Image-guided therapy and medical robotics tutorial using a LEGO Mindstorms NXT robot and 3D Slicer

Part III: The Advanced Tutorial

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Funding Information

This tutorial was made possible by grant numbers 5U41RR019703, 5P01CA067165 and 5U54EB005149 from the National Institutes of Health (NIH). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH. This tutorial was also in part supported by National Science Foundation (NSF) grant number 9731748 and the Center for Integration of Medicine and Innovative Technology (CIMIT).

Goals of the image-guided therapy and medical robotics tutorial

- To demonstrate the typical steps of an image-guided therapy (IGT) or medical robotics procedure.
- To learn in a hands-on manner using a LEGO Mindstorms NXT, a LEGO phantom and sophisticated medical image processing and IGT software (3D Slicer).

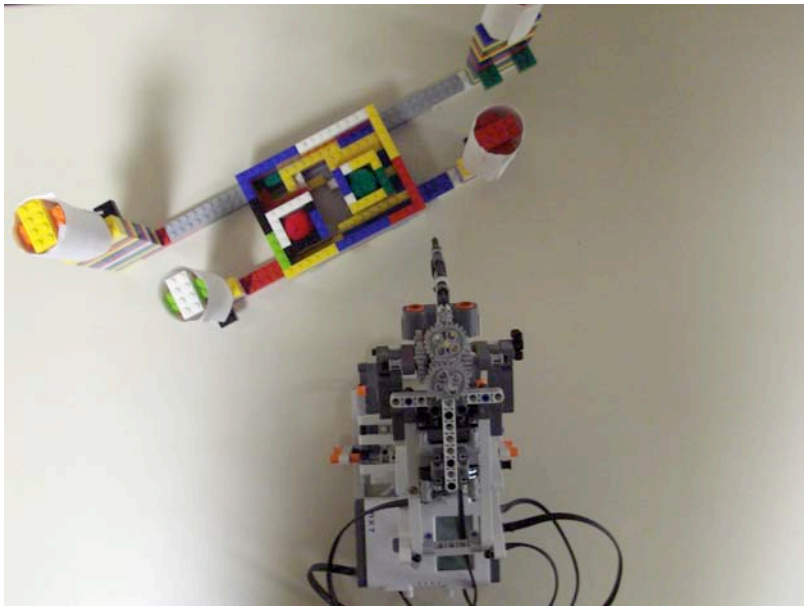
The example procedure that we will use to do this is a needle biopsy.

Goals of the advanced tutorial

- As in the basic tutorial, to learn about the following steps in IGT and medical robotics in a hands-on manner:
  - ✓ Imaging
  - ✓ Preoperative planning
  - ✓ Targeting and tracking
  - ✓ Navigation
- To learn about the registration step in IGT and medical robotics.

The advanced tutorial

In the advanced tutorial, the position of the phantom relative to the LEGO robot is not known.



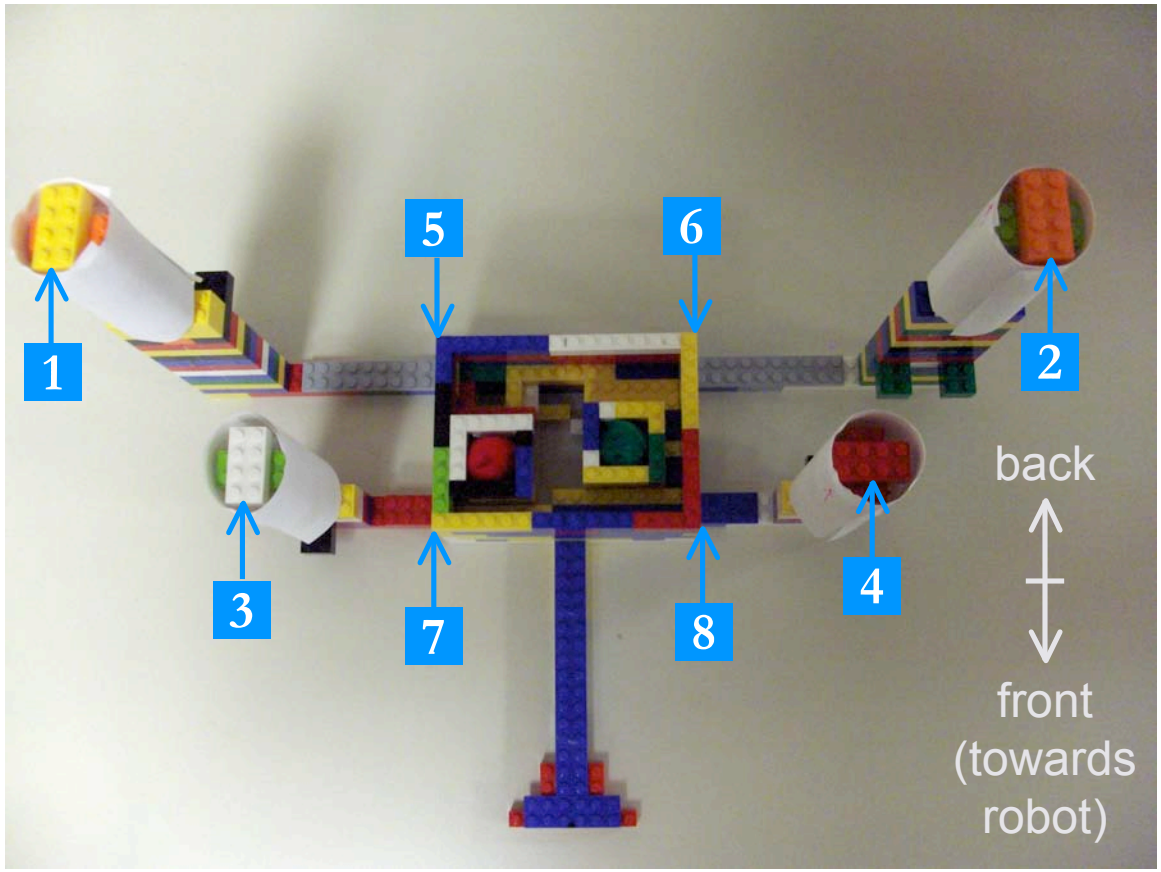
We must determine the relationship between the image coordinate system (*ICS*) and the patient (robot) coordinate system (*PCS*).

We must perform registration!

Registration in the advanced tutorial

- Fiducials are corresponding coordinates in the image coordinate system and the patient (robot) coordinate system.
- These fiducial points are input into a registration algorithm to determine the transformation between the two coordinate systems.
- We will use eight fiducials on the phantom to perform registration.

The eight fiducials



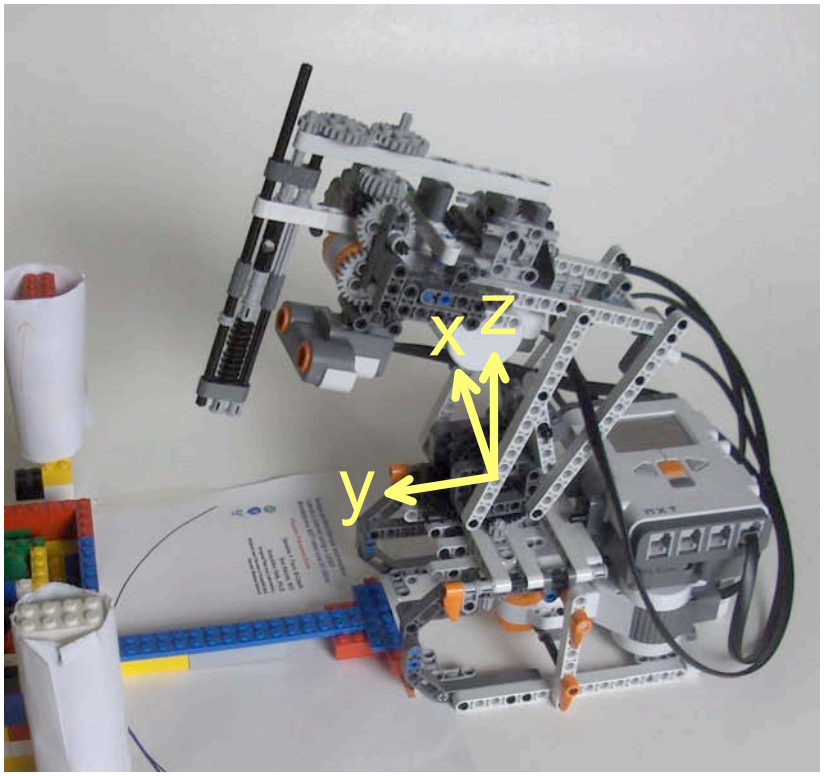
- One on the top surface of each pillar (centered on the front side)
- One on the top surface of each corner of the central box

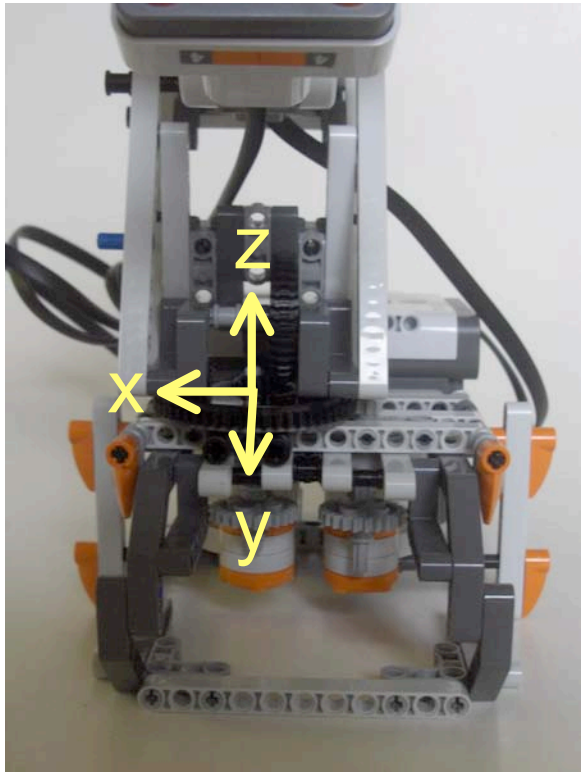
The registration procedure

1. Find the eight fiducials in the patient (robot) coordinate system (*PCS*)
2. Find the eight fiducials in the image coordinate system (*ICS*)
3. Use a landmark registration algorithm to determine the transformation from the image coordinate system to the patient (robot) coordinate system.

