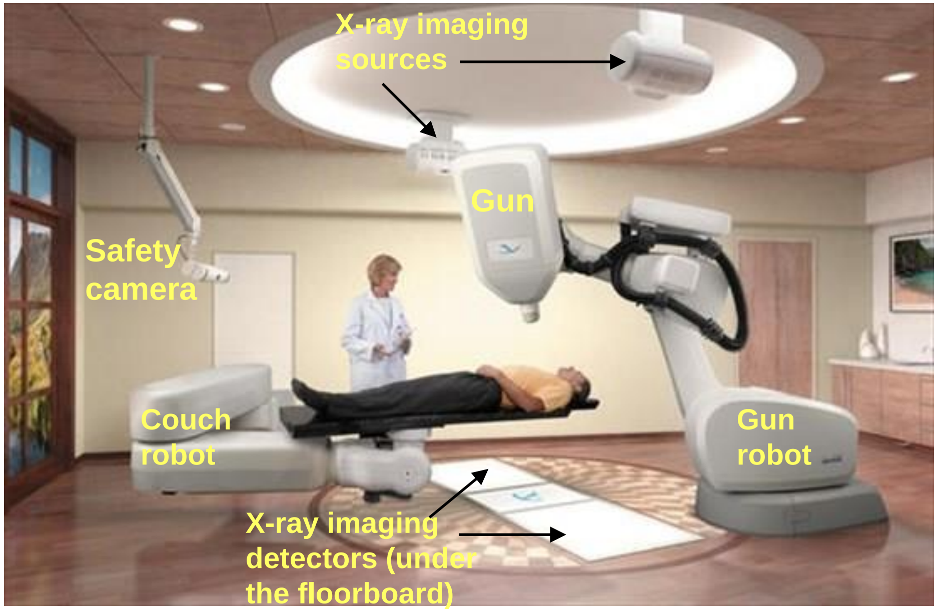
X-ray image guidance for Cyber Knife
Assignment for CISC/CMPE 330

