporation and at Eastman Kodak Company. Application to single-use cameras is being studied by us as well as digital video that need not be focused. The PI also made a presentation to a meeting of the Corporate sponsors of the Center for Electronic Imaging Systems (25 corporations) and a doctoral student explained the Fourier analysis along a GRIN array to the Industrial Associates of the The Institute of Optics. The PI also gave a video talk to Cornell/UR/Harvard on a system of anthrax detection and recognition.