Finding the fiducials in the PCS

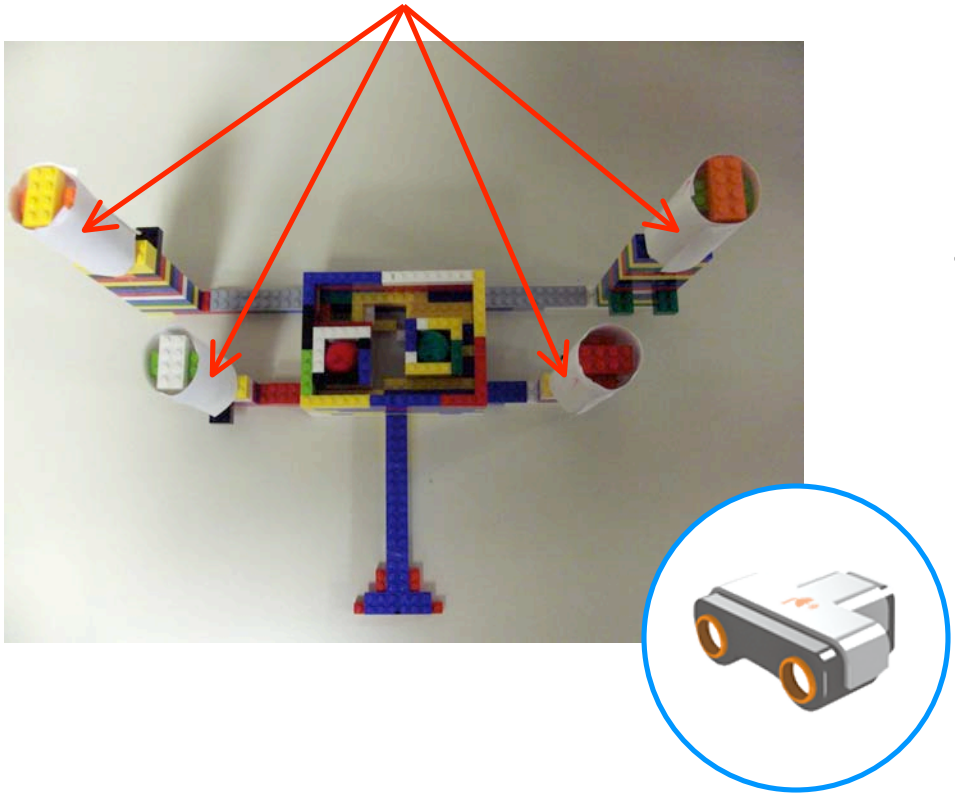
- Two views of the patient (robot) coordinate system:





Finding the fiducials in the PCS, continued

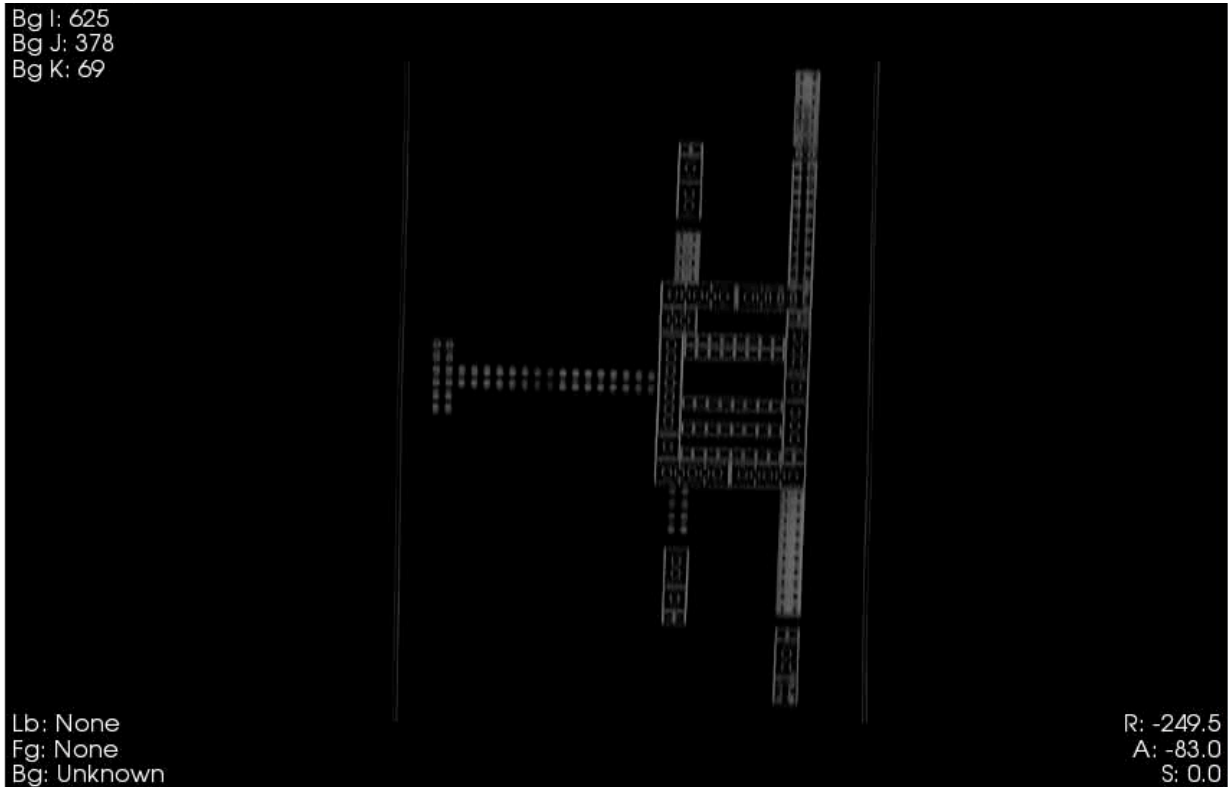
four "registration pillars"



- The LEGO robot's ultrasonic sensor detects distance to the nearest obstacle.
- We will find the phantom by using the robot's ultrasonic sensor to find the "registration pillars" on the phantom.

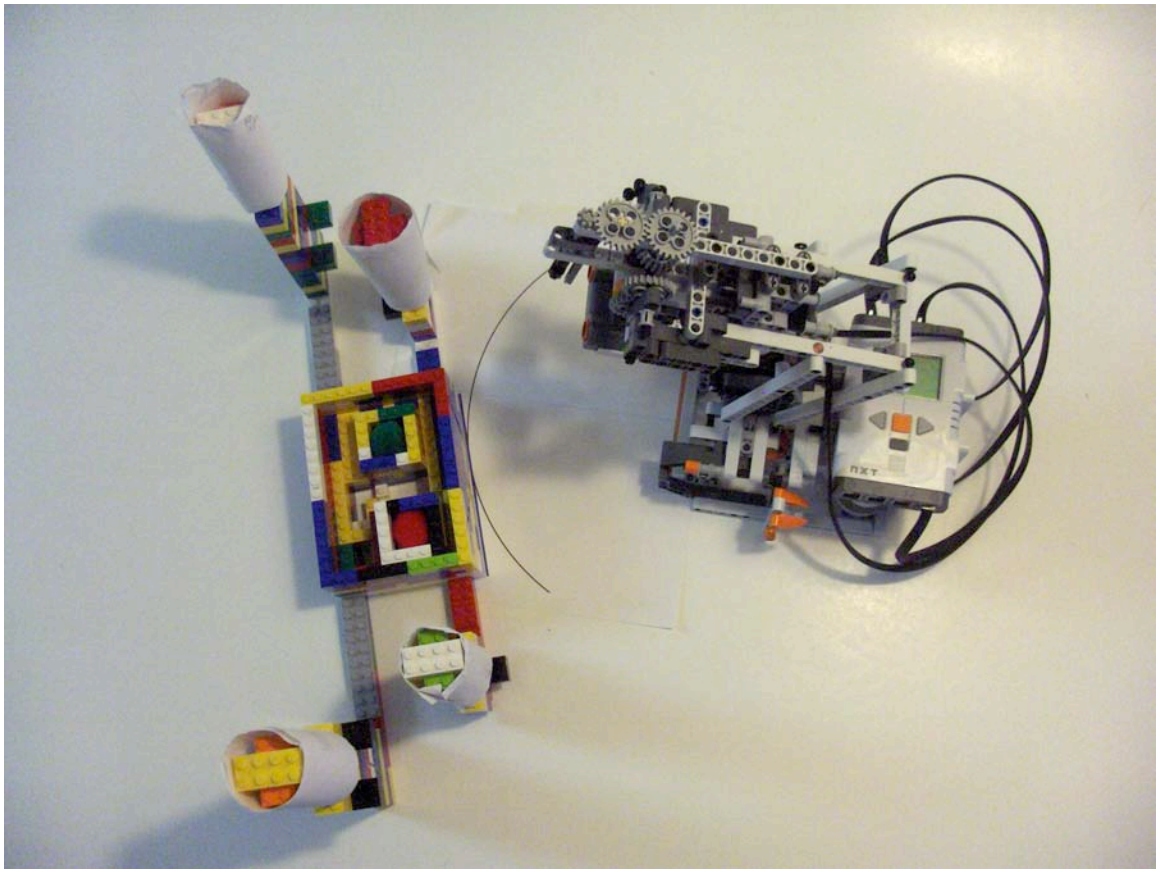
Finding the fiducials in the ICS

You will select the corresponding fiducials in the image coordinate system by clicking on the points on the CT volume.



Set up the LEGO robot and the phantom

The final setup:

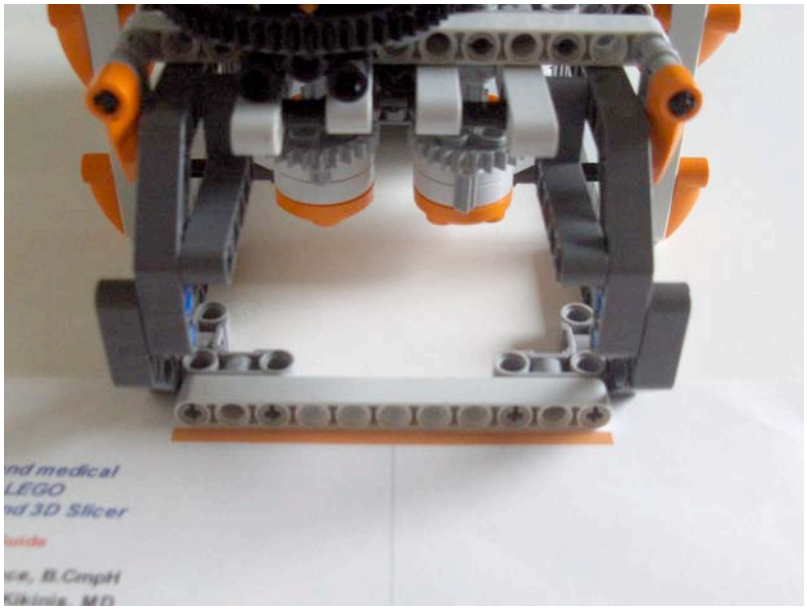


Instructions to follow are in yellow boxes

Set up the LEGO robot and the phantom, continued

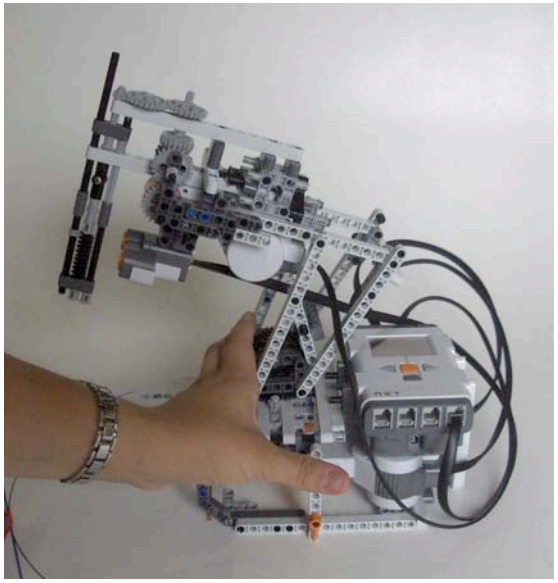
- Tape the phantom placement guide on a table
- Ensure that there is no wall or other object within a four foot radius around the robot, as walls or other objects will interfere with the ultrasonic sensor used in the advanced tutorial
- Remember that you need to use new batteries or a freshly charged battery pack on the robot.