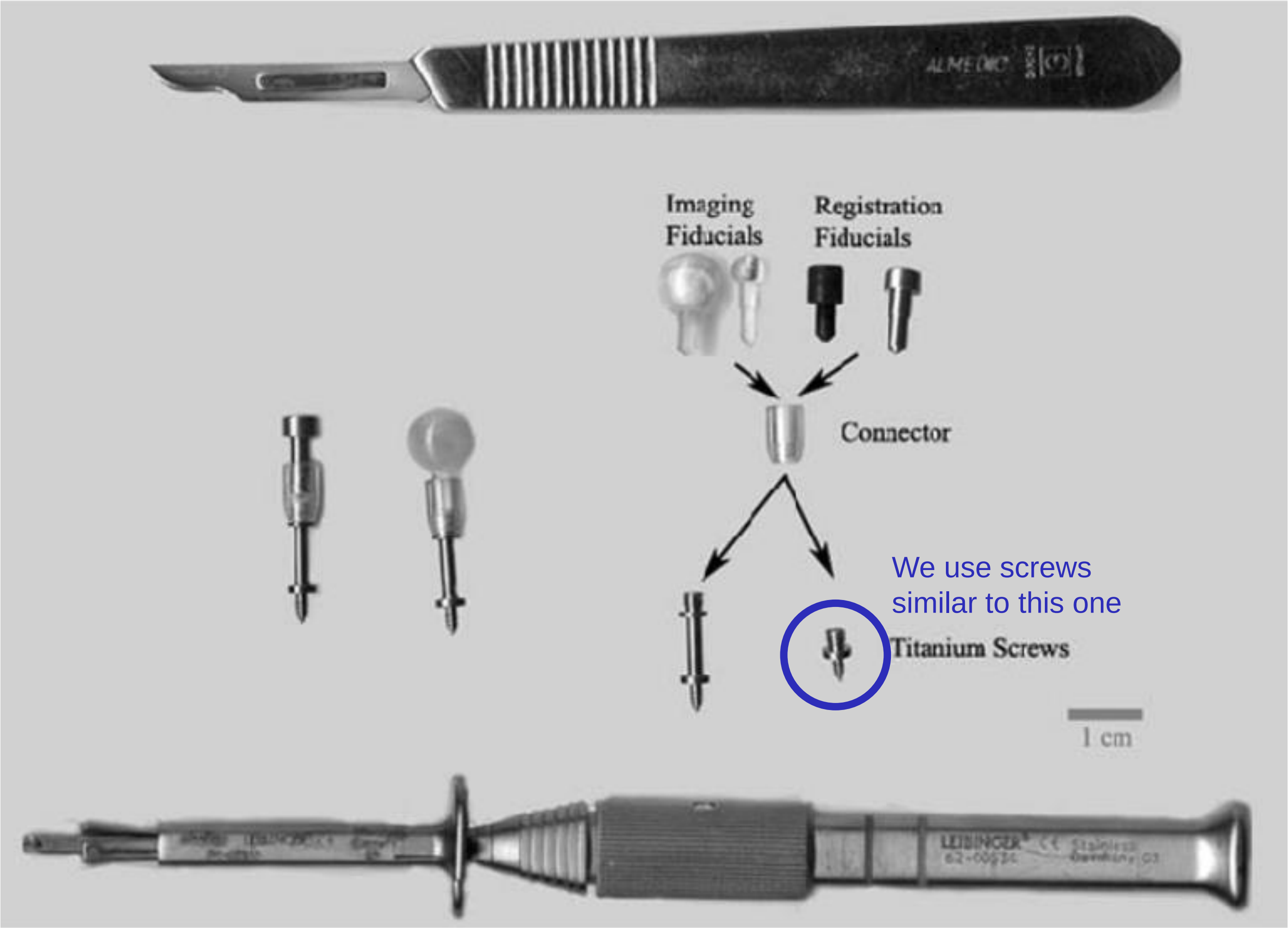
We will treat metastatic spine tumor with radiation therapy delivered by targeted high-energy X-ray beams. We will treat the target with the Cyber Knife (CK, https://cyberknife.com) shown below. CK uses a robotic arm to aim a conically shaped 6meV X-ray beam, to kill cancer with powerful radiation. CK also has a second robotic arm to move the patient's coach under the gun. The target is irradiated from many directions, to accumulate sufficient therapeutic dose inside the target and at the same time curtail the harmful toxic dose to healthy tissues. A video animation of Cyber Knife is here: https://www.youtube.com/watch?v=LwFGnDhZ89k. The CK is guided by kV X-ray imaging. As the soft tumor is not directly visible in X-ray, to indirectly target the tumor we implanted three Titanium screws as makers in the vertebral processes around the tumor. Your task is to develop computational X-ray image guidance for the Cyber Knife using three implanted markers…

Metastatic spine tumor



Cyber Knife treatment room

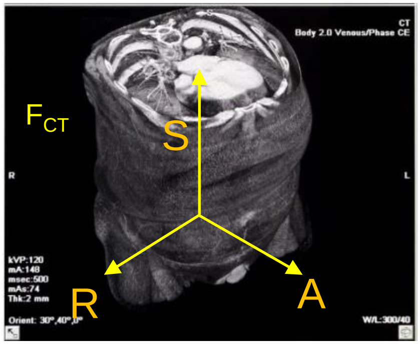
Marker screws and insertion instruments

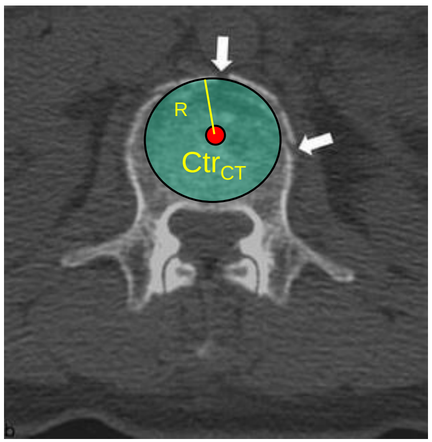


Titanium fiducial bone screw markers (Stryker Leibinger, Inc., Kalamazoo, MI). The screwdriver is used to place the self-drilling screws following local anesthesia and a stab incision.

Note: This image, as all others, is for illustration only. The screws in this image are similar but not exactly the same as you will see later in the X-ray images. Nevertheless,. you can estimate the realistic dimensions of the screws.

