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A Hands-on Model-computed Tomography Scanner for Teaching Biomedical Imaging Principles*

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The physical and mathematical foundations of computed topography are notoriously difficult to understand. A newly designed hands-on model laser optical tomography system—suitable for both classroom and lab—can help students grasp the abstract concepts, such as projections, the Radon transform, and filtered backprojection. The model bridges the gap between the well-known need and the lack of hands-on imaging equipment in most educational programs. The device consists of simple elements that can be easily fabricated and assembled, for example within a capstone design class. Image generation can be watched on the controlling computer in a step-by-step process. In class, the majority of the students attested to the effectiveness of the demonstration. Particularly students who had not taken a related class before favored the model and generally considered it a significant teaching help for biomedical imaging.

INTRODUCTION

BIOMEDICAL IMAGING (BMI)—such as the century-old X-ray radiography and the newer methods, such as magnet resonance imaging (MRI) and computed tomography (CT)—is one of the core fields of biomedical engineering [3]. These BMI methods noninvasively obtain images from inside a patient's body. Therefore, BMI methods have become standard tests in the disease detection and patient care, and research on BMI has become a large part on the agenda of the National Institute of Health (NIH) [16].

This huge importance of BMI methods is further emphasized by the NIH's creation of the National Institue for Biomedical Imaging and Bioengineering (NIBIB) in 2001 [11]. Clearly, rapid advances in BMI technology require a well-educated BMI workforce, who mainly work in biomedical instrumentation companies engaged in the production of imaging instrumentation [9]. This requirement was expressed in the second annual NIH Bioengineering Consortium symposium [16], where speakers and audience members conveyed to the NIH the need for new training programs, including laboratory experience, to prepare the scientists for the type of interdisciplinary research required for success in the imaging sciences. Now, many biomedical engineering educational programs offer biomedical imaging classes at the graduate and undergraduate level. These classes have become well-accepted to provide the necessary background to work in the field of BMI.

However, the theoretical principles of image reconstruction are difficult to understand. While many BMI textbooks are available, they are mostly targeted toward a clinical audience; on the other hand, opportunities for hands-on education are very limited because of safety concerns, high cost, and lack of availability. Therefore, use of models to help learn the principles of imaging is considered an inexpensive and useful alternative for hands-on learning [11].

In a lecture series for general audiences, the effectiveness of demonstration models was pointed out [1]. Two possible examples for a teaching demonstration are the use of software teaching tools [13] or Web-based demonstrations [8]. A sample image is usually provided in those demonstrations; therefore, purely software-based solutions lack the link to a physical object and the practical scanning process. A model that scans a physical object is more realistic than a pure software demonstration, because the image acquisition chain begins with the patient or object to be scanned as well. In addition, a scanner model that provides a physical sample allows us to study additional aspects, such as device calibration and alignment, spatial measurements and scanning artifacts. Unfortunately, detailed instructions for the construction and effectiveness of more complex imaging models have only rarely been described in the literature.

A simple CT teaching model for use by medical students was described [14]. That model is based on visible light and uses the cone beam principle where the cone is formed by 64 light emitting diodes (LED) arranged on a circular arc, and LED light is collected in a detector. This arrange-

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ment gives rise to several problems, including the complex geometry. First, it is unclear how the sample container was designed to minimize light refraction and refraction-related reconstruction artefacts. Second, 64 LEDs allow for only very limited resolution, although a scanner with multiplexed LEDs acquire the cross-section very rapidly. Therefore, I have developed a more effective computed tomography teaching model that performs like a first-generation CT scanner, where both the model hardware and the software permit us to follow the individual steps of image formation. With the model, students can gain hands-on experience on theoretical concepts and therefore better understand the basic functions of a device, as well as recognize and understand the artefacts associated with the operation.

BIOMEDICAL IMAGING CLASS DESCRIPTION

The undergraduate biomedical imaging class BE-4570 at the University of Missouri, Columbia aims at providing a broad understanding of the major imaging modalities: X-ray projection imaging (film-based and digital), CT, MRI, and ultrasound. Since the computer dominates image reconstruction, basic image processing algorithms are also covered. These include pixel-based operations, such as contrast enhancement and histogram correction, convolution filters, the Fourier transform, threshold-based segmentation and image measurements. The class includes clinical rotations and hands-on computer labs covering image processing and some modality simulations. In my experience, students found it particularly difficult to understand the abstract concepts of image reconstruction from projections. Particularly in CT image formation, the mathematical foundations of reconstructions preclude intuitive understanding. Therefore, I decided to design a computed tomography teaching model primarily to get hands-on experience on CT principles and CT image reconstruction.