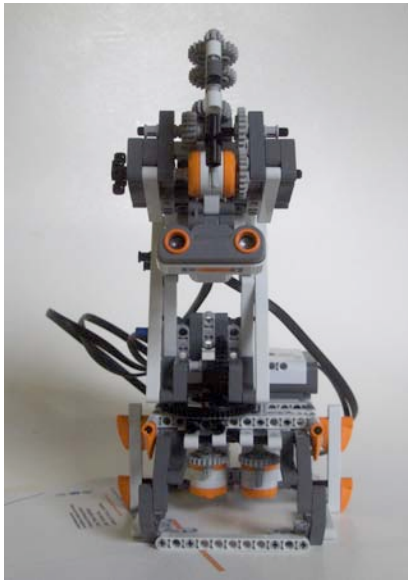
Set up the LEGO robot and the phantom, continued

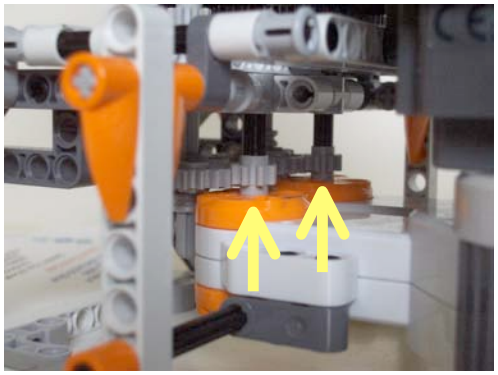


- Position the LEGO robot so that the front piece of the base lines up with the orange line of the phantom placement guide

Set up the LEGO robot and the phantom, continued

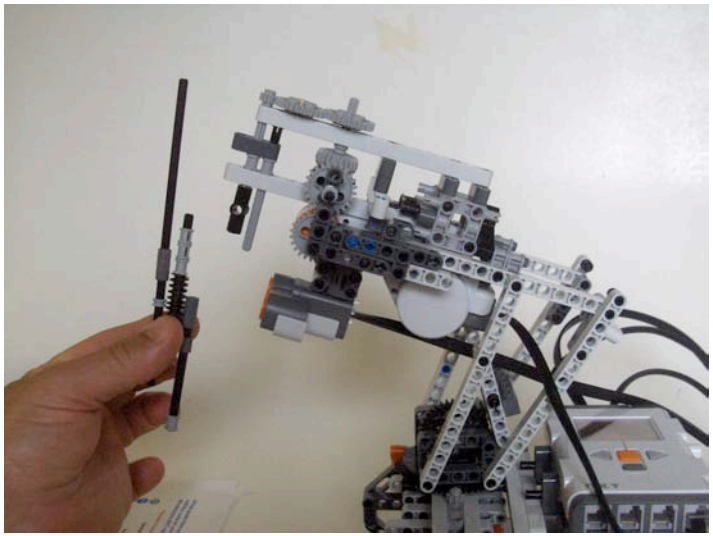


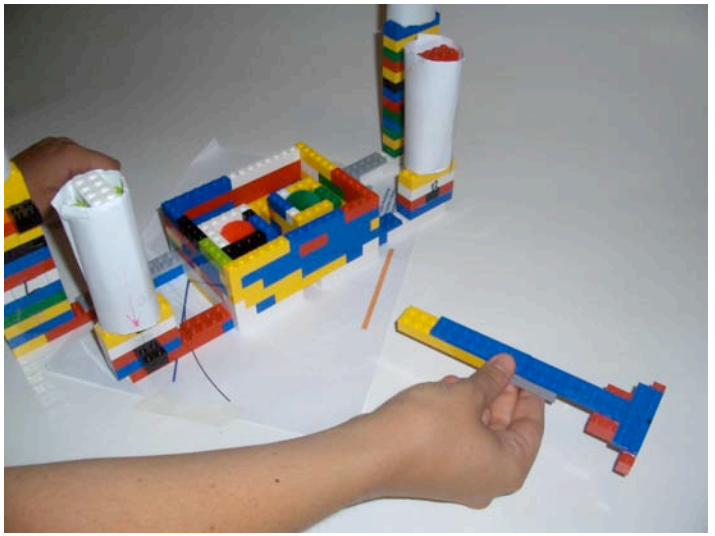




- Position the robot in the "initial position":
  - robotic arm is pushed all the way back
  - robotic arm is centered
- To move the robotic arm:
  - push the small gears at the back of the robot's base **up**
  - Freely move the robotic arm into position
  - Push the small gears at the back of the robot's base back **down** so that they catch on the larger gears

Set up the LEGO robot and the phantom, continued

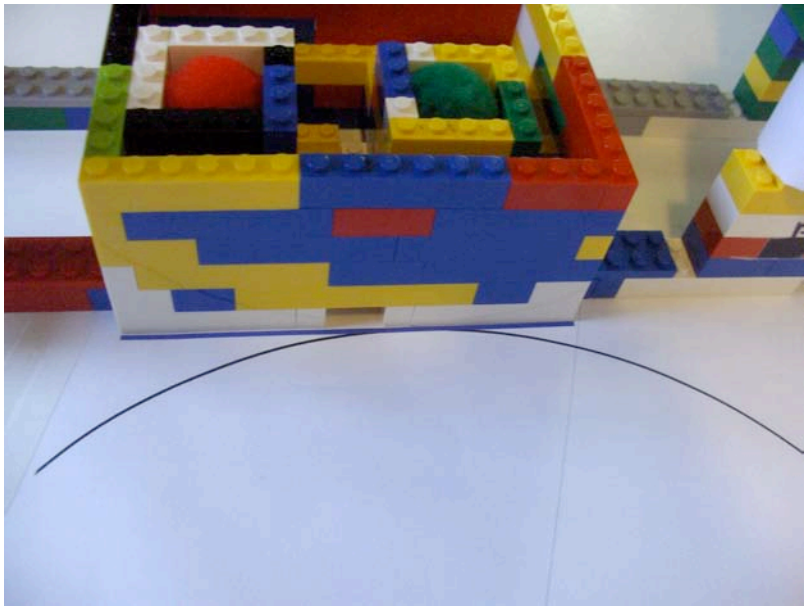




- Take the needle off of the robot arm so that it does not interfere with the ultrasonic sensor
- Take the bottom spacer off of the phantom

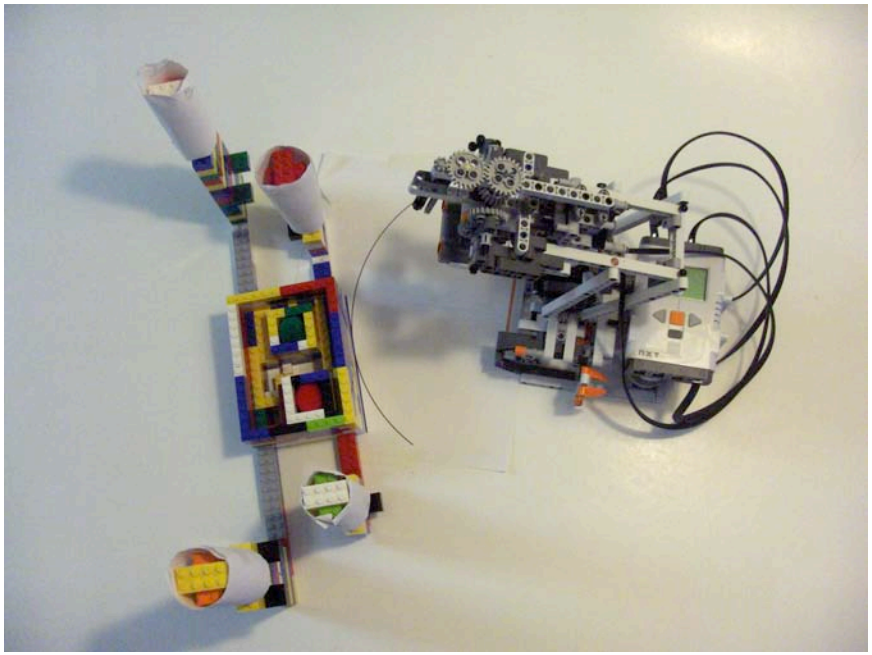
Set up the LEGO robot and the phantom, continued

- Position the phantom relative to the LEGO robot such that:
  1. The needle can reach **both** pom-pom targets
  2. The registration pillars will be in view of the LEGO robot's ultrasonic sensor as the robot arm scans from side to side
- For example, position the phantom so that it lines up with the blue line on the phantom placement guide



Set up the LEGO robot and the phantom, continued

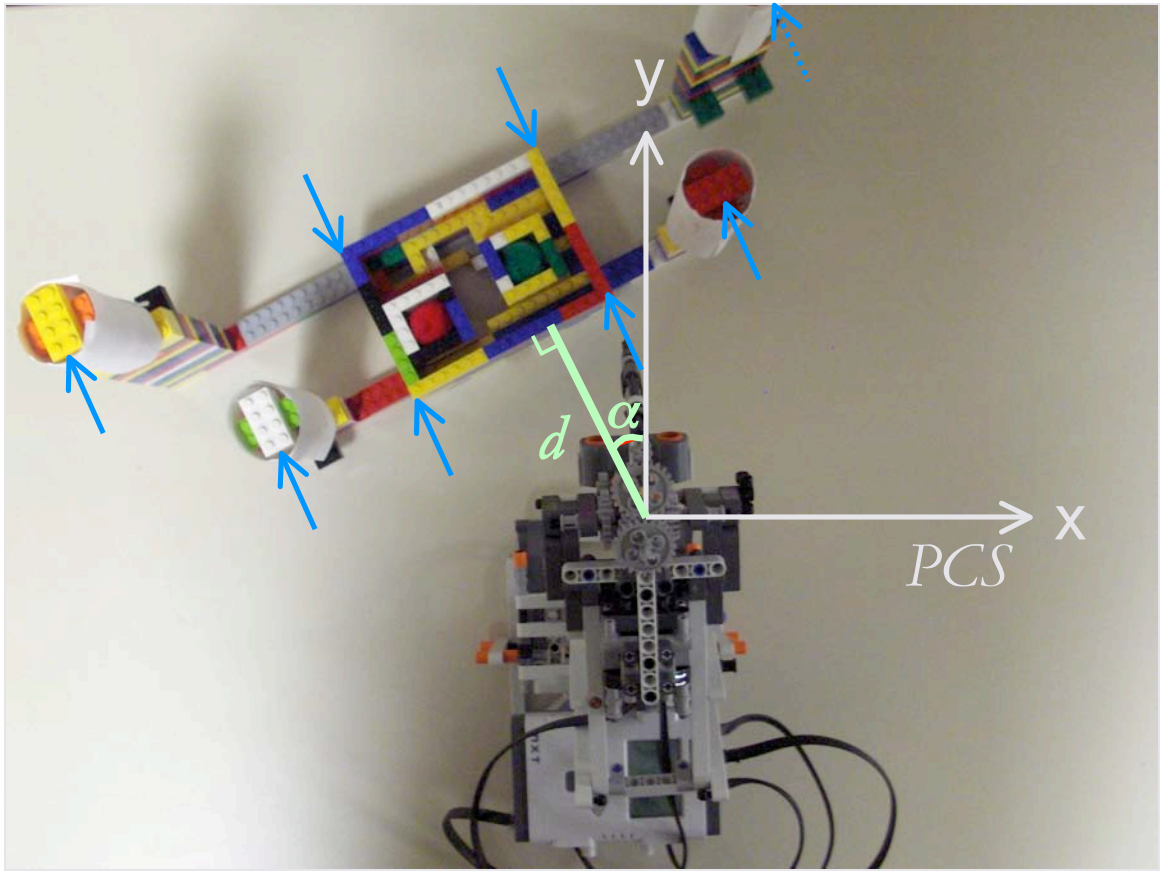
Your setup should look like this:



- Connect the robot to the Linux computer using the USB cable provided in the LEGO Mindstorms NXT kit
- Turn the LEGO robot on by pressing the orange button on the NXT brick.