Planning for Cyber Knife treatment in computed tomography imaging





Treatment planning is carried out in the Cartesian coordinate frame of the computed tomography (CT) frame (F_{CT}). in metric scale. We typically scan these patients in supine position.

The three implanted markers are localized in CT frame and become known as ($M1_{CT}$, $M2_{CT}$, $M3_{CT}$).

The main advantage of Cyber Knife is that it can deliver radiation from many directions to many target points, altogether envelop the target in sufficient dose kill the cancer while sparing healthy tissues from excessive radiation. The target locations are within some “target envelop”. Typically, this envelop is the tumor targeted for the therapy.

In this assignment, we are concerned with our ability to accurately compute in Cyber Knife frame any desired target position inside the target envelop.

For the purpose of this assignment, we approximate the target envelop (the tumor) as a sphere inside the vertebral body, with a radius of R, centered in C_{CT} point in the CT frame. All target positions that we may want to hit with the Cyber Knife gun lay inside this sphere.

During treatment, the implanted markers are continuously localized by the X-ray guidance system in Cyber Knife frame and become known as ($M1_{CK}$, $M2_{CK}$ $M3_{CK}$).

Using the marker positions in CT frame ($M1_{CT}$, $M2_{CT}$, $M3_{CT}$) and the marker positions in CK frame ($M1_{CK}$, $M2_{CK}$ $M3_{CK}$), any desired target position is registered from CT frame (where it was known as T_{CT}) to Cyber Knife frame (where it becomes known as T_{CK}), thus allowing the robot controlling the therapy beam to accurately follow the motion of the target.

