RAPID COMMUNICATIONS

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Three-dimensional information extraction from a coded-scan tomogram

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In this Letter we present the theory and preliminary experimental verification of a new method for obtaining many different in-focus planes from a single tomogram. A potential advantage of the method is a reduction in x-ray dosage to the patient because, conventionally, a new tomogram must be recorded for each in-focus plane the radiologist wishes to examine. A cassette[1,2] can be used to record several tomograms simultaneously, but the additional image-intensifying screens tend to oppose dosage reduction. Also the planes of interest must be selected in advance. This Letter deals with classical tomography, not computerized axial tomography.

Tomography[1-3] has been in clinical use for over forty years. The technique now has many different implementations, all of which have the following facts in common: The x-ray source is moved during the exposure, and this causes a shadow of each resolvable plane in the patient to move in the film plane. However, the photographic film is also moved; and, if this motion is properly coordinated with the source motion, a particular plane P_0 in the patient (called the pivot plane, plane of cut, in-focus plane, objective plane, etc.) stays fixed with respect to the film. After development, the film shows a sharp image of this plane; all other planes have been blurred out because of relative motion between plane and film and, therefore, do not cause obscuring or confusing images.

Moreover, this blurring is of a particularly simple nature if both the x-ray source and the film move in planes parallel to the pivot plane P_0. We will designate this movement as the Twining-like movement.[2] The blurring action is then described by a convolution of the object with a scaled (i.e., magnified or demagnified) version of the locus $h(\mathbf{r})$ of the x-ray tube motion. Thus if $P_i(\mathbf{r})$ denotes an arbitrary plane parallel to the pivot plane, the blurred record of $P_i(\mathbf{r})$ on the film is described by

$$P_i\left(\frac{r}{M_i}\right) * h\left(\frac{\mathbf{r}}{M_{hi}}\right). \qquad (1)$$

Here, the * denotes a convolution, M_i and M_{hi} are appropriate scale factors, and $\mathbf{r}$ is a two-dimensional position vector.

It is useful to consider Eq. (1) in the context of other forms of coded imaging. In coded-aperture imaging[4,5] Eq. (1) arises with P_i being, say, a plane in the patient's radioactive thyroid, and h being the coded aperture (perhaps a zone plate). In coded-source imaging[6] h is the coded-source distribution and P_1 is a plane in the patient. In all cases (i.e., Twining-like tomography, coded-aperture imaging, and coded-source imaging) the coded image contains the convolution of a scaled code with a scaled version of one plane in the patient. The scaling factors M_i and M_{hi} are determined by the distances between the various planes. Each patient-plane gives rise to a term such as Eq. (1), so the coded image is a superposition of such terms.

In tomography, $M_{hi} \rightarrow 0$ for the pivot plane, and h collapses into a Dirac delta function (ideally). The coded image therefore contains the convolution of a scaled version of the pivot plane with a Dirac delta function. The result is that the coded image contains a sharp image of the pivot plane. However, to recover any other plane P_i parallel to the pivot plane, we must undo the blurring, i.e., the convolution Eq. (1).

There are several ways to recover out of focus planes, both by optical and digital means. For example, we could do inverse filtering,[7] [i.e., Fourier transform Eq. (1)] divide by the transform of h, and inverse transform to recover P_i. The inverse filter should cut off at high frequencies so it does not become purely noise-amplifying. There are, of course, some well-known problems associated with inverse filtering, which we will not go into here. Another way to deblur is by matched filtering. We chose this method for our preliminary experiments because of its ease of implementation and its previous use in coded-aperture and coded-source imaging. The incoherent optical system we used is well known[8,9] and is shown in Fig. 1.

The tomogram T is placed at a distance s_0 from a lens of focal length f and is illuminated with incoherent light. The spatial filter containing the impulse response h is placed against the lens. The impulse response is simply a photoreduced negative of a tomogram of a pinhole located away from the pivot plane. For example, if T is a tomogram recorded with hypocycloidal motion, h is a conveniently scaled, transparent, hypocycloid on an opaque background.

If we look at a viewing screen in plane P at a distance s_i downstream of the lens, where s_i satisfies

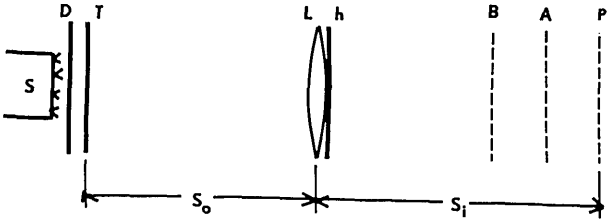

Fig. 1. Optical processing system: incoherent light source S; diffuser D; tomogram T; lens L; spatial filter h; planes B, A, and P.