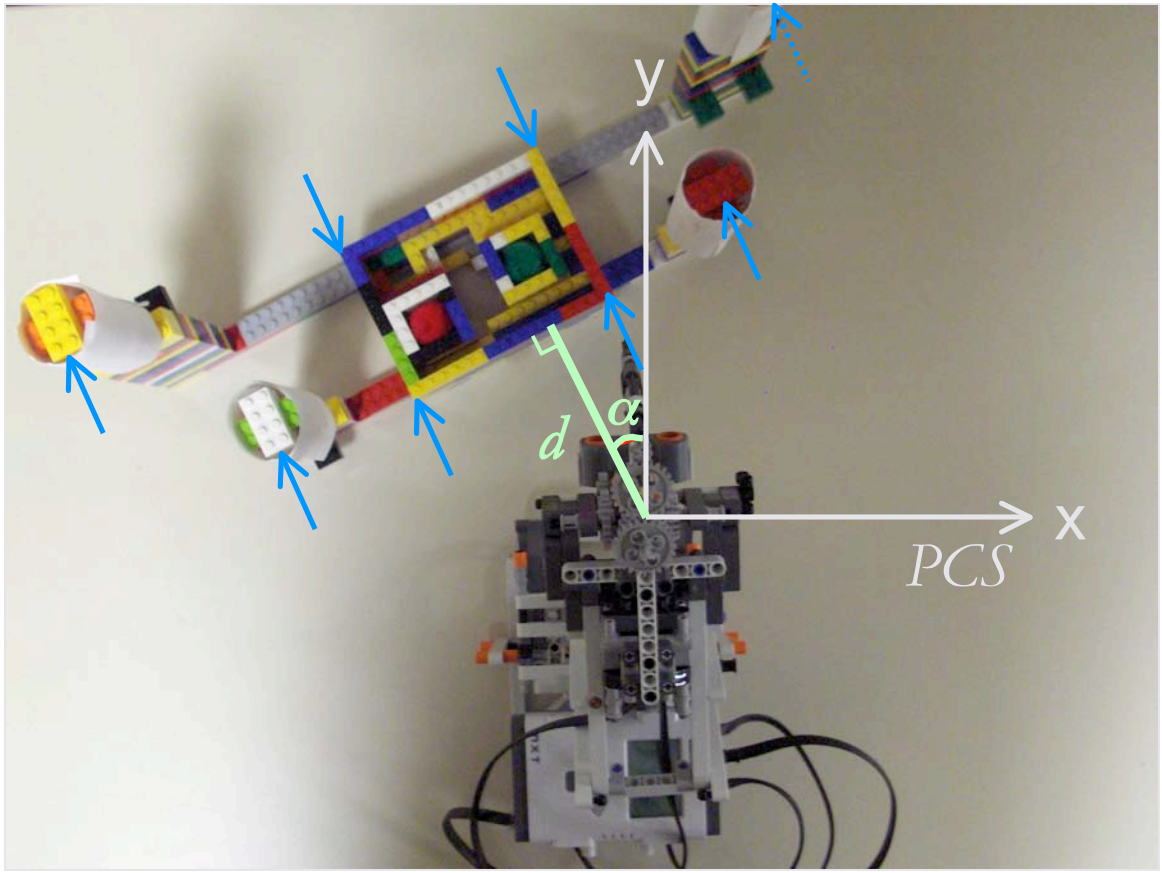
Finding the fiducials in the PCS - in more detail

Since we know that the needle can reach both pom-poms, we have an approximation of the distance *d* from the phantom to the origin of the *PCS*.



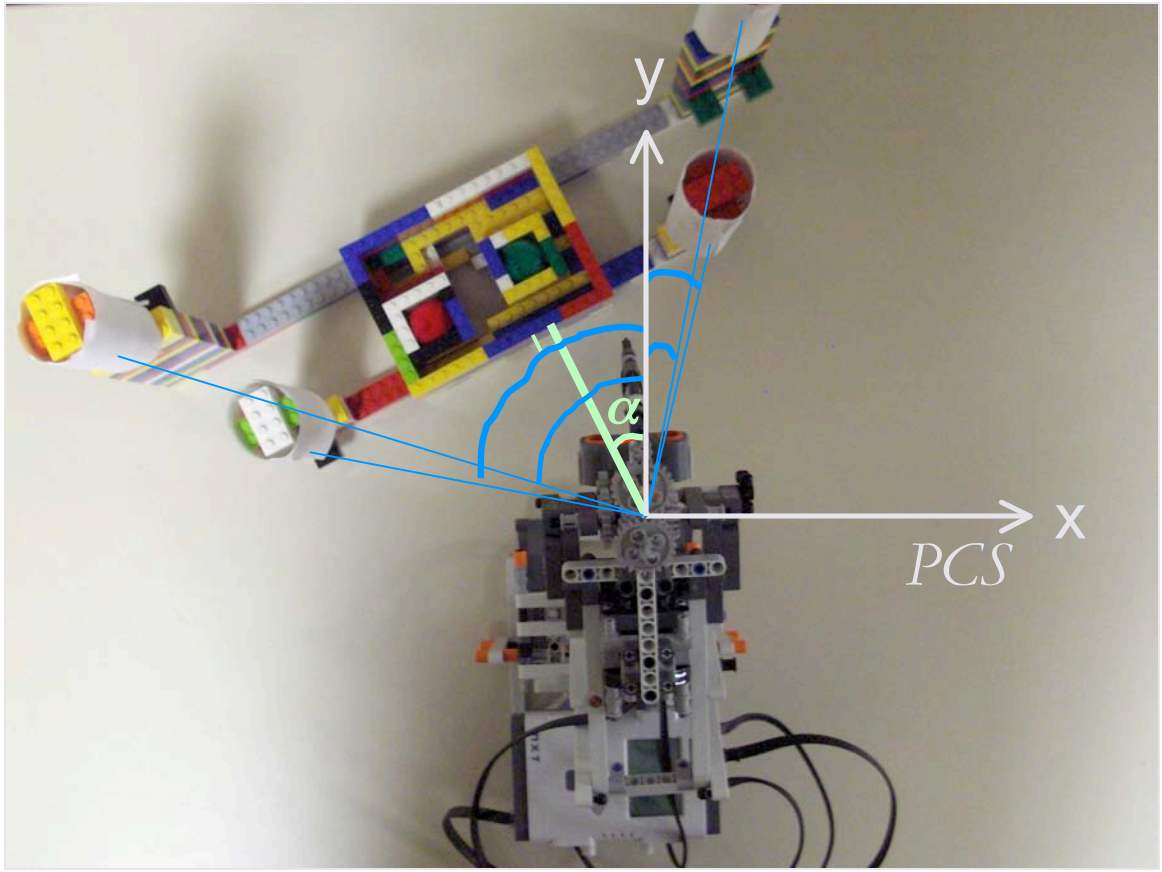
Finding the fiducials in the PCS - in more detail, continued

Knowing the structure of the phantom and *d*, we can find the eight fidicuals in the patient (robot) coordinate system if we can determine the angle α.



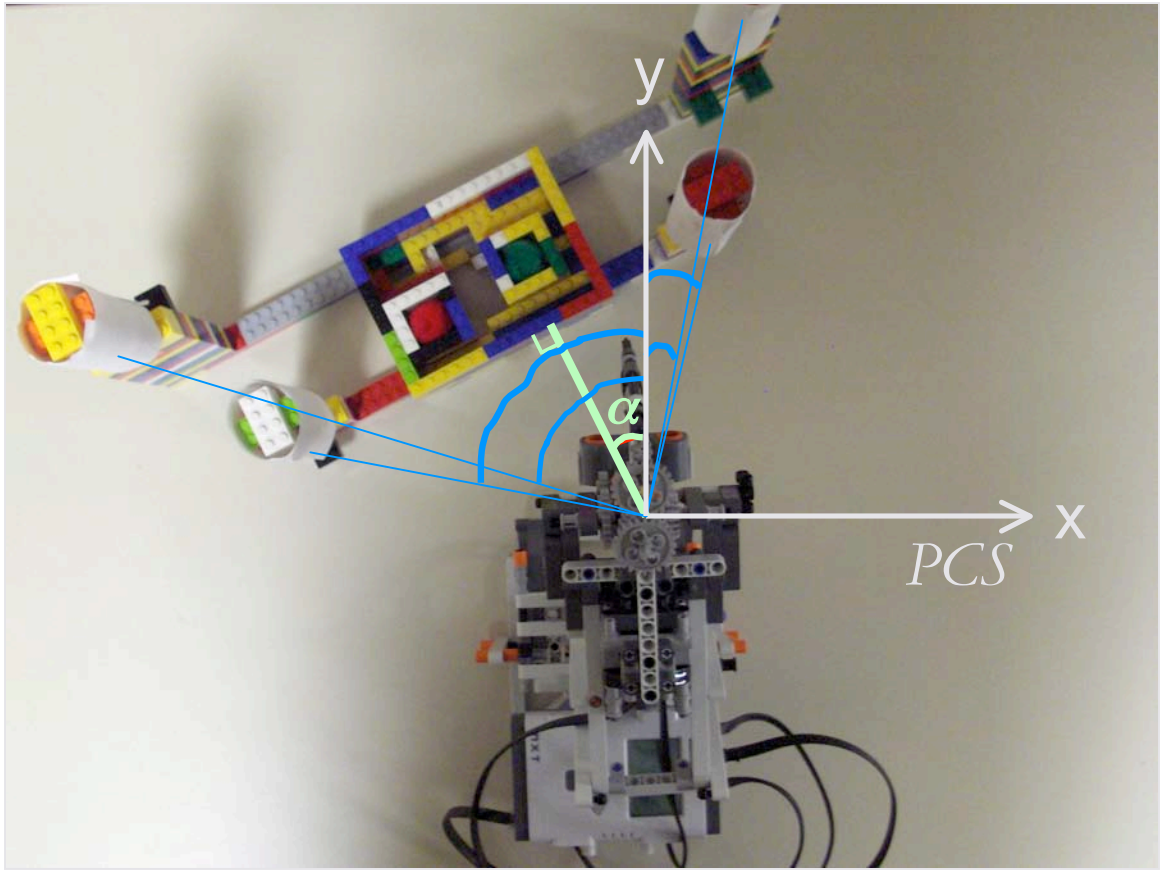
Finding the fiducials in the PCS - in more detail, continued

The average of the four angles between the y-axis of the *PCS* and the line segments from the origin of the *PCS* to the registration pillars gives us an approximation for angle α.