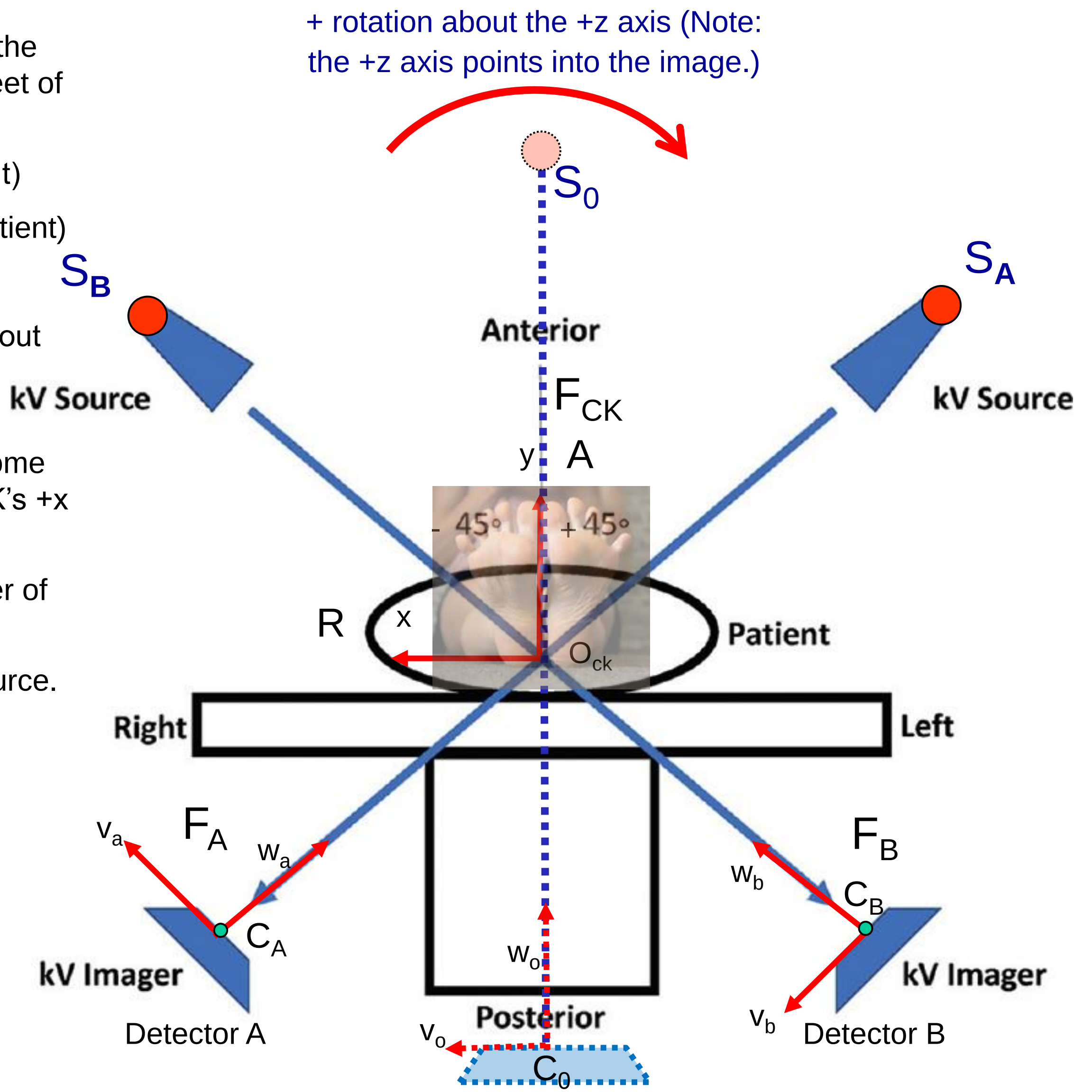
Coordinate frames in Cyber Knife

Coordinate axis directions

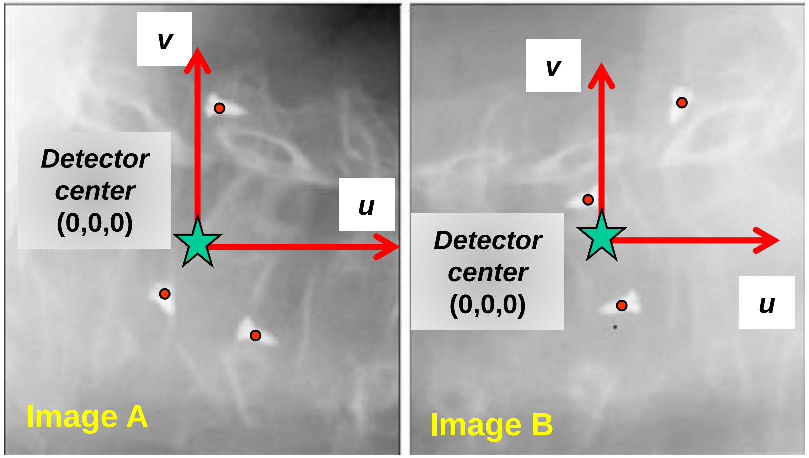
- The patient is in supine position on the table. In the figure here, we are looking the scene from the feet of the patient.
- +x points to the supine patient's right hand (Right)
- +y points to the ceiling (anterior of the supine patient)
- +z points from toe to the head (Superior)
- The source-detector combo "virtually rotates" about +z by +/- 45 degrees, into A and B position, respectively.
- Dotted lines mark the hypothetical zero-angle home position, where the detector's +v and +w and CK's +x and +y, respectively, are identical.
- The two beam central lines intersect in the center of the CK coordinate system.
- The detector's +w always points to the X-ray source.
- The detector's +u and the CK's +z are always identical.

Dimensions in the X-ray system:

- From construction we know:
- source-detector distance (SDD) = 200 cm
- source-axis distance (SAD) = 100 cm
- rotation in pose A = +45 degrees about +z
- rotation in pose B = -45 degrees about +z

