Toward robotic x-ray vision: new directions for computed tomography

Richard Gordon

With the advent of industrial computed tomography (CT or reconstruction from projections), which is of much wider scope than medical CT, the basic mathematical and physical assumptions need to be reconsidered. This paper considers the ramifications of the indeterminacy theorem and the underdetermined nature of the reconstruction equations. A search for truth rather than honesty in their solution is suggested. The use of steered microbeams, CT with few photons, multimedia CT, and the CT of soft (deformable) objects are discussed. The latter subject suggests that CT should become amalgamated with finite element analysis and computer-aided design. The computational load of 3-D robotic x-ray vision may require fifth-generation computers.

I. Introduction

Industrial computed tomography (CT) lifts many of the constraints imposed by medically oriented CT. Not only is there less concern for radiation dose, but the CT imager has available the whole universe of measurable radiations, fields, and particles. The size scales of objects being reconstructed can range from molecules[1] to galaxies.[2] The time constants for the phenomena being observed can range from picoseconds[3] to billions of years. The opportunities to build new instruments for entirely new purposes and markets allow us to shed old preconceptions.

Rather than review the electromagnetic and particle spectra and the variants of CT they lead to (masterfully done by Bates, *et al.*[4]; compare earlier lists[5–7]), I will concentrate on some general themes and opportunities that cut across many problems of nondestructive testing. I begin with the fundamental philosophical issue raised by the indeterminacy of the CT problem itself, which goes well beyond it being merely ill-conditioned. I then turn to problems that come out of our efforts at dose reduction in biology and medicine, not because dose reduction *per se* is of much importance in the industrial context, but because taking the CT problem to certain extremes leads to new ways of understanding it. I expect that this new understanding, once achieved, will lead to better imaging in all situations. In this category, I look at intelligently steered microbeams and getting by with small numbers of photons, and next consider multimedia CT, showing how the whole may indeed be more than the sum of its parts. Finally I take a glimpse at the CT of soft (deformable) objects, things that can change shape and structure over time, and estimate the computing speeds we will need to meet our ambitions.

II. CT is Worse than Ill-Conditioned

CT images are often remarkably good looking and are almost taken as a substitute for the reality they represent. It is hard to look at a good, clean CT image and suspect it of missing essential features any bigger than a few pixels. Yet this seems to be happening. Kennan Smith (Oregon State U.; personal communication; compare Smith and Keinert[8]) was puzzled by a patient in whom a brain tumor was found by surgery, although none had been seen by CT beforehand. Asking himself how this could come about, he arrived at the indeterminacy theorem: A finite amount of projection data does not determine a CT reconstructed image at all (in Smith *et al.*[9]). Any region, large or small, of a CT image can be replaced with any picture whatsoever. The complementary region can absorb this perturbation to the image in such a way that the projections of the reconstruction all match the data. A heuristic proof of mine, making this unpalatable theorem reasonable, is shown in Fig. 1. (For the rigorous proof, covering a wider range of cases than is evident in Fig. 1, see the original article.) Further examples of puzzling nonappearances of tumors in CT images are given by Messina[10] and Krudy *et al.*[11]

The author is with University of Manitoba, Department of Botany, Winnipeg, Manitoba R3T 2N2.
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