Laboratory #6: Optical Tomography
Assigned: Friday, March 29 (Week 9).
Due: Friday, April 12 (Week 11.)
Lab write-ups are to be submitted electronically on Blackboard

Aims of this Experiment

In this lab you will be constructing and experimenting with an optical tomography system. Your optical system will be set up to minimize refraction effects and emulate a standard fan-beam tomographic system. In this lab, you will

- Set up an optical tomography system.
- Figure out how to calibrate your measurement data and imaging geometry.
- Reconstruct your tomographic projection data into slice images.
- Investigate various imaging phantoms and develop good imaging protocols.

Materials and Supplies

1 CMOS Camera and Lens (mounted on 1-1/2" optical post)
4 Forked base clamps (plus tie down screws)
2 Vertical Supports
1 Backlight
1 Filter Wheel with filters (400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 650 nm; mounted on 1-1/2" optical post)
Rotary Stage, controller, and 1 A power supply
Magnetic Platform for Rotary Stage + 4 8-32 cap screws to affix to rotary stage
Phantom Chamber(s)
2 Corner Posts to secure Phantom Chamber in place
1 Transparent ruler (included in kit)

Words of CAUTION

While there is little concern for physical danger with the liquid-based phantom chambers (mineral oil is used and is relatively inert/non-conductive/etc.), there is substantial risk of spillage of the oil if one is not careful. We really, really, really, really want to avoid spilling oil in the lab!!
A few rules:

- Phantom Chambers are to be upright at all times – they are not sealed on the top (even if they look they are…)
- Do not hold the chambers by the lid – the lids will come off. Hold by the bottom and with two hands.
- Scratches, dirt, fingerprints, etc. on the sides of the phantom will degrade imaging performance. Avoid marking the sides in any way. Ask the course director or TA about ways to clean the sides, if needed.
- Report any spill or leakage immediately.