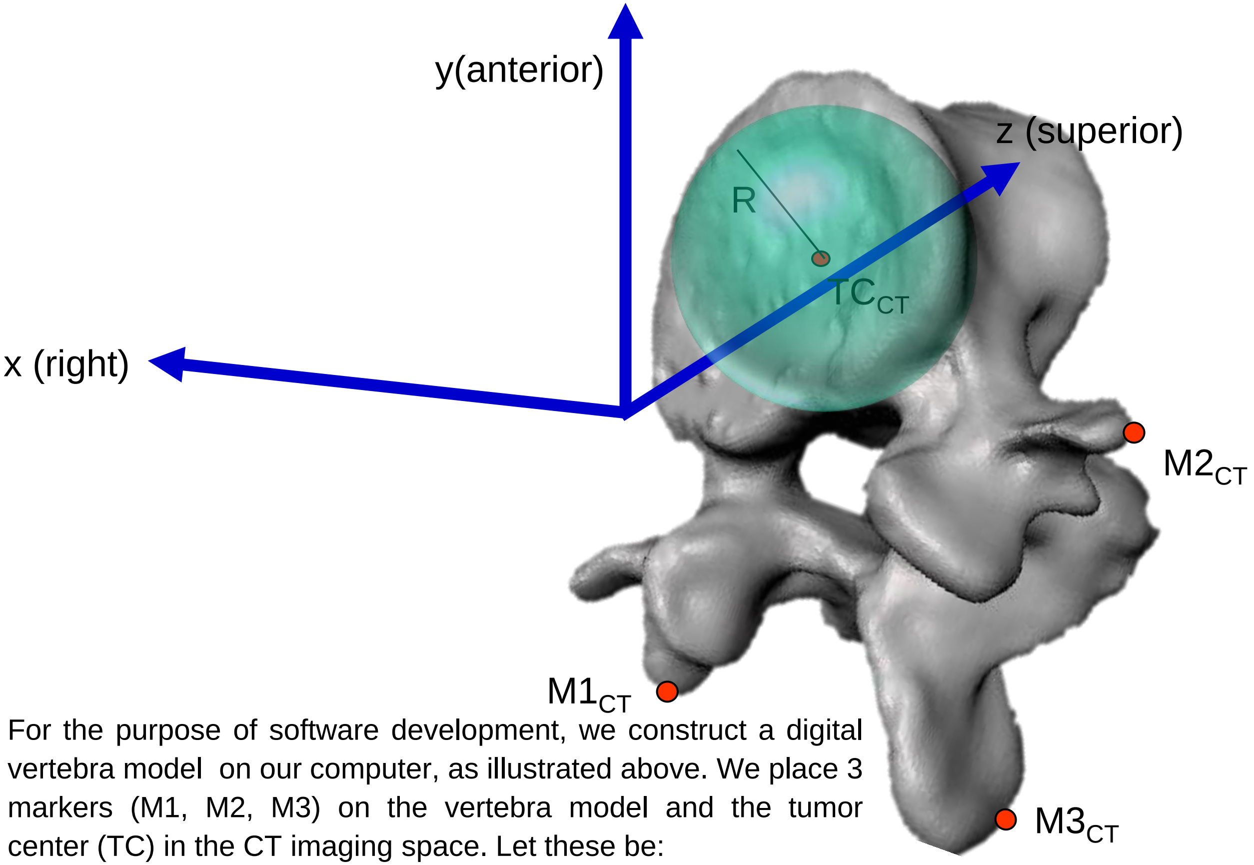


The Cyber Knife X-ray image guidance workflow



- The CK X-ray image guidance workflow is the following.
- Localize (segment) the three markers in each X-ray image. **Picking mathematical points to represent markers tends to cause error in computing the position of a target point in CK frame. The essence of this assignment is to examine how large marker segmentation error is allowed to be without causing a clinically significant error in target registration in CK frame**.
- The markers are expressed as some (u,v,0) in the image detector frame. The u and v are measured from center of the image. The third coordinate w is 0 in the image plane.
- The u and v are measured from center of the image.
- The third coordinate w=0 in the image plane.
- There is no distortion in the X-ray images.
- The center of the image is at (0,0,0)
- The (u,v,w) image coordinates have been scaled to metric units.
- Reconstruct the markers in CK frame.
- Register (i.e., transform) the target position from CT frame to CK frame. (Then we send this target position to the gun control robot which we operate in CK frame…)

Simulated ground-truth model in CT imaging space



For the purpose of software development, we construct a digital vertebra model on our computer, as illustrated above. We place 3 markers (M1, M2, M3) on the vertebra model and the tumor center (TC) in the CT imaging space. Let these be:

$M1_{CT}$ = [0, -40, -10]

$M2_{CT}$ = [-60, -10, 20]