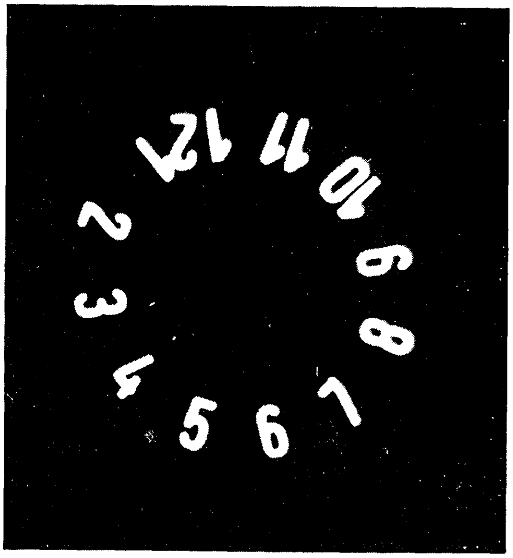

Fig. 2. A radiograph of the phantom (top view) used in the experiment.

Fig. 3. Circular-scan tomogram of the phantom of Fig. 2, with the pivot plane close to the 6-cm level.

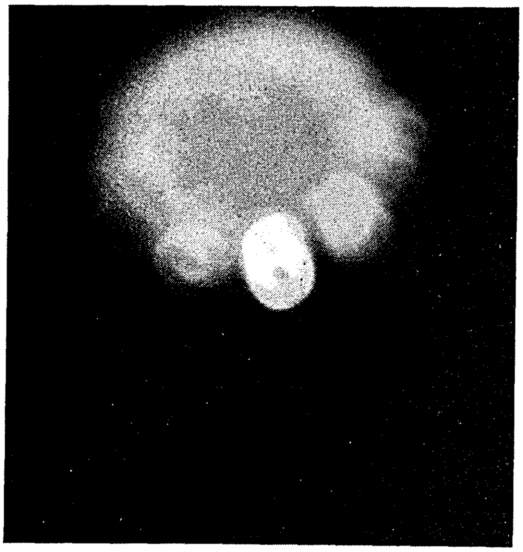

Fig. 4. The deblurred number 5.

$$\frac{1}{s_0}+\frac{1}{s_i}=\frac{1}{f},$$

we find an image of T; i.e., the pivot plane is in focus. But if we move the screen to other planes, we find the correlation of T with a scaled version of h. As we move from, say, plane A to plane B, we correlate with progressively larger versions of h. Suppose that we wish to deblur the ith plane. Then we move the screen to a location along the axis where the scaling of the blurring function and the impulse response of the matched filter are identical. This location is then the correct location for viewing the plane P_i, and the processed image is described by

$$\left\{\sum_j P_j\left(\frac{\mathbf{r}}{M_j}\right) * h\left(\frac{\mathbf{r}}{M_{hj}}\right)\right\} * h\left(\frac{\mathbf{r}}{M_{hi}}\right), \tag{2}$$

where the asterisk denotes correlation. This is the matched filtering operation. If the autocorrelation of $h(\mathbf{r}/M_{hi})$ is approximately a delta function, Eq. (2) contains the term $P_i(r/M_i)$; and deblurring is achieved. In the spatial-frequency domain, we require that the magnitude of the Fourier transform of h be, approximately, constant.

The cross-correlation of $\mathbf{h}$ with scaled versions of itself should be small; otherwise we would deblur several different planes simultaneously, thereby defeating the purpose of tomography. The autocorrelation function of h should also not have high secondary lobes; otherwise shifted, but overlapping, images of the same plane will appear simultaneously and confuse the observer.

Experimental results were obtained with a lead phantom and a Philips Polytome U machine, which was operated in the circular-scan mode. A radiograph (top view) of the phantom is shown in Fig. 2. Each number in Fig. 2 lies in a different plane, with the number 6 being 6 cm above the table, the number 5 being 5 cm above the table, etc. Figure 3 is a circular-scan tomogram with the pivot plane 6 cm above the table. Figure 4 shows the number 5 deblurred; the number 7 was similarly deblurred.

The impulse response h used in these experiments was simply a piece of black paper with a thin annulus (inner radius = 16 mm, outer radius = 18 mm) cut out from it. The simple circular (or, more accurately, annular) coding we used has also been used in coded-aperture imaging,[4,10] and its chief advantage is its simplicity. We are currently investigating codes that autocorrelate to give a better approximation to a delta function and cross correlate with scaled versions of themselves to yield negligible values. The x-ray source can be switched on and off (or perhaps even varied continuously) during a scan, so $h(\mathbf{r})$ need not be identical with the locus of tube motion. This should enable us to improve image quality and to deblur planes that are more remote from the pivot plane.

We are grateful to Stelios Orphanoudakis and Stephan Rothman of the Yale University Medical School for providing us with the necessary tomograms. This work was supported by NSF Grant GK-38308.