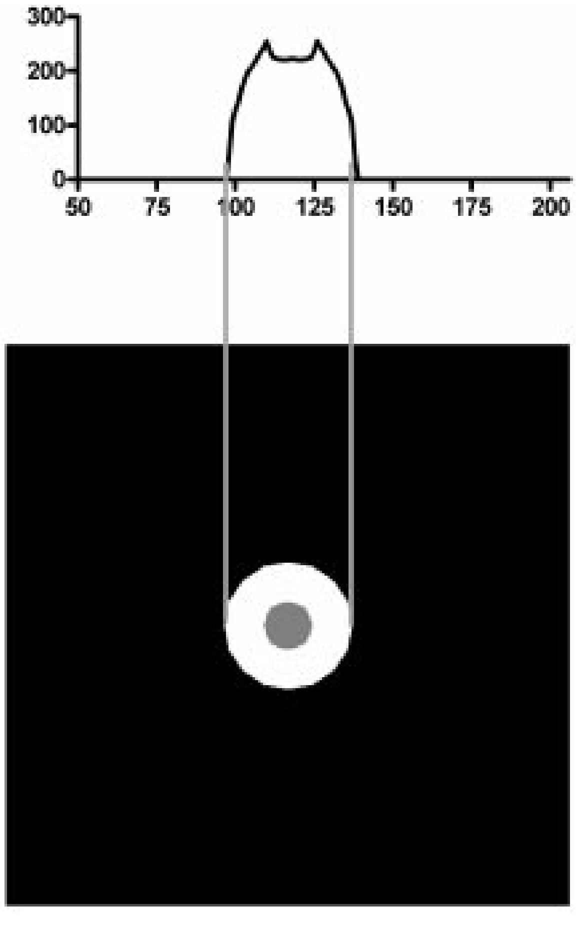

Fig. 1. Sample object and its attenuation profile along a 90° beam path.

COMPUTED TOMOGRAPHY PRINCIPLES

X-rays in the diagnostic energy range (from 35 keV to over 100 keV) pass through tissue in a straight line, undergoing attenuation along their path. Mathematical foundations to reconstruct the distribution of attenuators along the path were developed as early as 1917 [12] (Radon transformation). However, only the development of numerical data processing devices allowed use of the Radon transformation, which practically permits reconstruction of sample volumes from X-ray projections [4, 5] and led to the first working CT scanner in 1972 [2, 6]. The model presented here uses a pencil-beam X-ray source that is translated perpendicular to the beam direction to generate an attenuation profile (Fig. 1). By rotating the source-detector pair around the object, profiles can be collected at various angles. The principle of CT reconstruction is the Fourier slice theorem stipulating that the one-dimensional Fourier transform of a profile is identical to the one-dimensional slice of the object's two-dimensional Fourier transform (Fig. 2).

To generate a CT image, the CT collects many object projections. Their one-dimensional Fourier

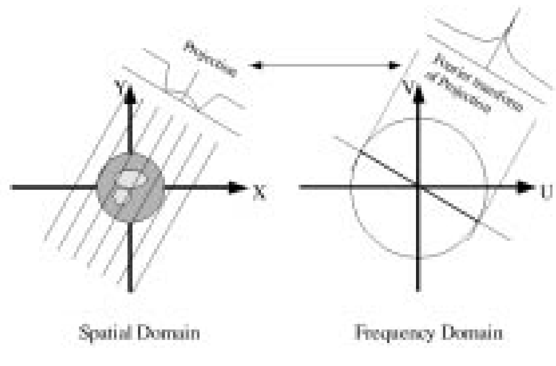

Fig. 2. Fourier slice theorem. The one-dimensional Fourier transform of a parallel projection of the image f(x,y)- taken at an angle—gives a slice of the two-dimensional Fourier transform of the image, F(u,v), along a line of the same angle—to the u-axis.