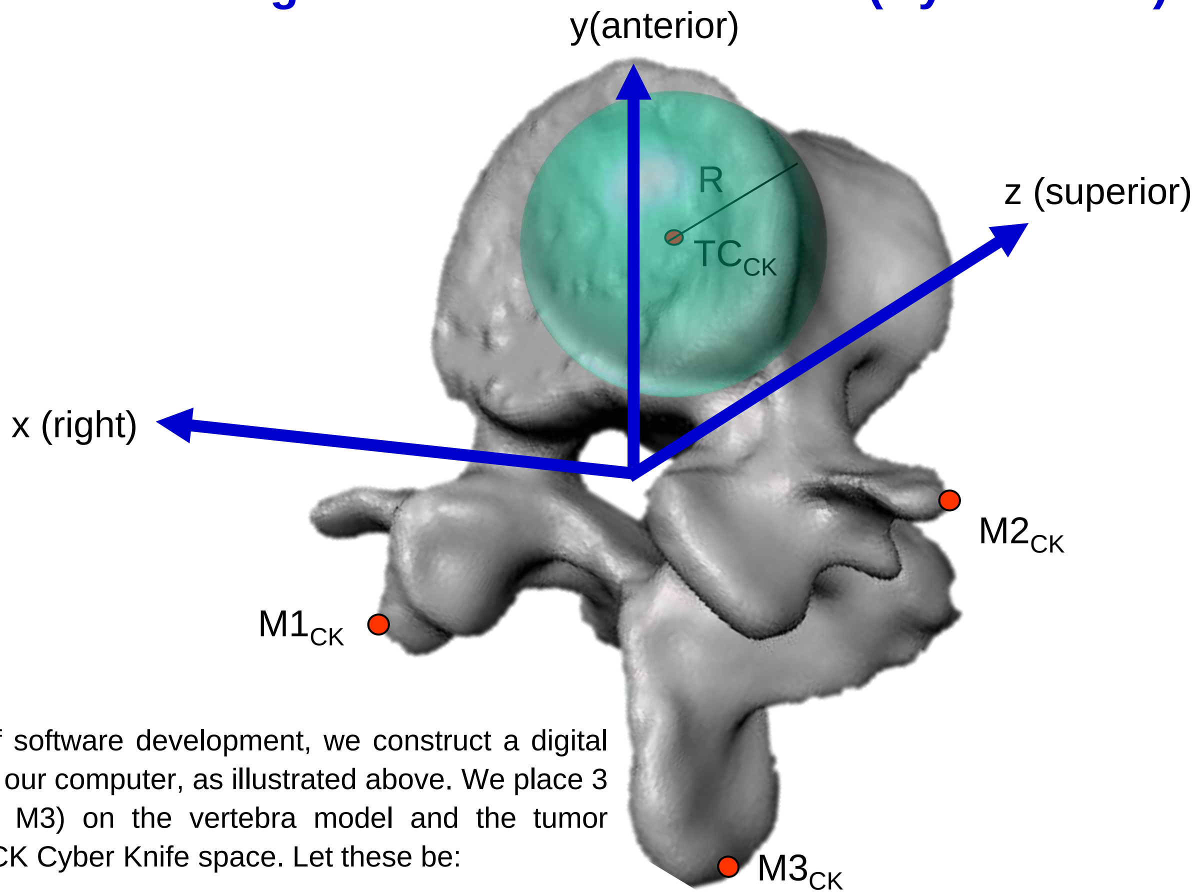
$M3_{CT}$ = [-30, -40, 50]

TC_{CT} = [-30, 20, 20]

R= 20

(Note: The ground truth marker coordinate values may not exactly correspond to the qualitative illustration above.)

Simulated ground-truth model in CK (Cyber Knife) space



For the purpose of software development, we construct a digital vertebra model on our computer, as illustrated above. We place 3 markers (M1, M2, M3) on the vertebra model and the tumor center (TC) in the CK Cyber Knife space. Let these be:

$M1_{CK}$ = [30, -30, 0]

$M2_{CK}$ = [-30, 0, 30]

$M3_{CK}$ = [0, -30, 60]

TC_{CK} = [0, 30, 10]

R= 20

Note: The ground truth marker coordinate values may not exactly correspond to the qualitative illustration above. Using skin marks and the robot controlling the Cyber Knife table,. the radiation therapy technicians are very skilled in reproducing the rotational position of the patient from the CT scanner table on the Cyber Knife table. The difference is usually only a few degrees, or sometimes even there is no discernable rotation between patient's pose between CT imaging and Cyber Knife treatment. Our ground truth reflects this situation. Nonetheless, in your navigation software, you should assume the general case with some rotation.