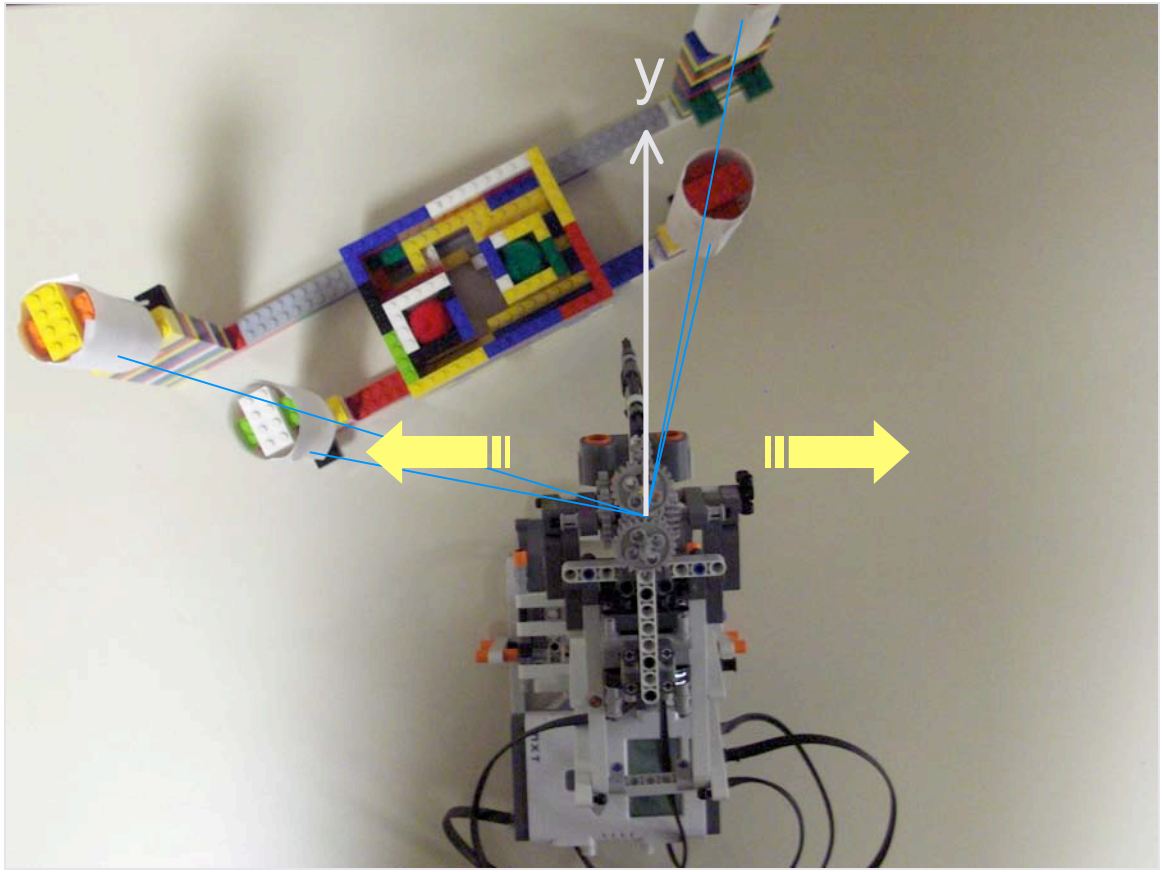
Finding the fiducials in the PCS - in more detail, continued

We will use the ultrasonic sensor to find the registration pillars, and therefore these four angles.



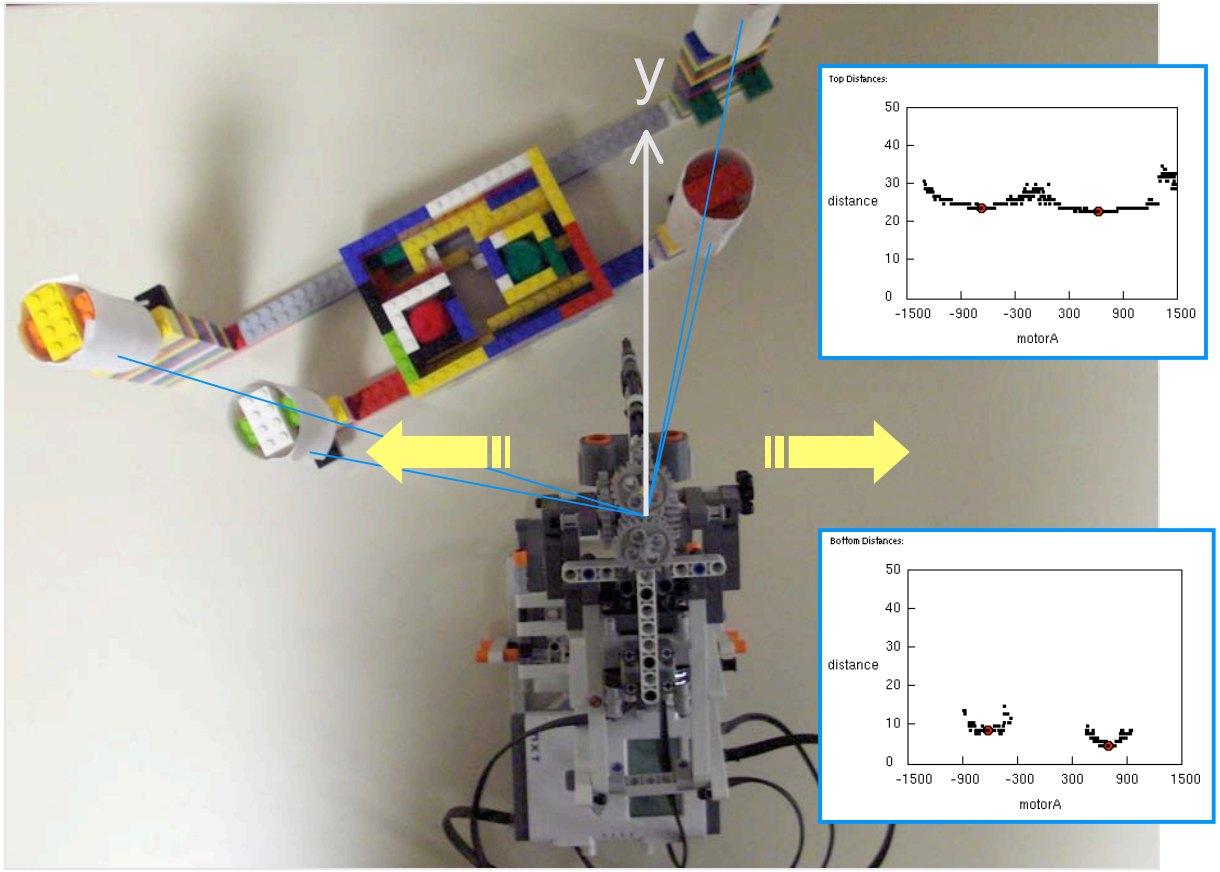
Finding the fiducials in the PCS - in more detail, continued

- The robotic arm will move slowly from left to right (using motor A) while continually polling the ultrasonic sensor for distance measurements and motor A's rotation sensor for the number of degrees it has rotated.
- This will occur twice - once for the taller "top" pillars and once for the shorter "bottom" pillars.



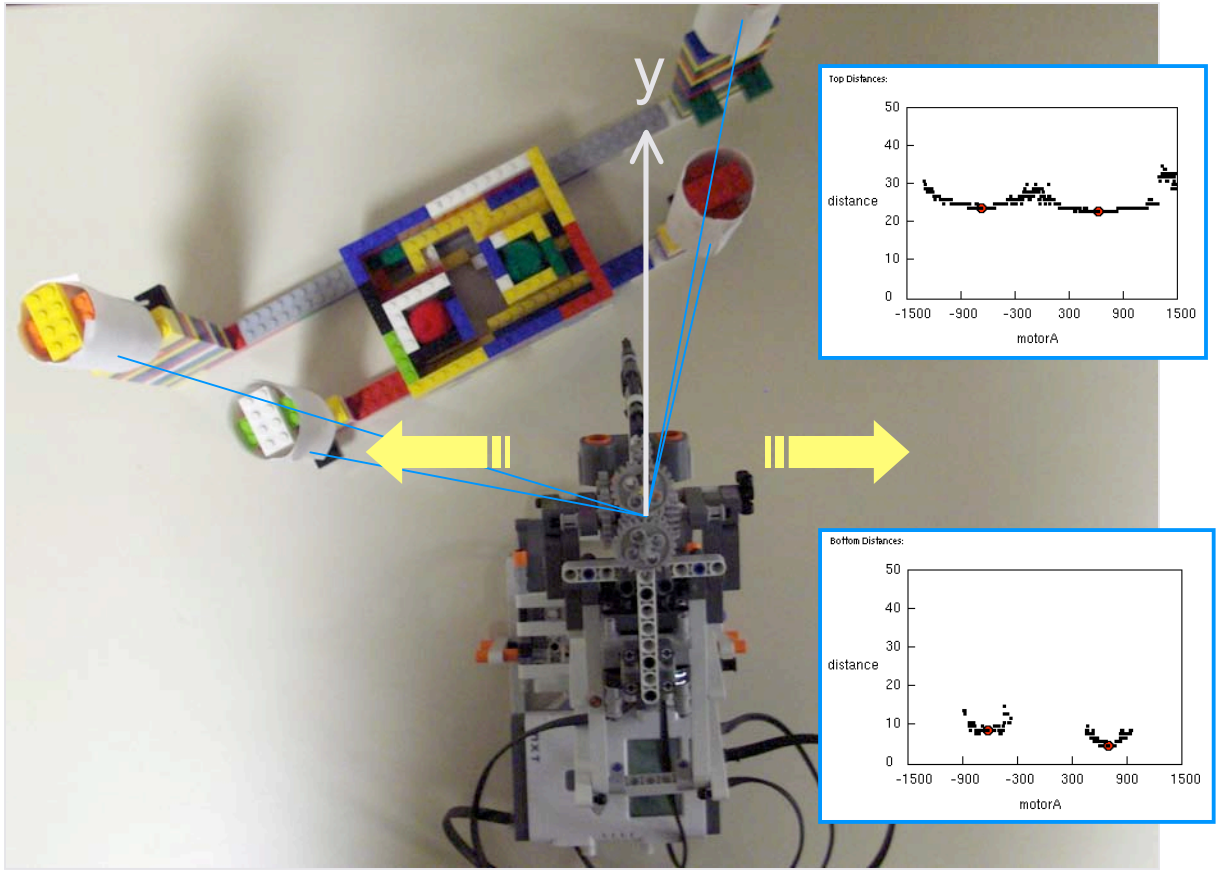
Finding the fiducials in the PCS - in more detail, continued

Profiles of *motorA* (the number of degrees that the motor has turned to move the robotic arm left to right) vs. distance (in centimetres, returned from the ultrasonic sensor) are generated for the top and the bottom swipes.