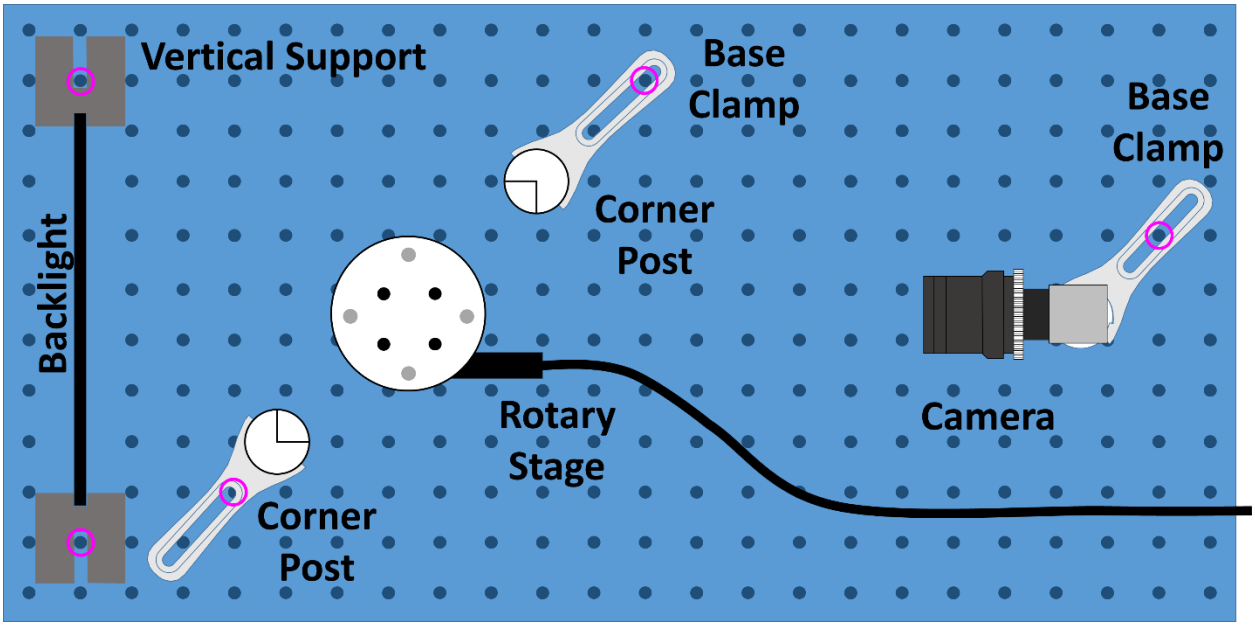
System Setup

The system setup for this lab is shown in the following figures and uses a few new components including the rotary stage. This stage should be affixed directly to the optical breadboard using short ¼-20 screws. After the stage is secured to the breadboard, a magnetic platform needs to be affixed to the stage using 8-32 screws. (You won't be able to attach the stage to the breadboard with the platform in place.)

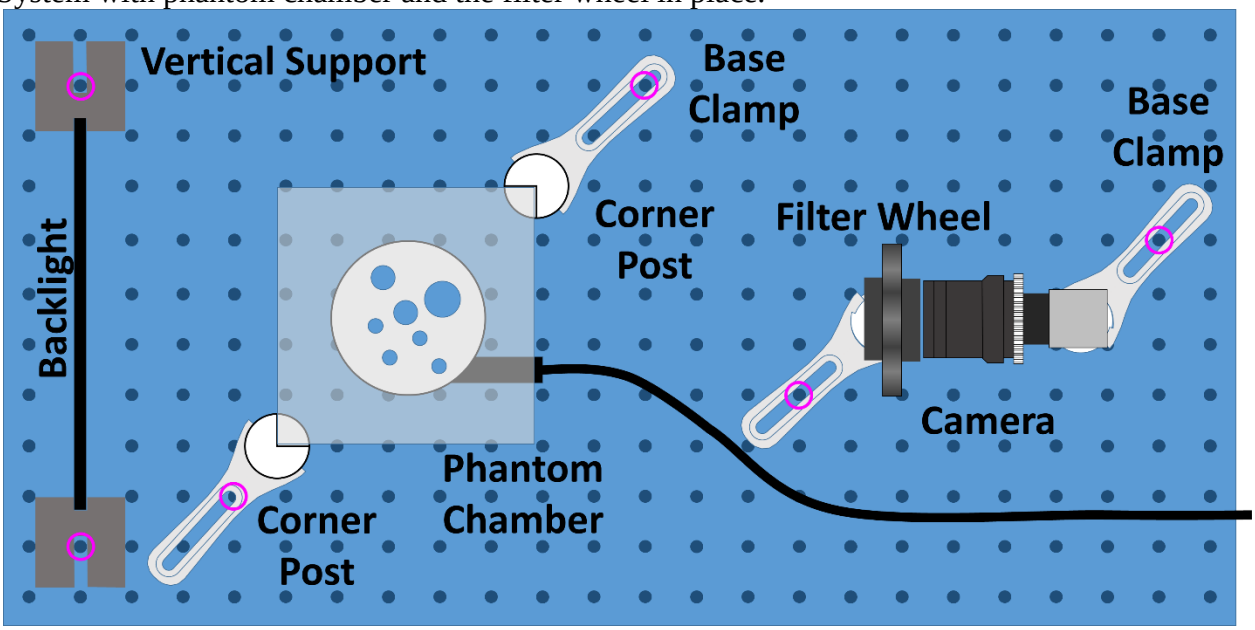
The camera is placed in the same position as previous labs; however, you will need to mount the camera on a 1-1/2” optical post. Make every effort to ensure that the center of the magnetic platform is aligned closely with the center of the camera/imaging field of view.

The phantom chambers are magnetically coupled to the platform allowing the imaging targets to be immersed in an index-of-refraction matched oil. The chamber is placed directly on the platform; however, to prevent the transparent box from rotating, two corner posts are used to secure the phantom chamber.