Questions and Problems

Frame Transform: Develop a module to generate frame transformations from the CK frame to the A and B detector image frames. (Feel free to implement it as one function or two separate functions, one for each detector.) Input: none. Output: 4x4 homogeneous matrices for transforms. Test each transforms on at least 3 suitable points of your choice, make a sketch, run your module and show that it produces the predicted results.

X-ray Projection: In order to test the X-ray reconstruction software that you will develop, you first need to develop a digital X-ray projector to create ground-truth X-ray images. For our purpose, the fake X-ray images do not need to have any greyness or to show anatomy. It will be sufficient to project a point in CK space onto the two imaging detectors and report the resulting coordinates in detector image frame. This will simulate a segmented marker in the X-ray images, which you will use as input for the reconstructor software. (Feel free to implement it as one function or two separate functions, one for each detector.) Input: Point in CK frame. Output: Points in the A and B detector image frames. Test each projector on at least 3 suitable points of your choice, make a sketch, run your module and show that it produces the predicted results.

Marker Reconstruction: Develop a module to reconstruct a point in CK frame from two detector image points. Also compute appropriate residual error metric (REM). Input: Point in A image frame, Point in B image frame. Output: Reconstructed point in CK frame and REM. Test the module on the same simple ground truth points you used for testing the X-ray projector. Then test the module by projecting C_{CK}, $M1_{CK}$, $M2_{CK}$, $M3_{CK}$ onto the detectors, reconstruct them, and show that your reconstructor produces perfect results, with zero (or rather near-zero) residual error metric.

Marker Correspondences:

Develop a module to resolve the correspondences in the reconstruction of 3 identical markers. Explain your method in comments. Input: Three points in A image frame , three points in B image frame. Output: Correspondence matrix (refer to class notes.) Test: Project the $M1_{CK}$, $M2_{CK}$, $M3_{C}$ onto two the X-ray detectors – you have already done this. (1) Feed the resulting image points to your module and show that you resolves their correct correspondences. (2) Swap M1 and M2 in image A, feed the points to your module and show that you can resolve correct correspondences. (3) Run the above for a slightly different set of marker screws: $M1_{CK}$ = [30, -30, 0], $M2_{CK}$ = [-30, 0, 0], $M3_{CK}$ = [0, -30, 60]. Report and explain your findings.

Target Registration: Develop a module to register a tumor target point from CT frame to CK frame. Input: target point in CT frame, three marker points in CT frame ($M1_{CT}$, $M2_{CT}$, $M3_{CT}$), three marker points in CK frame ($M1_{CK}$, $M2_{CK}$, $M3_{CK}$). Output: target point in CK frame.(1) Make a sketch and determine the ground-truth $F_{CK \leftarrow CT}$ frame transform. (2) Run the registration module, compute the tumor target in CK frame, and run the registration on $M1_{CT}$ $M2_{CT}$ $M3_{CT}$ and demonstrate that your frame transform yields the correct $M1_{CK}$ $M2_{CK}$ $M3_{CK}$ points.

Target Registration Error Simulation

Develop a module to analyze the robustness of target registration against marker segmentation errors. For the sake of this exercise, we assume that marker segmentation in the X-ray images s the only source of error target registration error (TRE) in our system. (As no error is being carried over from CT space, we can carry out our analysis entirely in the CK frame.)

Let the allotted maximum target registration error (maxTRE) for this clinical application be 1.0 mm.

We will simulate the marker segmentation error as a vector of random direction and of a fixed magnitude (Emax). We will start with zero error (Emax=0) and gradually increase the magnitude of the marker segmentation error by a small increment which should match the resolution of the detector - i.e., pixel size in the X-ray images, the ultimate technical lower limit to marker segmentation error; let this be 0.1mm for the purpose of this exercise. We will stop the simulation when the target registration error exceeds the clinical limit (maxTRE).