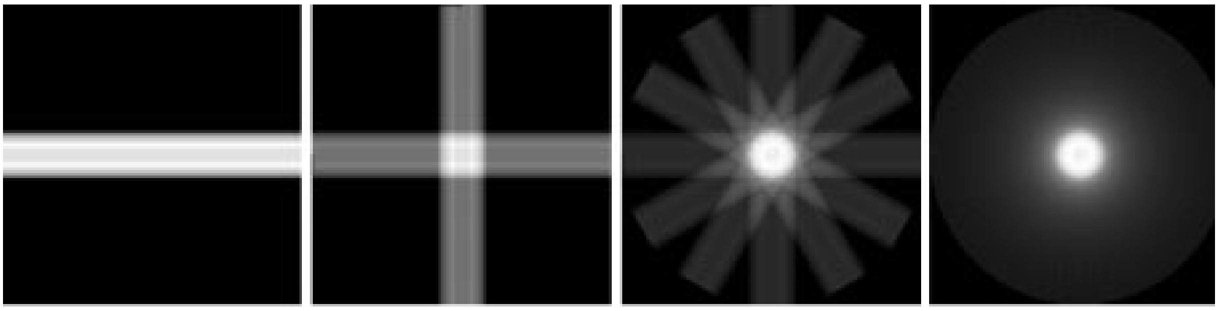

Fig. 3. Reconstruction process through backprojections. Individual projections (Fig. 1) are backprojected along the object plane. From left to right, one, two, six, and 36 projections were used. As more projections are used, the reconstructed object more accurately approximates the original.

transforms are entered into a two-dimensional frequency-domain matrix. Since it is practically impossible to fill all matrix elements of the frequency-domain matrix, the CT must interpolate the missing elements. This interpolation process is the single most important disadvantage of reconstruction in frequency space [10]. Once the matrix is completely filled, the object is reconstructed by the two-dimensional inverse fast Fourier transform (FFT) of the matrix.

The so-called filtered backprojection (fbp) is an alternative reconstruction method [10]. For fbp, the profile is backprojected ('smeared') into the original object plane along the projection angle. The backprojections of all profiles are added to form the reconstruction of the object. Unfortunately, even with a high number of projections, the reconstruction appears blurred (Fig. 3). This is a consequence of the point-spread function of the backprojection, which shows 1/r-characteristic. However, the 1/r function can be compensated for by applying an appropriate high-pass filter to each profile, and the reconstruction no longer appears blurred when the projection is appropriately filtered (Fig. 4). A comprehensive treatment of the mathematical foundations for CT image reconstruction can be found in [7].

DESCRIPTION OF THE MODEL

The model consists of three major components, the mechanical part, the electronics, and the software.

Mechanical part

All components were mounted on a baseplate, which rests on four feet. Two slots were milled into the baseplate to accommodate the lateral motion of the laser/detector assembly. A stepper motor-based actuator (Anaheim Automation 23A102C) was mounted underneath the base plate, and its spindle was connected to the slider of a linear stage (Small Parts Inc. R-LMS-800). A U-shaped piece of aluminum (U-bracket) was mounted to the slider so that the upper parts of the 'U' protruded through the two milled holes of the base plate. Through this arrangement, the stepper motor can