System shown without phantom chamber in place.



System with phantom chamber and the filter wheel in place.



Your Goals:

Data Acquisition

1. Data collection is relatively straightforward. You should collect 360 projection images (1° angular spacing) of the phantom. This requires use of rotary table commands:
    a. `s = APT.getstage('rotation','timeout', seconds);` will return a object handle to the rotation stage.
    b. `s.move_rel(degrees,'timeout',seconds);` or `s.move_abs(degrees,'timeout',seconds);` permits relative or absolute angular motion of the stage.
    c. `s.flush();` A convenient command to flush the stage buffer – if you need to cancel/control-C a motion in mid-execution.
2. Choose camera settings to obtain high-quality images. There will be a trade-off here. You will want the phantom to be in-focus; however this will be impossible to do perfectly for the 3D phantom. A small aperture will minimize blur over the depth of the phantom but will lead to increased exposure times to get low-noise data. Find a good trade-off and be sure to discuss what you did in your report.
3. Try data collections with and without different spectral filters. Determine which filter is best and worst for your particular phantom chamber – also note how this compares with the unfiltered "broadband" data.
4. Collect data on at least two phantom chambers of different types – check with the course director or TA to make sure the two (or more) phantoms are sufficiently different.
5. Bonuses:
    a. One phantom chamber is more spectrally complex. Can you find a way to use the filters to decompose the data into different material components/dyes/colors/etc.?
    b. Investigate short exposure times. How fast can exposures be made so that you can still obtain a "good" tomographic slice image?
6. Hints:
    a. Make sure your data is well-centered and avoid lateral truncation at all costs.
    b. Tomography can be sensitive to noise. Make sure your initial data acquisitions make use of the camera's dynamic range and are fairly low noise.
    c. Avoid any motion of the system/change in light during acquisitions or between calibration and acquisition.
    d. Not all phantom chamber orientations are equally good. Any scratch or defect on the sides of the phantom where light enters or exits the chamber can generate problems. Pick the best sides and gently clean/remove any debris that might be on the surface.

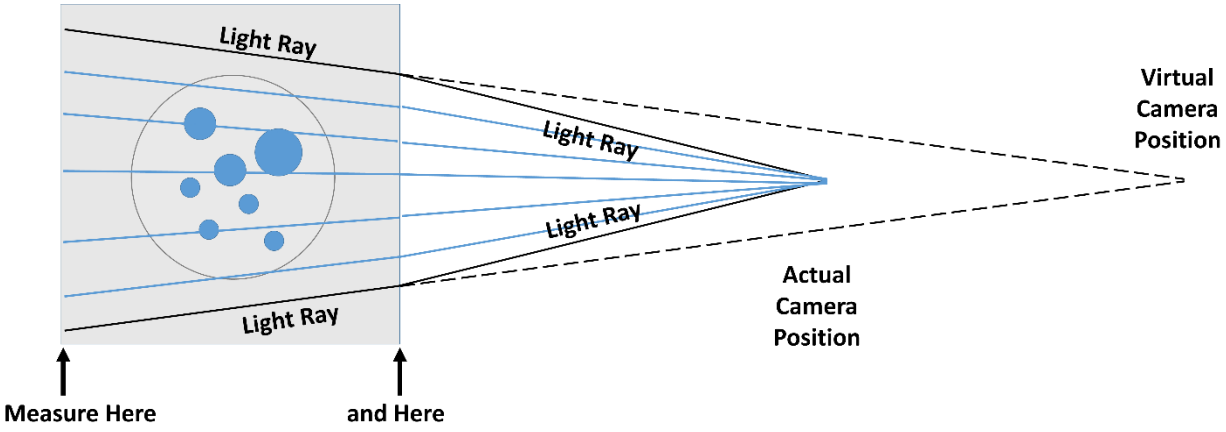
Data Calibration

Recall from class that the tomographic forward model is

$$y = I_0 \exp(-\mathbf{A}\mu) + s$$

In addition to the Beer's law negative exponential and the projection operation, **A**, your measurements, *y*, include two other terms you may want to account for in your quest to estimate the attenuation values, μ. Specifically, I_0 is a gain term associated with the number of photons incident on the phantom and any systemic sensitivities, and *s* is an additive term (e.g. dark current).

