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1 Introduction

 Please contact Anton Deguet (anton.deguet@jhu.edu) if you need more information.

Notes regarding the c-arm calibration phantom designed for the RUF (Registration of Ultrasound and Fluoroscopy) group working on seed reconstruction in prostate brachytherapy. Credit goes to (in alphabetical order):

- Gouthami Chintalapani (software and design)
- Anton Deguet (GUI, these notes and design)
- Gabor Fichtinger (design)
- Iulian Iordachita (manufacturing and design)
- Ameet Jain (design)

For our specific application, the requirement was to provide a good image distortion correction and a decent camera calibration for different c-arms. The goal was not to provide an extremely accurate calibration device as our algorithms can perform fairly well with a poor c-arm calibration.

Also, since we had to use whatever c-arm provided in the operating room, we decided to build the phantom to handle most 9 inch c-arms. A 12 inch c-arm can still be used but only with some magnification turned-on. To mount the calibration phantom on different c-arm we decided to use a removable mounting flange.

2 Hardware

2.1 Phantom design

For the RUF c-arm calibration phantom we decided to use only two plates rigidly attached with a fixed spacing (see figure 1). Some calibration templates use three different plates, one for image distortion correction and two for the camera calibration. In our design, the plate closer to the image intensifier (aka upper plate or dewarping plate) is used for image distortion correction. This plate defines a virtual image plane. The plate further away from the image intensifier (aka lower plate or calibration plate) is used only for camera calibration.

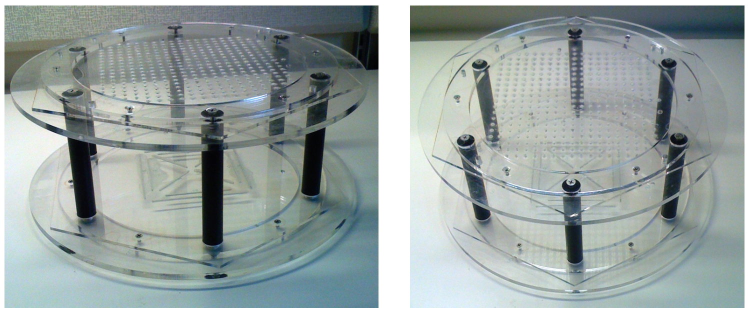

Figure 1: Calibration phantom overview

For the image distortion correction, the upper plate contains metal BBs (aluminum) placed on a regular square grid, 10 millimeters apart (see figure 2). We found the density high enough to obtain a good distortion correction while not adding too much to the manufacturing process. A higher number of BBs also increase the chance of occlusion when looking for features in the lower plate. We choose metal BBs as the image segmentation is trivial using morphological filters. BBs also cover less space and therefore create less occlusion for the lower plate.

To find the orientation for the camera calibration, some of the BBs must be identifiable. We chose to place larger BBs on two orthogonal axes with a different pattern (all large BBs versus alternate large and small) on each axis. This allows to differentiate the two axis and determine the orientation of the plate.

The lower plate contains lines used for the camera calibration (see figure 3). The pattern is composed of two "concentric" squares and their diagonals. This pattern provides plenty of features for the calibration. The main significant issue for our design was to have more features, widely spread across the image intensfier for accurate calibration and to place these lines so that the likelihood of being hidden by the BBs remains low. To avoid too much overlap, the lower plate pattern is placed off-center and the lines have

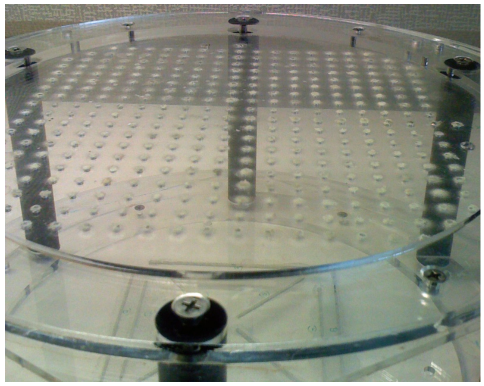

Figure 2: Calibration phantom upper plate, pattern of BBs

been positioned based on the typical c-arm we have access to, i.e. with a focal length circa 900 millimeters.