Finding the fiducials in the PCS - in more detail, continued

The two local minima in each swipe are automatically detected and represent the registration pillars. We can use the *motorA* values of these minima to find the corresponding angles that we need.

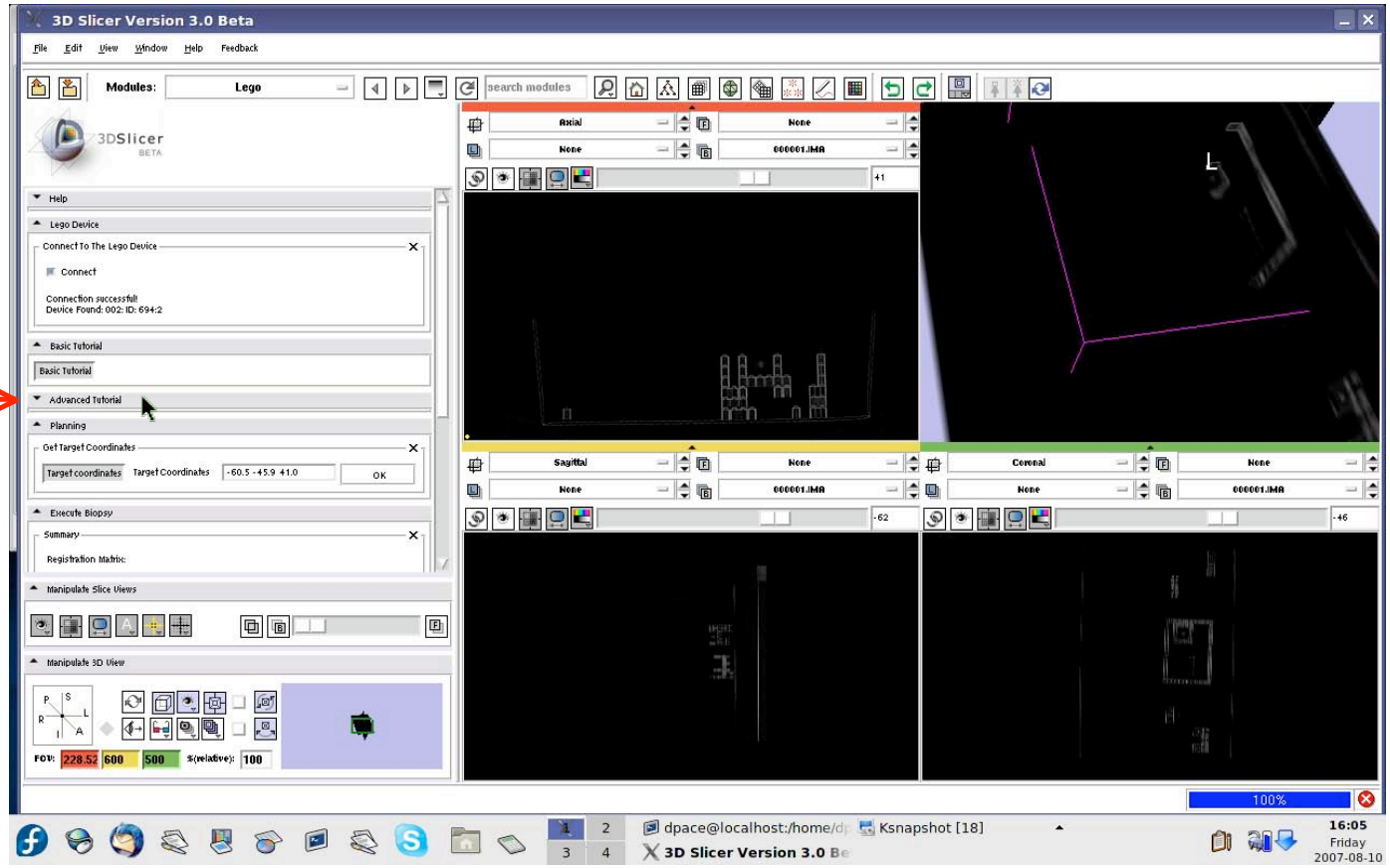


1) First steps

- Follow steps 1-3 of the basic tutorial to connect to the LEGO robot and load the CT volume of the phantom.

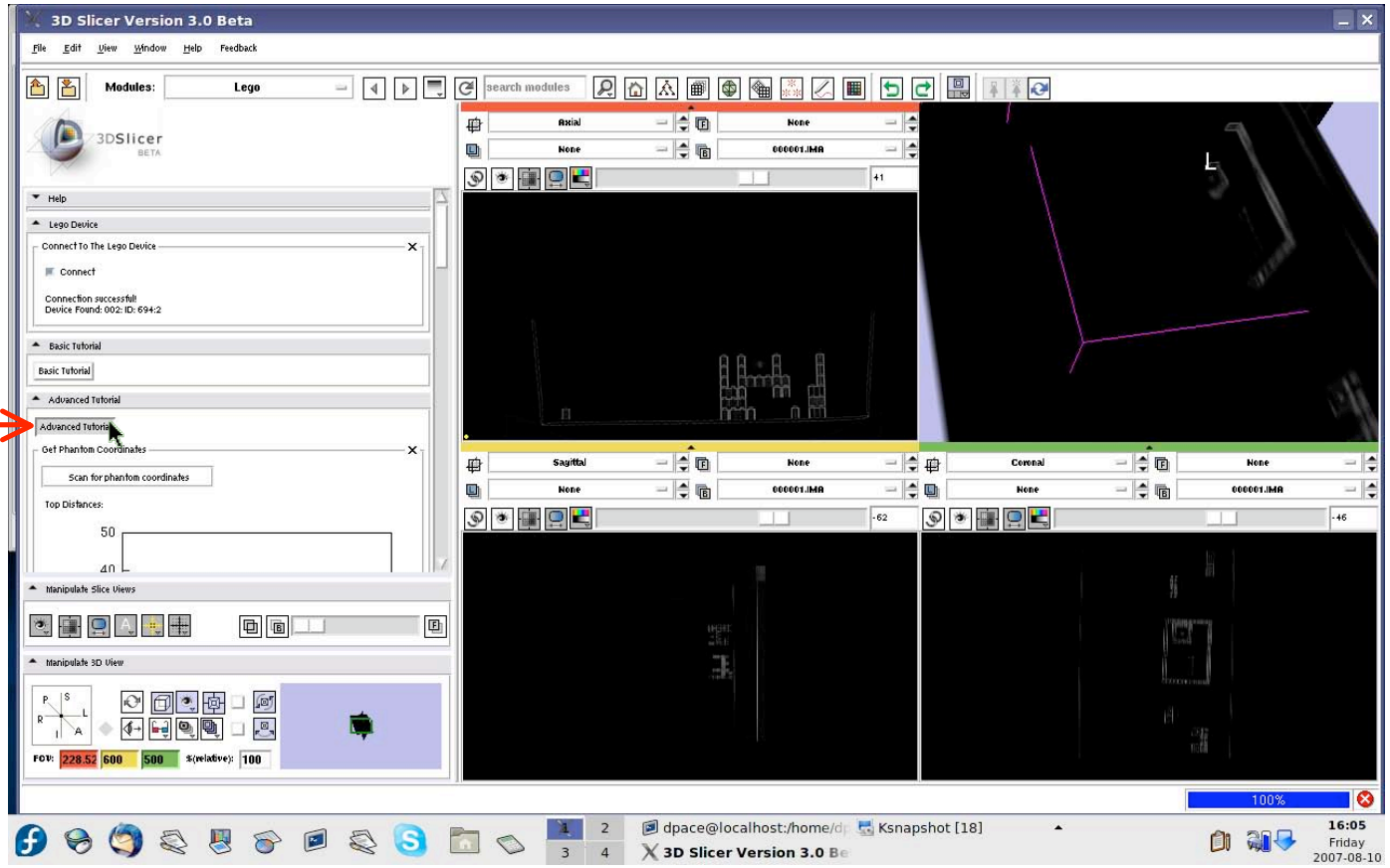
2) Select the advanced tutorial option

Open the "Advanced Tutorial" pane



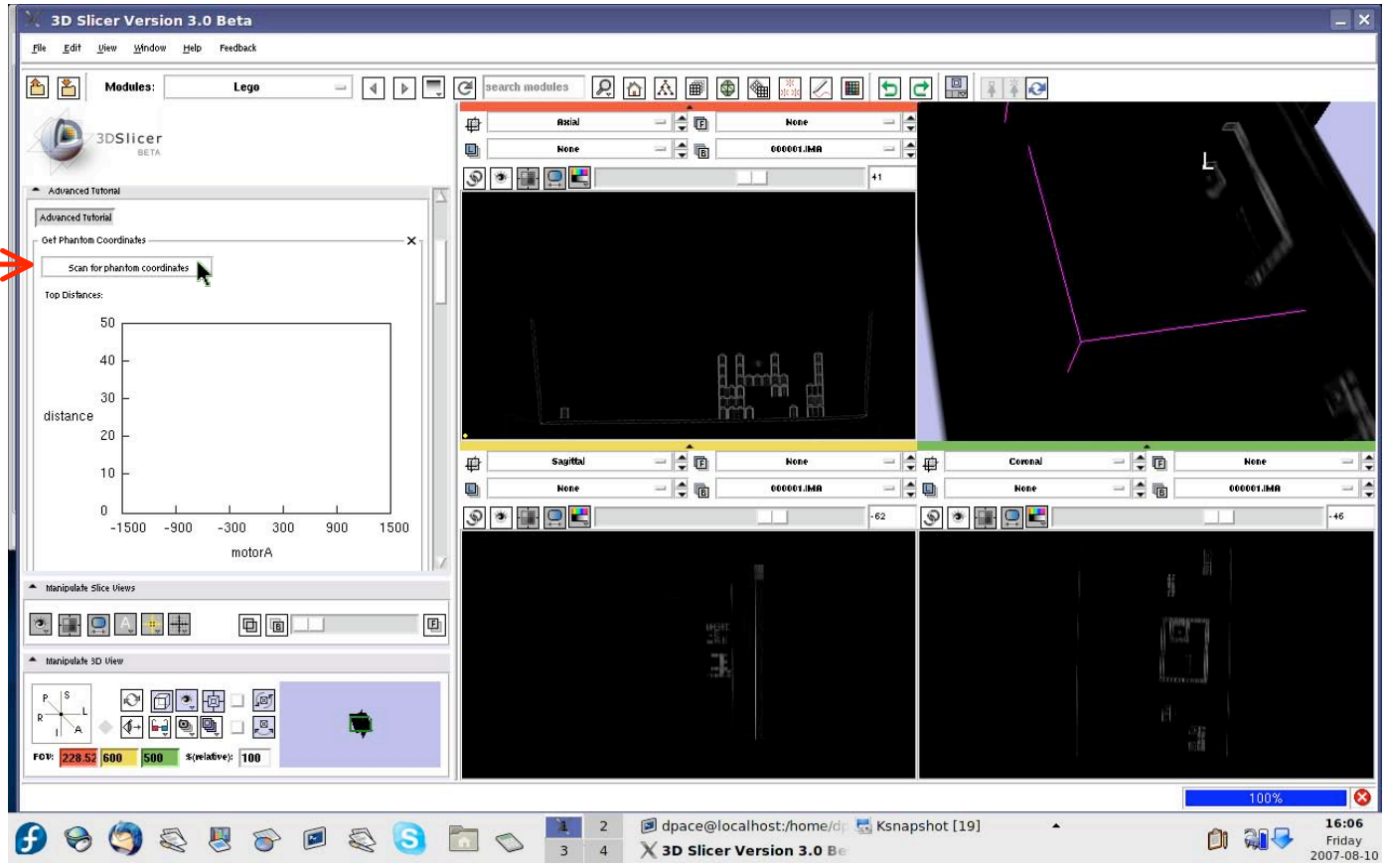
2) Select the advanced tutorial option, continued