1. From previous labs, you know how to estimate the additive term.
2. I_0 can be estimated in various ways. If the photon fluence and system sensitivity is uniform you need only to find measurements that include no object (e.g. $y = I_0 \exp(\mathbf{A} \cdot 0) = I_0$). However, this is more difficult if I_0 varies over the field. An empty phantom chamber will be provided if you wish to conduct a "gain" scan to estimate I_0.
3. In order for your reconstruction code to work properly, you need to know the geometry of your imaging system. In essence, you need to be able to "put the rays back in the right spots" in order to form an accurate image. In x-ray CT, the system geometry is specified by values including source-to-axis distance (axis=center of rotation), source-to-detector distance, etc. Specifically, you need to determine where the fan of light rays exists in space for each angular projection. This is somewhat non-intuitive since things like the equivalent of "source-to-axis distance" (actually camera-to-axis distance in our system) are complicated by refraction at the edge of the phantom chamber. Note in the image below that due to refraction, the *actual camera position does not form the fan you need*. There is a virtual camera position based on vertex to which light rays converge from within the phantom chamber.
   You can establish where this fan lies in space by imaging the transparent ruler you have at the entrance and exit of the phantom chamber. One simple approach is to measure the width of the field of view at the phantom chamber entrance and exit (forming a trapezoid – presuming a well-centered phantom) and using this to extrapolate a virtual camera position.



4. Despite your best efforts at centering the camera and the axis of rotation, they will typically be at least slightly off. This is can be accommodated by the u_0 offset we discussed in class. Recall that u_0 is the distance of the "central ray" to the origin of your detector. (Where your origin lies depends on how you wrote your backprojector.) One simple way of estimating this is to look directly at your sinogram data and find the lateral extremes of a particular feature in your data (e.g. the edge of one tube on the left and right). The average of these two positions should be the center of rotation which you can relate to your detector origin. (You may find that slight tweaks in the u_0 values can improve your image quality.)

Data Reconstruction/Analysis

1. Despite collecting 2D projections, this lab only requires a 2D reconstruction of the central slice of your phantom image. That is, you only need the data from the center row of the

camera (but all 360 angles) to form a sinogram. You may choose to average a few of the central slices (e.g. 512±a few rows) to reduce noise/improve signal.

2. You have already been provided with ideal sinogram data on which you may test your filtered-backprojection (FBP) code. If your code does not produce a high quality slice image on this data, talk with the course director or TA to ascertain what the problems are.
3. With functioning FBP code, reconstruction of your optical tomography data is straightforward presuming you have an accurate system geometry and calibration. Despite this, your initial images will likely be subject to so-called artifacts. While the course director and TA will help you diagnose and solve artifact issues, here are some hints:
    a. Blurry reconstructions (especially donut-like rings around everything) – your u_0 is probably wrong.
    b. Rings in your reconstruction; cupping/capping artifacts (high/low values in the center of your reconstruction as compared with the edge) – your I_0 is likely wrong or inaccurate.

Report:

Please include a general introduction to your experiments, a photograph of your setup, and any challenges you experienced in this lab. Specific items that should be included in the lab write-up include:

- Show all reconstructed slice data (at least two phantoms; no filter, good filter, bad filter for each). Images should be grayscale with a colorbar showing attenuation values and units.
- Interpret no filter, good filter, bad filter results. What is the difference between these reconstructions and what is the physics behind what you see? In what way are the images good or bad. How does this change based on the particular phantom you scanned?
- Estimate the relative concentrations of the dyes in each tube of the phantoms you scanned.