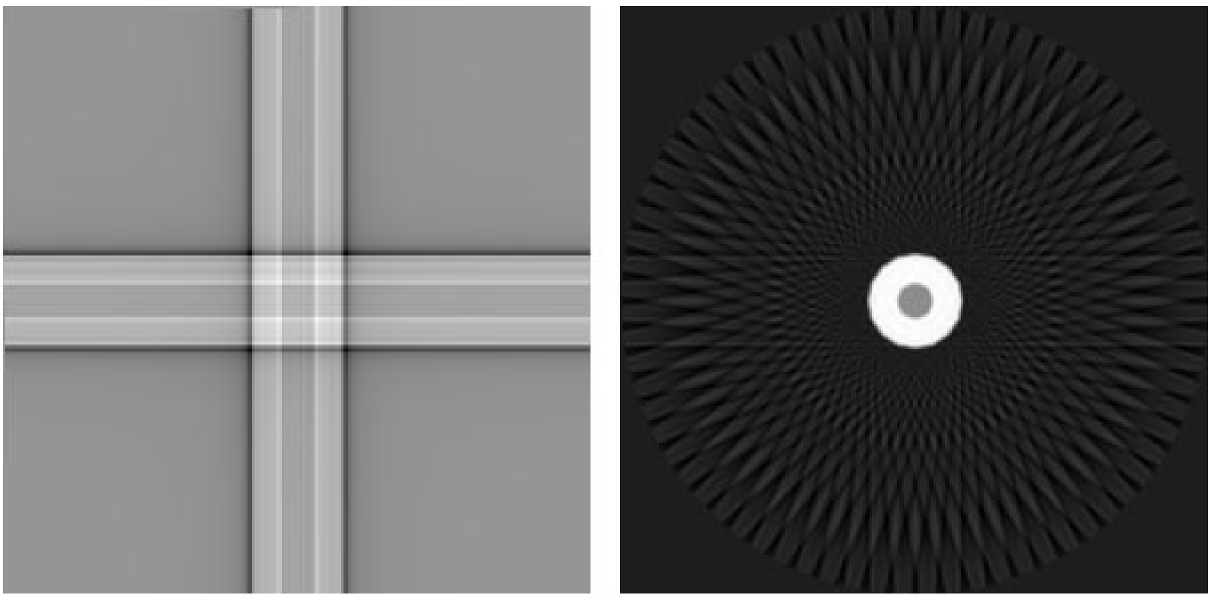

Fig. 4. Reconstruction process through filtered backprojection. The backprojections correspond to the second and fourth reconstruction in Fig. 3, but a filter has been applied. The blurred appearance has been corrected.

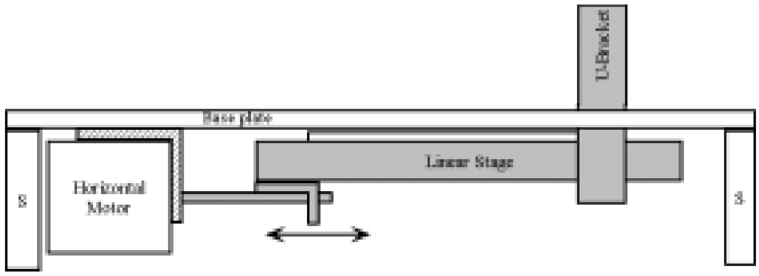

Fig. 5. Side view of the base plate and the horizontal translation mechanism. The grey shaded parts (actuator spindle, L-profile mounting piece, slider of linear stage, and U-bracket) can move horizontally under control of the horizontal motor. Motor and linear stage are attached to the base plate, which in turn rests on support posts (S).

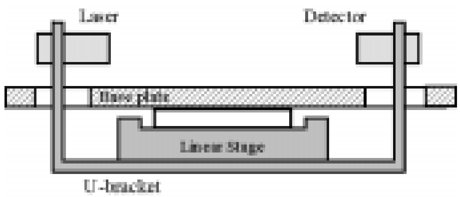

Fig. 6. Front view of the base plate with the linear stage and U-bracket. Moving parts are shaded. The upper part of the U-bracket bears circular holes for the laser collimation package and the photodetector.

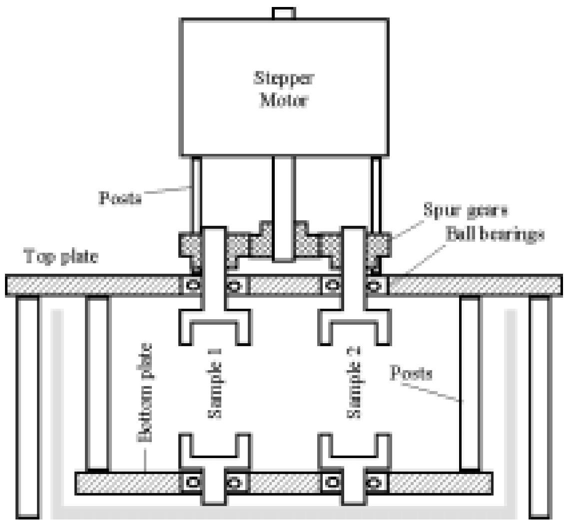

Fig. 7. Schematic of the sample holder and rotation mechanism. Two Delrin plates contain holes for ball bearings. The sample holders can freely rotate inside the ball bearings. The top sample holders are connected to spur gears. A central spur gear, attached to a stepper motor, allows for controlled sample rotation. The top plate is connected to the base plate of the system through four posts. The gray shades indicate the position of the water tank.

provide translational movement to the slider and U-bracket (Figs 5, 6).

The most complex part was the sample holding and rotation unit. To take projections at different angles, the samples needed to be mounted on bearings. Two plates were cut from black 5-mm thick Delrin. Two holes of 19 mm diameter were drilled into each plate to hold nonmetallic ball bearings (Small Parts R-BNM-412). The bearings were fixed with epoxy glue.