- Initialization: Generate N random ground-truth target points inside the target envelop, in CK frame. We must pick a large enough N to obtain good statistical power without drowning our computer. Something like N=100 is more than enough for our purpose. (You can go down to N=50 if you lack CPU power.) Also initialize the relevant variables.
- Project the 3 ground truth markers ($M1_{CK}$, $M2_{CK}$ $M3_{CK}$) onto the X-ray detectors.
- Start the simulation cycle:
    - Spoil each marker image point by a segmentation error vector of random direction and of Emax magnitude, within the detector plane.
    - Feed the error-spoilt image points to the marker reconstructor module to obtain three markers in CK frame. (These markers will be different from the ground truth markers because we spoilt their image points with error.)
    - For each of the N ground-truth target points in the envelop, register the target point from CT frame to CK frame and compute the target reconstruction error (TRE) between the ground truth target and registered target. When TRE is larger than the clinically allotted maxTRE, then we exceed the clinical limit, and exit the simulation.
    - Otherwise, increase the magnitude of the marker segmentation error (Emax) and continue the simulation cycle.
- Report the maximum allowable marker segmentation error that still guarantees clinically acceptable target registration error for all targets within the envelop.
- Discussion: How would you judge this outcome? Is the target reconstruction robust to marker segmentation errors? Or is it fragile and susceptible to marker segmentation errors? (Consider the dimensions of the screw, the object magnification in the X-ray imaging system, the resolution of the detectors, etc.)

A brief "thought guide" to the questions

You may find these clues and tips helpful in cracking the specific problems in this assignment…

Frame Transforms: You need to compute center and the base vectors of the destination frame in the home frame. Think about how the X-ray system is constructed geometrically: first shifting of the x-y plane, then rotating by +/-45 degrees about the z axis. In HW1, you may have done the same when you constructed ground-truth transforms for testing the Frame Transformation routine. Also consult the lecture slides.

Marker Projector: Again, consult the lecture slides. Remember: just like in a real X-ray machine, the act of projection takes place in CK frame, and the resulting point is transformed from CK frame to detector image frame, where it is a 3D point, with the third coordinate being zero (or rather very small.)

Marker Reconstructor: Note that the marker image points are in detector image frame, but the reconstruction is done in in CK frame, alas you first need to transform the input to CK frame. And consult the lecture notes re X-ray reconstruction.

Marker Correspondence: Consult the lecture slides, they contain detailed explanation of the correspondence problem with alternative solutions and a likewise detailed explanation of ambiguities.

Target Registration: Consult the lecture slides.

TRE Simulator: The problem statement's text has detailed explanation that leads you through the simulation process, step by step.

On software design: In naming points, always indicate their home frame(like M1inCK). In naming frame transforms, always indicate the source frame and destination frame (like TransformFromCKtoA). Do not worry about memory efficiency or dynamic memory allocation, as this is not a software engineering course. You can (slightly) over-estimate your memory needs, and if you run out of space, adjust the buffers and rerun the simulation which, in this case, is not computationally expensive. As always, do not enter input from the command line.

Points

Frame Transforms		
Transform from CK to A		
Compute center and bases	3	
Compute transform	2	
Test	3	
Transform from CK to B		
Compute center and bases	3	
Compute transform	2	
Test	3	
Total		16

X-ray Projection		
Project to detector A (beam line 1, projection 2, transform 1)	6	
Project to detector B (beam line 1, projection 2, transform 1)	6	
Test	3	
Total		15

Marker Reconstruction		
Compute transformations	4	
Construct back projection lines	4	
Compute reconstruction	4	
Compute REM	2	
Test	3	
Total		17

Marker Correspodence		
REM Matrix	6	
Correspondance matrix	6	
Test1	3	
Test2	4	
Total		19

Tumor Target Registration		
Compute frames (centers and bases)	3	
Compute transform	3	
Construct ground truth transform	3	
Test	3	
Total		12

Target Reconstruction Error Simulation		
Generate random targets in the envelop	3	
Project markers to the detectors	3	
Blend segmentation error	3	
Target reconstruction	3	
Target registration	3	
Compute TRE	3	
Discussion	3	
Total		21
TOTAL		**100**