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X-ray microscopy with synchrotron radiation

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We have built a microscope for soft x radiation using zone plates as imaging optical elements. The experiments were done at the Deutsches Elektronen-Synchrotron (DESY), Hamburg, using holographic zone plates and gratings made at the Optical Laboratory of Göttingen Observatory.[1–3]

The wavelength region between 1–10 nm is suitable for x-ray microscopy. In this region the image formation is dominated by photoelectric absorption, which depends critically on the wavelength used and the density and chemical composition of the microscopic object. A great advantage of x-ray microscopy is that biological objects can be examined directly in a living state without severe radiation damage.

We used the synchrotron radiation at DESY because of its high intensity and because we could select the wavelength. Figure 1 shows the experimental arrangement. The polychromatic, slightly divergent radiation is dispersed by a 100-mm holographic laminar grating with 600 lines per millimeter used in grazing incidence. A holographically made zone plate with a diameter $D = 5$ mm, 2600 zones, and a focal length of $f = 522$ nm for 4.6-nm radiation generates a reduced monochromatic image of the synchrotron source in the object plane. A magnified image of the object is generated by a microzone plate in the image plane. Up to now we used a holographically made microzone plate with a diameter of 1 mm, 850 zones, and a resulting focal length of $f = 64.5$ mm for 4.6-nm radiation. A zone plate with high zone numbers behaves as a lens and resolves, according to the Rayleigh criterion, two pinholes with a separation of $s = 1.22\ \lambda \cdot f/D$. In this case the theoretical value is $s = 0.4$ μm when the zone plate is used in the first order. The first tests with synchrotron radiation showed that a distance of 0.5 μm has been resolved.

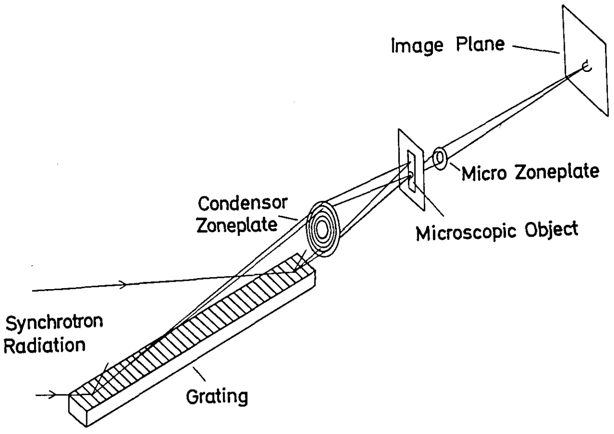

Fig. 1. The experimental arrangement.

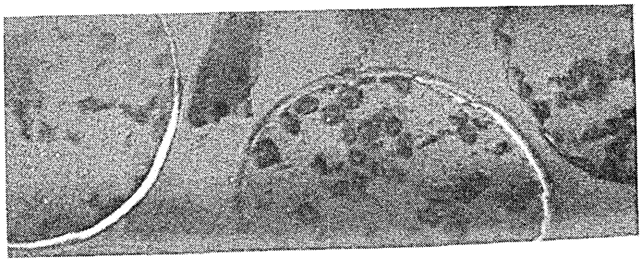

Fig. 2. A 3-μm section of *Eremosphaera viridis:* x-ray magnification 15×, total 330×, $\lambda = 4.6$ nm.

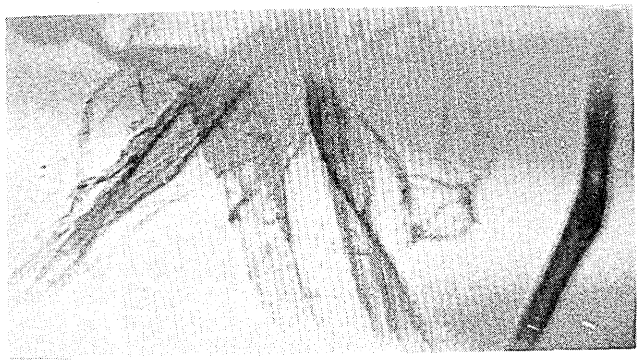

Fig. 3. Cotton fibers: x-ray magnification 15×, total 330×, $\lambda = 4.6$ nm.

Figure 2 shows an enlarged image of a 3-μm section of *Eremosphaera viridis,* stained with osmium acid and embedded in epoxy resin. Figure 3 shows an enlarged image of cotton fibers. In both figures the x-ray magnification was 15×, and total magnification is 330×.

The next experimental steps will be (1) to reduce the exposure times which are now some minutes long, (2) to improve the resolution, and (3) to do microscopy on biological objects *in vivo*, embedded in thin chambers filled with air or water and separated from the vacuum by thin organic windows.