Sample holders were fabricated from 19 mm diameter brass rods as follows. A 20-mm section of the rod was cut off and a 6-mm hole drilled into the center of the rod. In the upper half, the hole was extended to 16 mm, thus forming a cup. A thinner section of 6-mm brass rod was tight-fit into the cup. The thinner brass rod fit the inner hole of the ball bearing and was cut flush with the lower end, but extended above the upper end to accommodate two spur gears (Small Parts R-GBS-3214). A third, identical, spur gear was attached to a stepper motor (GBM 42BGY, Jameco Electronics) which in turn was mounted onto the top plate by four support rods. Four additional support rods connected the bottom and top plate, and the latter rested on four support rods attached to the base plate (Fig. 7).

The samples were immersed in water to minimize beam refraction. The design incorporates a custom water tank (Vitri-Forms, Brattleboro, VT) of 50 mm height, 40 mm depth, and 100 mm length. The long sides were made of quartz glass with high optical quality. Samples were made from transparent Teflon tubes (outer tube: 4 mm diameter, inner tubes 1.5 mm diameter; Small Parts, Inc.) fixated inside the sample holder cups with thermo glue and filled with water.

Controller

The stepper motors, particularly the motor for translational movement, require precise timing. Therefore, a controller was designed with an independent microprocessor rather than relying on the timing of a PC multitasking operating system (Fig. 8). The microprocessor was a MICROCHIP PIC 18F452. Stepper motor phase current was provided through IRL640 transistors, of which the gate pins were directly connected to output ports of the microprocessor. Dedicated microprocessor ports were fed into a MAX-232 serial line converter to allow interfacing to a host computer. A closed-loop laser diode driver was designed around a 670-nm Sanyo DL-3147 laser diode (Thorlabs, Newton, NJ). Visible light was chosen to allow observation of the probing light beam. Four levels of laser power were selectable under control of the microprocessor. For light detection, a photo diode (Edmund optics R54–523) was used, and its signal was fed into an analog input of the microprocessor after current-to-voltage

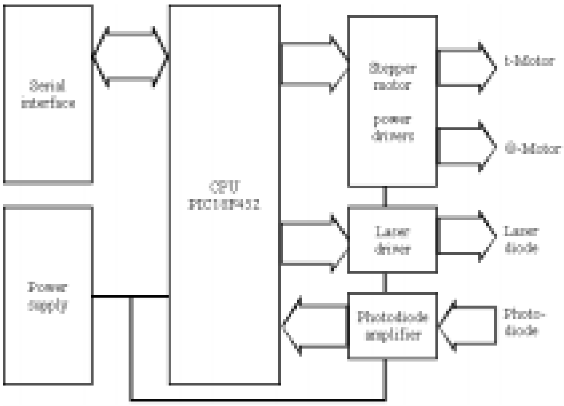

Fig. 8. Block diagram of the controller.

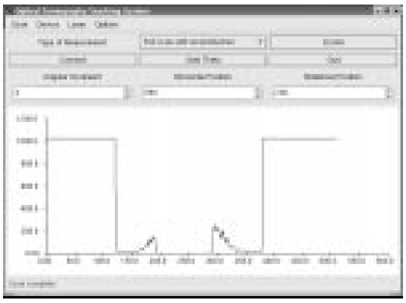

Fig. 9. Main window of the tomography teaching software. The main window allows to control the scan options and displays the most recent absorption profile.

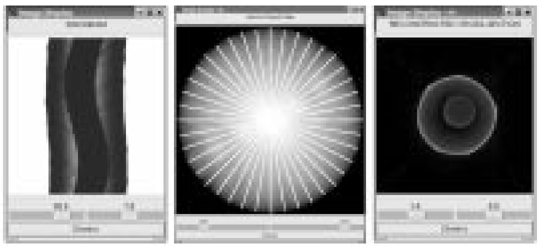

Fig. 10. Steps in the reconstruction process. Profiles are collected over 180° rotation of the sample. The collection of profiles usually shows sinusoidal traces of objects and is therefore often referred to as the sinogram (left). Each line of the sinogram is Fourier-transformed and entered into a two-dimensional array at the angle of acquisition, represented by the white lines in the Radon transform window (middle). Values between the white lines are obtained by interpolation. This interpolated array corresponds to the Fourier transform of the original cross-section, so that the cross-sectional image (right) can be obtained by inverse Fourier-transform of the middle image. In the Fourier transform, interpolation artefacts can be identified.

conversion. Laser light collimation was provided by a collimating diode housing kit (Digi-Key HK-10.4); the detector diode was placed in a 20-mm long aluminum tube with a 5-mm central bore to shield the detector against environmental light. Power was provided to the entire system through a 20-V, 3-A switching tabletop power supply, from which the individual supply voltages for the digital circuitry, the laser, and the stepper motors were derived. The entire controller circuit was assembled in wire-wrap technique on a 100×160-mm prototype board.