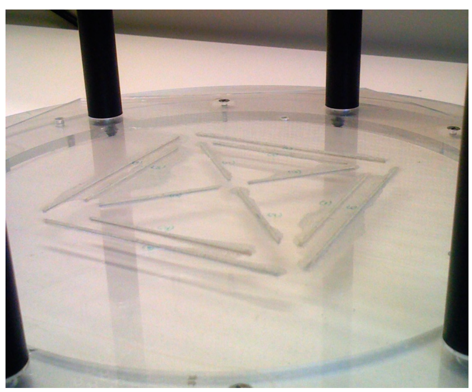

Figure 3: Calibration phantom lower plate, pattern of lines

2.2 Phantom manufacturing

For this phantom we tried to avoid using a full fledged machine shop as much as possible. Since we had access to a laser cutter we decided to use this tool. The phantom plates are made of three layers of translucent acrylic which once stacked and glued to create the 3D shapes desired. The main idea was to cut the space for the BBs and lines on one plate and then simply fill these holes with standard BBs and wires. This simple design allowed us to control the depth accurately without having to use a computer driven drill. To ensure that the layers glued together are well aligned, each layer has a couple of holes to place guiding pins. A third layer has been added mostly to re-enforce the phantom.

The two plates are holding together using six posts of black delrin which have been drilled at their ends using a lathe. The main issue is to make sure that all posts have the same length.

As the whole assembly might not correspond exactly to our specifications, we decided to use an optotrak to check the relative position of the two plates. One solution is to use dimples on the surface of each plate but this seemed harder to achieve using our simple tools (whole depth is not that accurate using a laser cutter). Another solution, very simple to implement, was to create lines on the edges of each plate. We use these lines to "swipe" a calibrated optotrak tool. The lines are created by having one of the glued layer wider that the other. The edge of the smaller layer create an hexagon on each plate. Finding the transformation between these two hexagons allows to determine the relative position of the two plates.

2.3 Mount

As the calibration phantom was expected to be used on different c-arms, the phantom is not directly attached to the image intensifier. It is attached to a mounting flange using four thumb screws (see figure 4). The mounting flange itself is very light and can be attached and removed fairly easily.

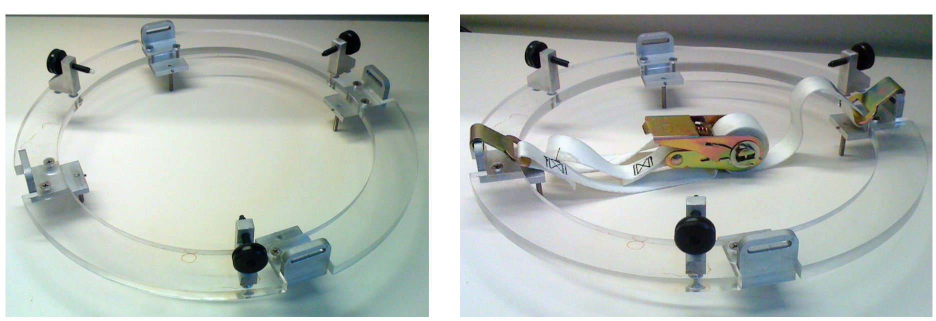

Figure 4: Mounting flange, four hooks for the straps, three screws to center

To carry most of the weight, we decided to use straps. These are flexible and can adapt to the different shapes of image intensifiers we encountered. The straps themselves do not prevent lateral shifts and can not maintain the phantom centered. To maintain the mount centered we added three brackets on the side of the flange with thumb screws. These screws MUST not be tightened too much as they bend the mounting flange. It is tempting to use them to hold the weight but they are not strong enough for this, the straps should always be used.

To accommodate different image intensifiers we built different mounting flanges.

3 Software

The calibration software has been written using Matlab. It can be used in "text" mode or with the RUF GUI. The RUF GUI includes image capture from live video or import of DICOM images.

3.1 Masking

The goal of the masking is to remove any noise or useless information outside the circular field of view of the c-arm. As any pixel outside the field of view can have an arbitrary high value, these are likely to fail our segmentation algorithms using thresholds based on grey value histograms. We offer three different ways to mask:

1. The video mask is computed using a morphological filter to identify the background (removing the text) and then finding the largest connected area (see figure 5).

2. For plain DICOM images, the GUI offers the option to use a centered circle. This mask turned useful with some OEC DICOM images with a bright artifact on the top right corner.

3. Finally, as some images don't require any masking, the GUI offers a null mask.

3.2 Dewarping

The image distortion correction consists in finding a transformation or mapping (aka dewarping) to straighten the image. The general idea is to locate

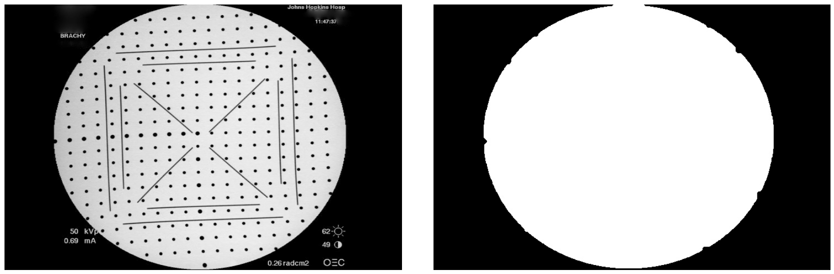

Figure 5: Video capture of c-arm image and computed mask

fiducials on the image and find the correspondences on the actual device (as defined by its CAD model). In our case the fiducials are small aluminum BBs on a regular grid.