Click on "Advanced Tutorial"



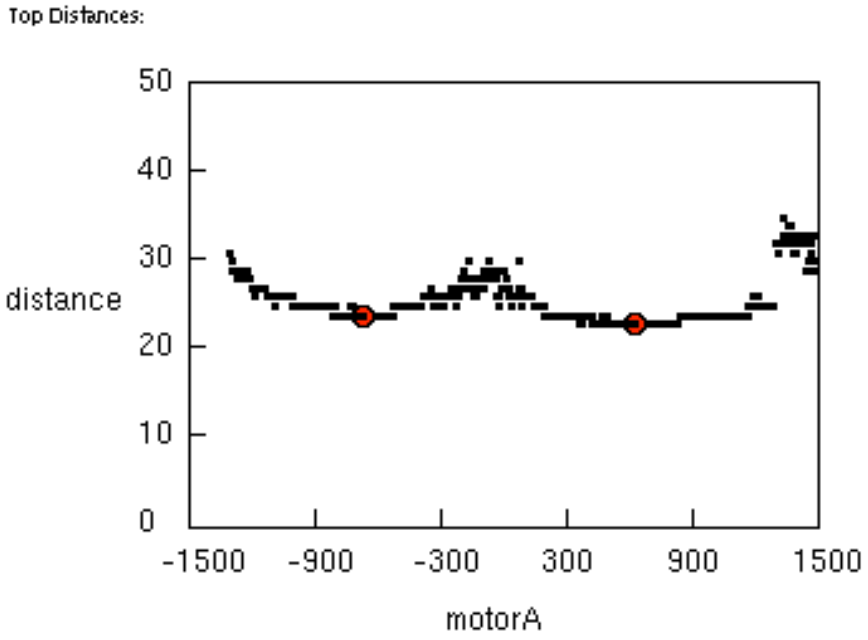
3) Get the fiducials in the patient (robot) coordinate system

Click on "Scan for phantom coordinates"

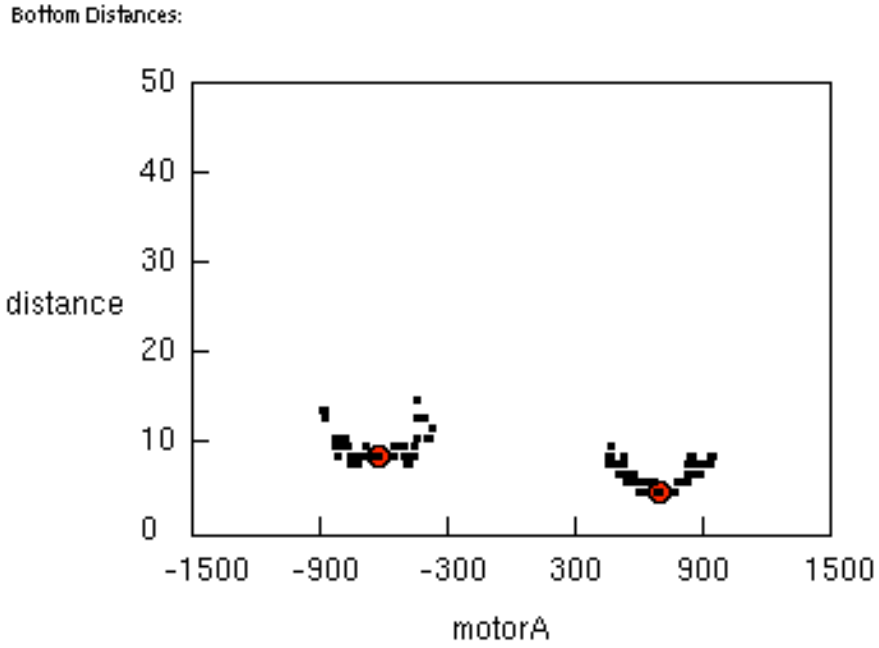


3) Get the fiducials in the patient (robot) coordinate system, continued

Sample results from top swipe

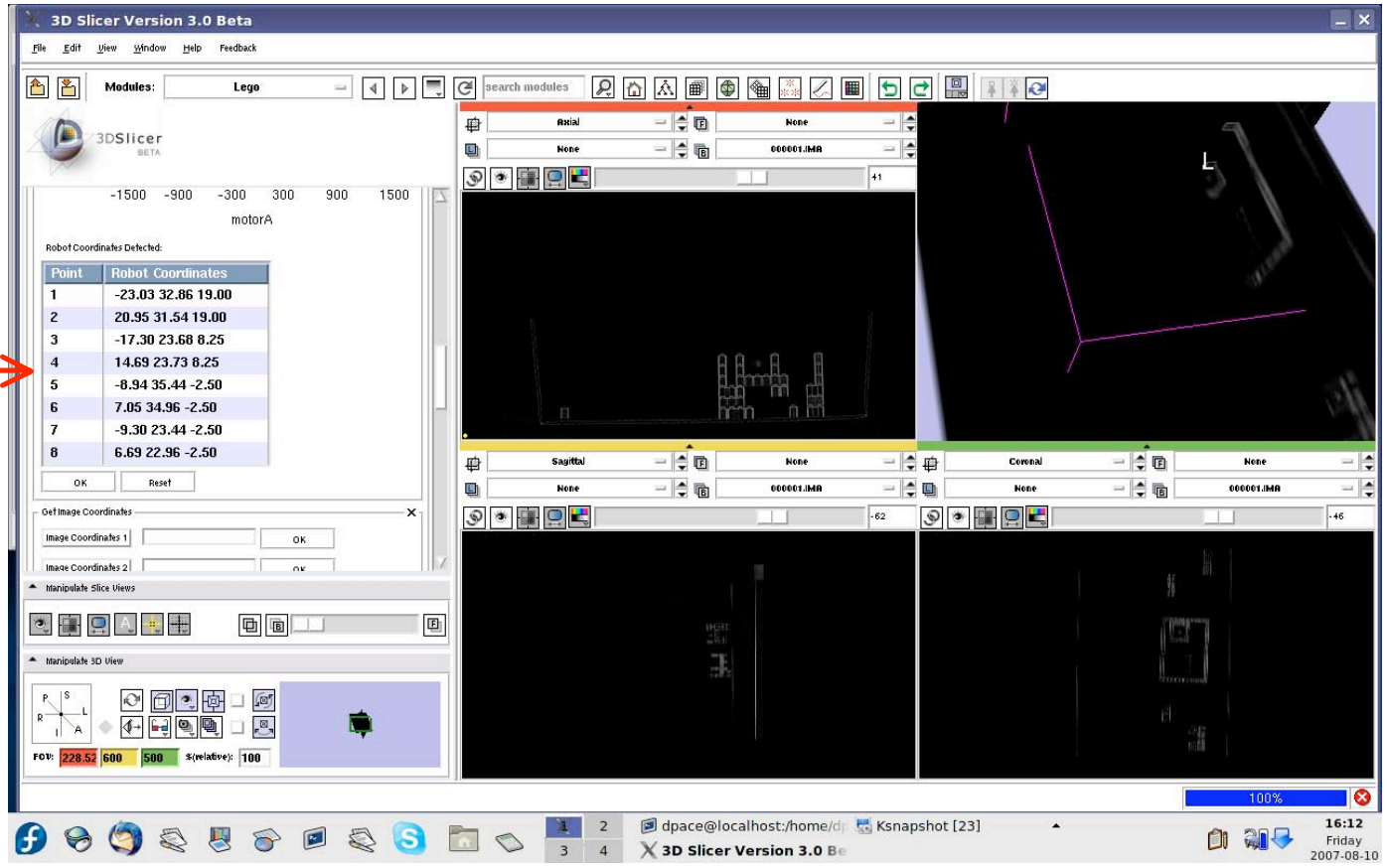


Sample results from bottom swipe



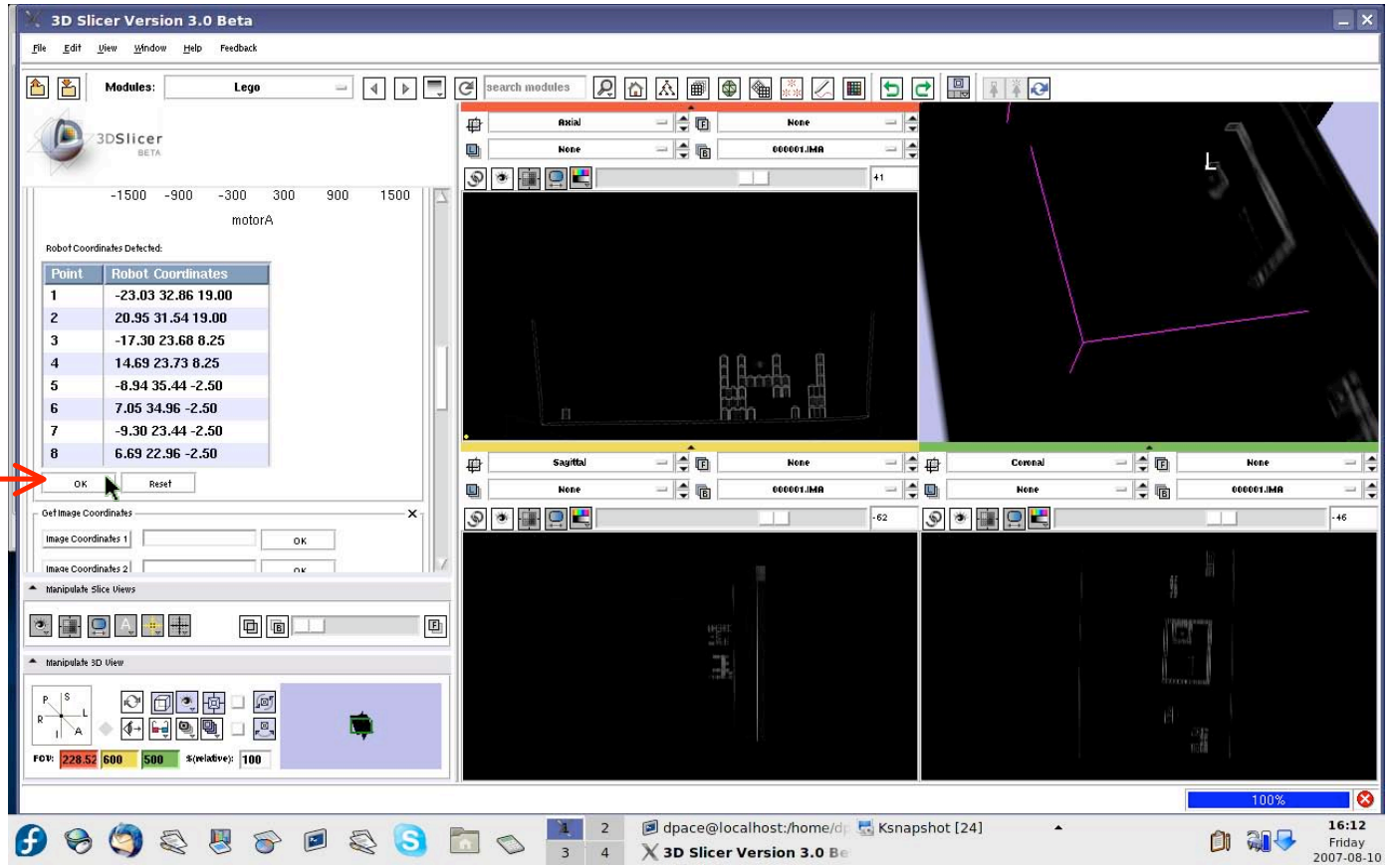
3) Get the fiducials in the patient (robot) coordinate system, continued