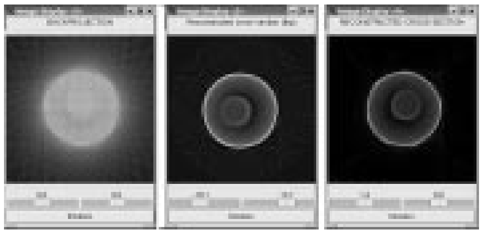

Fig. 11. Comparison of different reconstruction processes. The sample was a tube of 4 mm diameter with a 1.5 mm tube inserted off-center. The left image shows a backprojected image without filtering. The middle image shows a backprojection image, too, but after high-pass filtering. The right image is the result of Fourier-domain reconstruction.

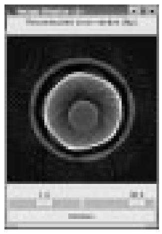

Fig. 12. Simulated detector failure creates an artefactual ring in the reconstructed image.

Software

The teaching software consists of two separate components: the controller microcode and the reconstruction/visualization software on the host PC. Both components communicate through a simple protocol over the serial interface. The controller microcode can interpret simple commands, such as 'move the translational motor to position 1500', or 'scan the object and transmit the attenuation data' into the control signals for motors, laser, and photodiode. The scan data are collected by the host software, where they are processed and displayed. Using an independent microcontroller allows optimizing the software for low-end host computers: while the controller scans the sample, the computer simultaneously performs the necessary data processing steps, thus accelerating the scanning process. The complete source code for the software (the controller part was written in assembly code, while the main reconstruction algorithms were written in C) as well as the schematic diagram may be obtained from the author upon request. The software will be released under the terms of the GNU public license, so that modification by instructors or students is allowed.

The teaching software demonstrates the following steps in the image generation process of a computed tomography scanner: Absorption profile (Fig. 9), sinogram, Radon transform, Fourier slice theorem (Fig. 10), and final cross-sectional image. In addition, the influence of various factors can be examined. These include the angular resolution (number of projections), a comparison of reconstruction algorithms (filtered backprojection versus Fourier-domain reconstruction, Fig. 11), and the influence of the filter in the filtered backprojection process.

In addition to the basic functions, student may study artefacts such as detector failures or misalignment on the teaching model. A simulated detector failure (exaggerated), for example, causes an artefactual ring to appear in the reconstructed image (Fig. 12). Additional examples include misalignment of the detector-source pair, focal point size (simulated by defocusing the beam), and poor signal (by reducing laser intensity). A slight modification of the software would even allow to introduce motion artifacts. Therefore, the tomography teaching model not only allows the students to understand the image generation and reconstruction process, but also to examine various engineering aspects, including misalignment, partial failures, or reconstruction algorithm issues.

Device performance and limitations

The device takes horizontal scans with 512 samples at a resolution of 16 μm per step (8.2 mm total travel distance). Therefore, the reconstructed pixel size is 16×16 ?m. However, the focus of the laser beam, which is approximately 50 μm full width half maximum in the reconstruction plane, limits the true resolution. The scanner allows bidirectional scanning, thus minimizing horizontal movement. Students can complete a typical high-quality scan with 100 projections in less than 2 minutes. This time is short enough not to lose the students' attention. By increasing the angular increment, acquisition time may be further reduced at the expense of image quality.

The sample holding and rotation unit (Fig. 7) was relatively complex to manufacture. The reason for this complexity was the desire to allow access to two different samples without the need to dismount the sample holder. It is possible to simplify this unit by directly attaching the sample to the shaft of the stepper motor. However, in practical demonstrations, the use of different samples turned out to be advantageous. Particularly in-class demonstrations benefit from the ability to quickly switch between a simple and a more complex object.