The different steps are:

1. Segmentation. To locate the BBs we use morphological filters to remove the background and find large connected areas on the masked image. Once the connected areas have been found, we remove those with a maximum dimension greater that the BBs diameters. These usually correspond to the lines from the lower plate. We also sort the BBs by diameter to locate the large BBs used to define the center and the main axes.

2. Orientation. As the mounting flange and the phantom itself don't have any mechanical system to constrain the orientation, we need to find the orientation of the image. To do so, rotate the image from -90 degrees to +90 degrees and project/add the pixel values along the X axis. The maximum entropy (highest peaks) correspond to a straight image. Using the large BBs allows to differentiates between the 0, 90, 180 and 270 degree rotations. Basically this design allows us to break the symmetrical nature of the phantom.

3. Matching fiducials. Starting from the center BB (large) and assuming an approximated resolution, we proceed along the axes by labeling each neighboring BB. The output of this step would be a set of matchings for each BB on the image to the BB location on the CAD model.

4. Polynomial fitting. We fit polynomials on the grid defined by the BB correspondences from the previous step. We use Bernstein polynomials

(in tensor form) of degree 4 or 5 to fit the segmented BBs to the actual ones as defined in the CAD model. Once the polynomial coefficients are found, we can compute a deformation map. Both coefficients and maps are saved.

The GUI provided for the prostate brachytherapy displays the original image as well as the distortion corrected one with the corrected BB locations overlaid (see figure 6). This allows a fast and reliable check from the user.

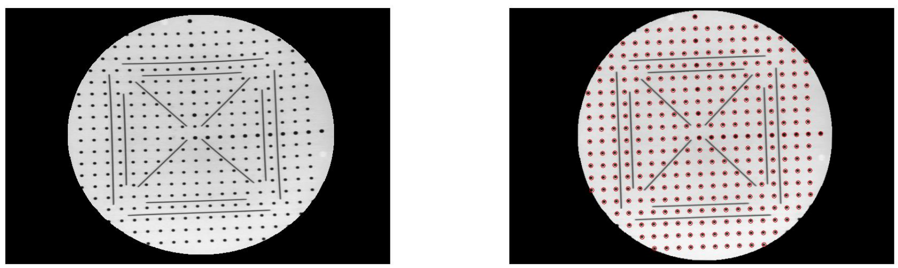

Figure 6: Image before and after distortion correction (with BB locations)

3.3 Calibration

The general idea is to find planes in 3D, defined by features in both the image and the upper calibration plate (CAD model), and determine how these features get projected on the image. Then, one can reconstruct these planes and figure out the camera position as well as its focal length.

The different steps are:

1. Segmentation. The image segmentation starts with the distortion corrected image and removes the BBs found to compute the distortion correction. Morphological filters are used to remove the background and find the connected areas, i.e. lines, of the image.

2. Line fitting. For each large connected area, a line is fitted using a Least Square optimization.

3. Model. The lines are well defined in the CAD model, i.e. with respect to the calibration plate. Their position with respect to the virtual

image plane (dewarp plate with BBs) can be found using the optotrak tracking features (hexagonal shape around each plate) and the results of the optotrak calibration (transformation between the two hexagonal shapes).

4. Matching. The lines as found in the segmented images must be matched to the actual lines as defined in the CAD model. A simple heuristic could be used for this task but since we had a prior experience and implementation of the Hungarian algorithm, we used it.

5. Camera parameter computation. The core of this operation consists in fitting planes to the line features in the distortion corrected image and the lower plate and find their intersections to locate the focal point.

The GUI displays the input image with segmented lines overlaid and prints the focal length and the coordinates of the focal axis intersection with the image in pixels.

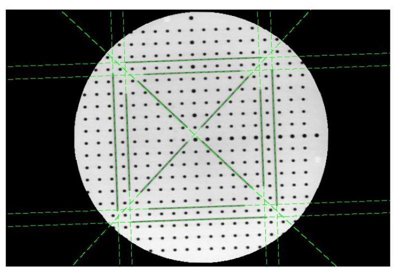

Figure 7: Segmented lines used for the calibration