Concerning biological objects, the smallest details that can, in principle, be recognized have dimensions of about 50 nm. This value will be achieved by improved zone plates under construction at the Göttingen Laboratory.

We thank H. D. G. Robinson and H. Sachs, Cytologische Abteilung der Botanischen Anstalten Göttingen, for providing us with biological material. The Deutsche Forschungsgemeinschaft supported the construction and testing of zone plates. We are grateful to the DESY for the opportunity to perform the experiment.

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Meeting Reports

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Canadian Society for Color, 4th annual meeting, Ottawa, 11–14 May 1976

Reported by David H. Alman
National Research Council of Canada

This year's program, consisting of nineteen papers on the topical subject of Colorants, was presented to about 100 participants at the University of Ottawa. The Society is a multidisciplinary group including fine artists, designers, technologists, and scientists, all of whom share a common interest in color. Because of this diversity of background it was necessary for the speakers to present the technical content of their papers in a descriptive rather than a quantitative manner. Thus this conference was more valuable for the person with a general interest in color than for the color scientist. I have commented on key papers and indicated the general areas covered by the remaining presentations.

The meeting was opened with introductory comments by **Jean Sutherland Boggs** (National Gallery of Canada). **A. F. Styne** (U. Miami) reported on the universal color language, which was particularly useful for this audience. This work (originally by Kelly of NBS) introduces a series of levels of color description, which allows for easier and more precise specifications of color by individuals with widely varying degrees of sophistication in color science. Other technical papers dealt with the production of colorants and their end uses in various industries. **J. D. Easton** (Reed, Ltd.) gave a paper on commercial pigment production, which was a thorough introduction to pigment technology. **W. E. Cooke** (Aluminum Co. of Canada, Ltd.) discussed coloring of anodized aluminum by various surface treatments including the use of alloying elements, organic dyes, inorganic pigments, and ac electrolysis of metal salt solutions. This paper was especially interesting since these are coloring techniques that are different from the common methods employed in most industrial or artistic situations.

Several papers dealt with control of colorant formulation or specification of commercial color products. **J. O. Elstad** (3M) discussed color control of retroreflective traffic signs. He stressed the difficulties of controlling a material which is meant to have similar signal colors under daytime (diffuse) and nighttime (retroreflection) viewing conditions. The problems of geometric factors influencing color measurements was extensively illustrated for both bidirectional and integrating sphere geometry instruments.

Several papers concerning subjects that might be described as being at the science–art interface were the highlight of the conference. **H. C. Van Imhoff** (Parks Canada) discussed art conservation and restoration with a detailed presentation of how a particular damaged artwork was restored. The application of techniques ranging from uv excited fluorescence photography to microscopy and radiography interested both scientists and artists. **R. Furbacher** (Concordia U.) assisted by **I. S. Butler** (McGill U.) presented a discussion based on an interdisciplinary educational experience in which art students chemically synthesized organic and inorganic pigments, dispersed these pigments into paint vehicles, and compared the resulting paints with commercial artists colorants. **R. Rawlinson** (Toronto Institute of Medical Technology) presented a paper on the history of natural dyestuffs. His point of view was as a user of dyes for staining human tissue to improve contrast in optical microscopy for medical diagnosis. However, he strayed widely from his professional interests to give the audience a fine overview of animal, vegetable, and mineral dye history and usage.

Other papers covered coloring of textiles, paper, and styrene plastics, as well as color control in paint and paper systems. Color rendering of light sources, a color system for use by graphic designers, artists colorants, photographic dyes, and artistic use of colorants for crafts were also discussed.

In addition to the formal papers a variety of other methods were employed to stimulate discussion between sessions. These included a visit to the National Research Council Optics Section, an evening showing of films dealing with various aspects of color, a book show, a hallway slide show, and a demonstration of polarization colors being employed as an art medium.

OSA Florida section, spring meeting, Florida Technological University, 1 May 1976

Reported by Neil Mohon, Naval Training Equipment Center

The Electrical Engineering Department of Florida Technological University in Orlando was host to the Florida section's spring meeting; Ron Phillips of that Department was in the chair.

Phillip Mallozzi (Battelle Columbus Laboratories) was the invited speaker for the session. He presented some results of his laser fusion research at Battelle and discussed many of the applications now available as a direct result of the work. One interesting application consisted of an injectable x-ray probe the size of a hypodermic needle.

Gottfried Rosendahl (Naval Training Equipment Center) discussed an error in first-order chromatic aberration equations that has been carried in textbooks for about 100 years. He showed that when a certain portion of the derivative, which had previously been assumed to be zero, is included in the summation of the thin lens set, better system agreement can be achieved. **Harry Bates** (Florida Technological University) presented a theoretical study of multiwavelength noncollinear phase matching in KDP crystals.