Light refraction is an issue with all visible-light scanners. The parallel-beam principle in conjunction with a cubic sample bath provides the necessary geometry to minimize refraction. Samples are made of thin-walled Teflon. Therefore, the weakly refracted beam is still captured by the detector. Consequently, the scanner is able to scan samples with compartments of different light absorption (for example by using different concentrations of absorbing ink). With more complex samples, reconstruction fidelity may be further improved by using index-matching fluids. Two examples are aqueous solutions of sugars and mixtures of water and glycerol.

CAPSTONE PROJECT

Originally, a student group in the senior capstone design class under my mentorship created the design of this tomography teaching model. The goal of the class was to design an optical tomography system that generates cross-sectional images of small sample objects on a computer. One of the core requirements was portability, so that the device could be used in traveling exhibits. Also, it should address high school students to spark interest in biomedical engineering. Further requirements were use of a laser-photodiode optical system, use of translation/rotation scans for projection generation, digital signal acquisition, and process reconstruction on a personal computer. For the translation and rotation system, maximum step sizes of 0.1 mm and 1.8° respectively, were required. As an option, students should also discuss battery operation. Finally, students should not exceed the given material costs of \$800. Electronic control and software were provided by the mentor.

During the course of the class, students discussed several designs. One design using rods and linear ceramic bearings for translational movement was partly built and discarded due to mechanical problems. To solve the problem, students used a linear stage. Overall, the capstone group focused on easy implementation of the mechanical parts—all components can be manufactured by students in a moderately well equipped machine shop. Tools needed are a drill press, a lathe, and a milling cutter. Total materials cost was approximately \$500, thus allowing the additional purchase of a used laptop computer. The students completed the mechanical part in the departmental machine shop during the capstone semester. The finished prototype is shown in Fig. 13. A closeup of the sample compartment with the rotational motor can be seen in Fig. 14.

STUDENT FEEDBACK

Within the last year, I used the teaching model in three different scenarios:

- in a graduate-level *seminar*, where the device was introduced as a novel teaching tool;
- in a *summer camp* for high school students;
- in the Biomedical Imaging *class* described above.

In the seminar and in the class session, questionnaires were given to the students to evaluate the effectiveness of the teaching tool.

Seminar

The question, 'How would you grade the overall usefulness of the teaching demo?' was answered by all students with either 'very useful' (80%) or 'somewhat useful' (20%). The highest effectiveness was attested to the demonstration of the projections

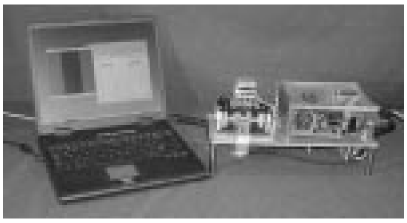

Fig. 13. Photograph of the final prototype. The compartment for the controller has been kept transparent. On the left side of the prototype, the sample holder with the stepper motor and the sample compartments can be seen.

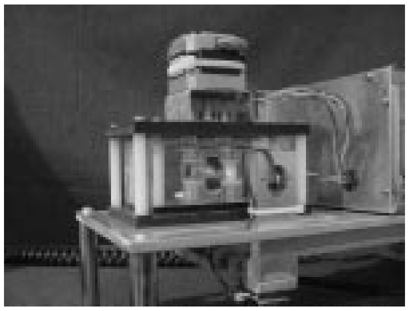

Fig. 14. Closeup view of the sample holder. The laser is presently turned on for scanning and illuminates one of the two samples. The details shown in this figure correspond to the schematic in Fig. 7.

(80% 'very useful' and 20% 'somewhat useful'), followed by the demonstration of the backprojection (47% 'very useful', 40% 'somewhat useful' and 13% 'undecided') and the Fourier-based reconstruction (47% 'very useful', 40% 'somewhat useful' and 13% 'not very helpful'). The seminar was attended by 6 students who previously attended the Biomedical Imaging class and by 9 students who did not. The responses displayed a slightly more positive trend in the group of students who attended Biomedical Imaging before. These findings suggest that a theoretical treatment of the problem, followed by the practical demonstration, is the optimal way to administer the knowledge of computed tomography principles. In addition, written comments provided by the students prompted the addition of the backprojection function (Fig. 3) to further improve the usefulness of the model. Of the 15 respondents, eight wrote the following responses:

- 'Very cool; somewhat useful. The back projection method is pretty intuitive without the teaching device. The device helped my understanding of the Fourier-based reconstructions. The most confusing part to me is the math concepts which the device can't help with.'
- 'Nice teaching innovation.'
- 'Definitely not a lecture for high schoolers. Sinogram negative of that for image.'
- 'Explain where the object being scanned is located.'
- 'May add a function of 'different color for each scan'. Therefore, people can see the change of each scan of intensity.'
- 'I think this would be very helpful for the BE 4570 class as well. It really helps to clarify the concepts of the sinogram. FBP, and the Fourier space transform.'
- 'Perfect presentation and well organized. Very easy to follow, even if the person does not have any imaging background.'
- 'Need to define some terms during demo (example sinogram) for new students. During scanning a drawing showing position of sample may help to mentally reconstruct the image.'

Class

Out of 25 students enrolled in the undergraduate class, 20 returned the questionnaire. Once again, the response was mostly positive, but a little more critical than the graduate seminar. The question, 'How would you grade the overall usefulness of the teaching demo?' was answered by all students with either 'very useful' (65%) or 'somewhat useful' (35%). The highest effectiveness was attested to the demonstration of projections (55% 'very helpful' and 45% 'somewhat helpful'), followed by the backprojection (50% 'very helpful', 30% 'somewhat helpful', 15% 'undecided' and one respondent (5%) 'not very helpful') and the Fourier-based reconstruction (30% 'very helpful', 45% 'somewhat helpful', 20% 'undecided' and 5% 'not very helpful'). Out of the 20 respondents, 13 provided written additions which are listed below. The students apparently agree that the practical demo and the visual aid provided by the device are important. Several answers indicate that a repetition of the demonstration including the explanations would be helpful. The responses also make clear that the reconstruction in Fourier space (Fourier slice theorem) is indeed the most difficult part to understand. I surmise that the visually presented collection of angular projections (Fig. 10 middle) is indeed more helpful than the students realize.

- 'I would like to see more of the technical aspects of the demo device (i.e., how it works, scans, etc.). I'm still unclear on Fourier-based reconstruction, though.'
- 'The device seems to be very useful but I have too little to compare it with since the topics are somewhat new.'
- 'I would have no idea what was going on without the demo. Visual aids are extremely useful for giving meaning to the transforms.'
- 'I think visual aids are always useful, even if you don't get the concept right away, you at least have a picture in your mind.'
- 'I think the tomography demo device is very useful. However, I think that it should be used in 2 class periods. I was starting to understand the tomography concepts in class, but I need another day to let it soak in. And then see examples with the device again.'
- 'I believe the tomography demo device helped to better explain the material. It was definitely better than learning it mathematically. I think

I must need a little more time to understand the concepts it showed.'

- 'The visuals were very helpful in seeing how the images are projected and I think it is a very good idea to be using it in the class.'
- 'I say 'somewhat helpful' because I still think the concepts are confusing, although it is helpful to see the images. I don't quite understand why the image looks like it does and have trouble seeing a 'sinewave' in most of the images.'
- 'Better explanation of each step and what we are looking at.'
- 'Even more projections would enhance the presentation—it's helpful to try to anticipate the image resulting from rotation projections.'
- 'Hard to see values used on monitor screen.'
- 'Would be very hard to understand without it. Still hard to understand because it is a new concept.'
- 'Very cool device. Helps me a lot to understand the principles of CT image.'

FUTURE PLANS

It could be shown that the tomography teaching device is an efficient tool to teach the principles of image formation in computed tomography. While the device hardware itself is complete and does not need any additions or changes, some additions to the software are necessary. With the relatively high quality of image reconstruction, this device can compare different reconstruction algorithms. Therefore, I will particularly implement advanced interpolation in Fourier space [15] and arithmetic reconstruction techniques in the future. In consequence, students will be able to compare the influence of these algorithms on image quality, particularly with respect to modified acquisition parameters, such as reduced angular resolution.

One disadvantage of this model is the lack of a reference image, particularly when studying the subtle differences of various reconstruction algorithms. If the error image (difference between the reference image and the reconstructed image) needs to be analyzed, a simple software extension could be able to load the reference image and provide more accurate quantitative error analysis.

The device design was a successful capstone project for BE students, but students needed a variety of information from fields other than bioengineering to develop the control electronics and software. Therefore, plans were developed to offer joint capstone projects between the departments of Bioengineering, Electrical Engineering, and Computer Science.

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