The eight detected fiducials in the patient (robot) coordinate system are shown



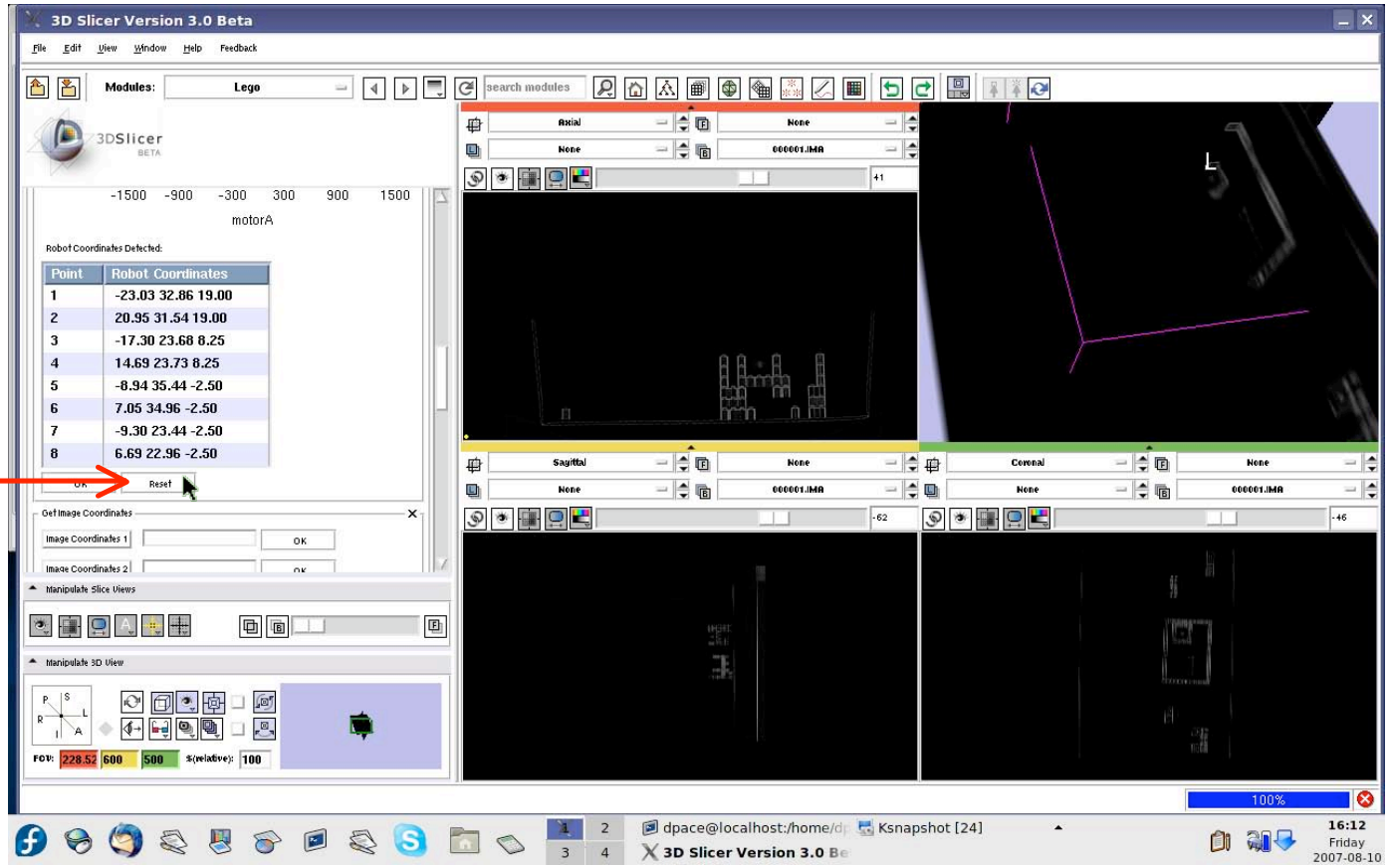
3) Get the fiducials in the patient (robot) coordinate system, continued

If your scan results are similar to the samples on slide 30: click "OK" to keep the fiducial points.

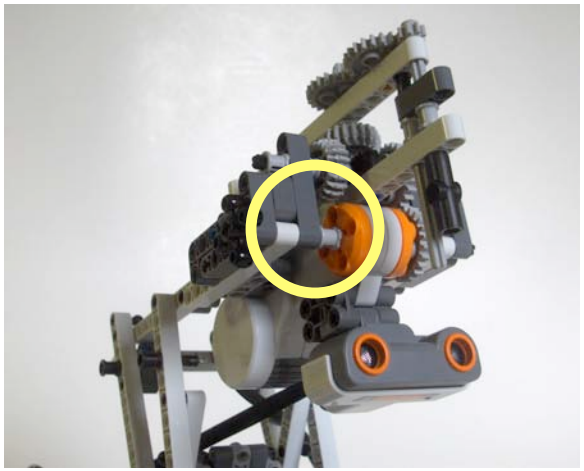


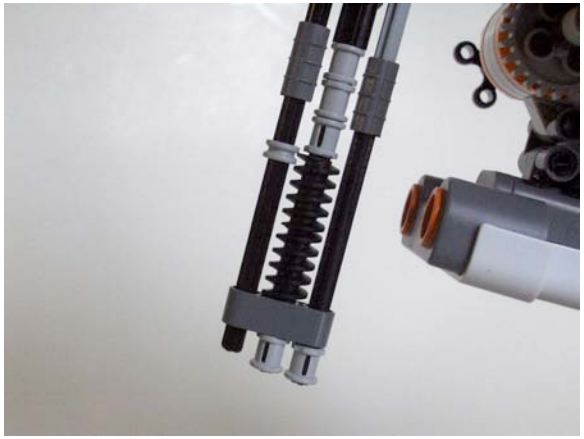
3) Get the fiducials in the patient (robot) coordinate system, continued

If your scan results are NOT similar to the samples on slide 30: click "Reset" to reject the fiducial points. Then click "Scan for phantom coordinates" again to re-scan.



3) Get the fiducials in the patient (robot) coordinate system, continued

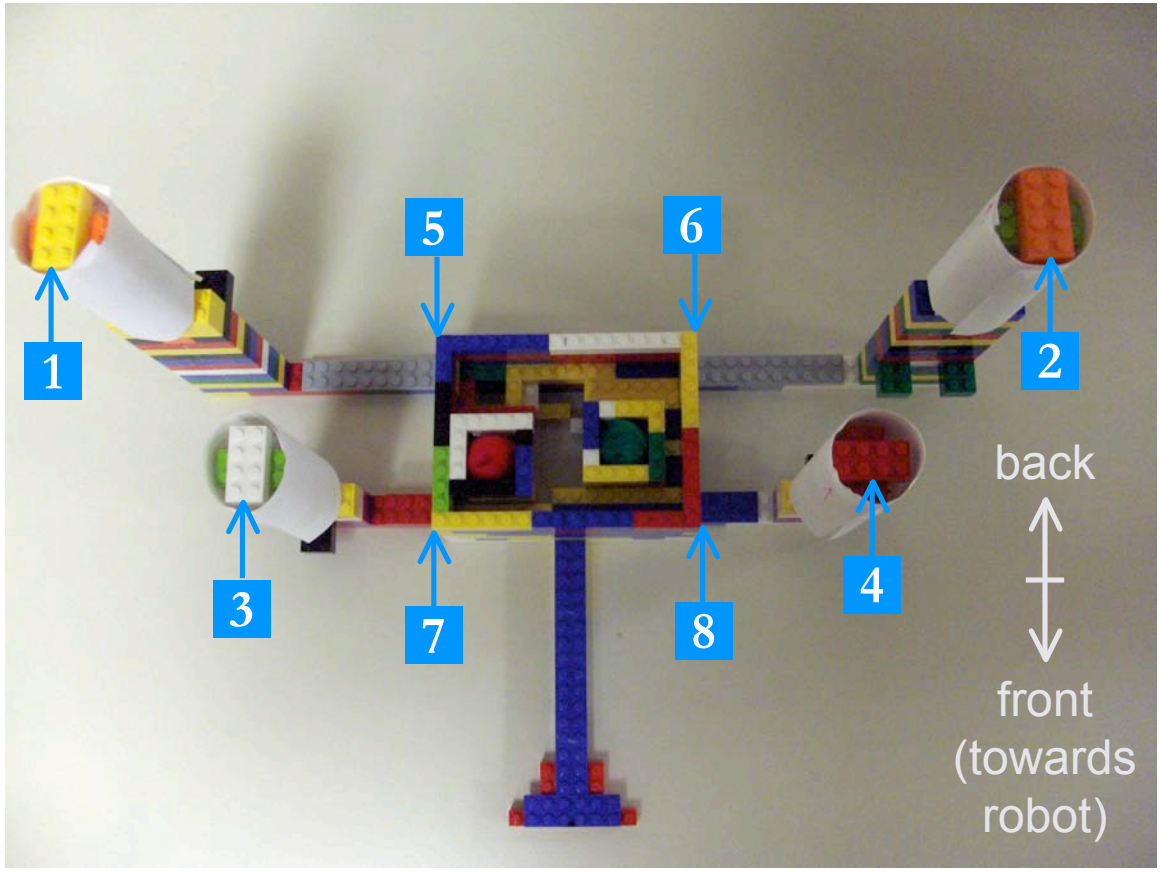




Once you have the fiducials in the *PCS*, you can put the needle back on the LEGO robot.

- Using the gear on the upper right side of the robotic arm, adjust the needle so that it is at its highest possible position while still remaining on the thread.
- If it is not already in the initial position, adjust the robotic arm so that it is centered and all the way back.

4) Get the fiducials in the image coordinate system

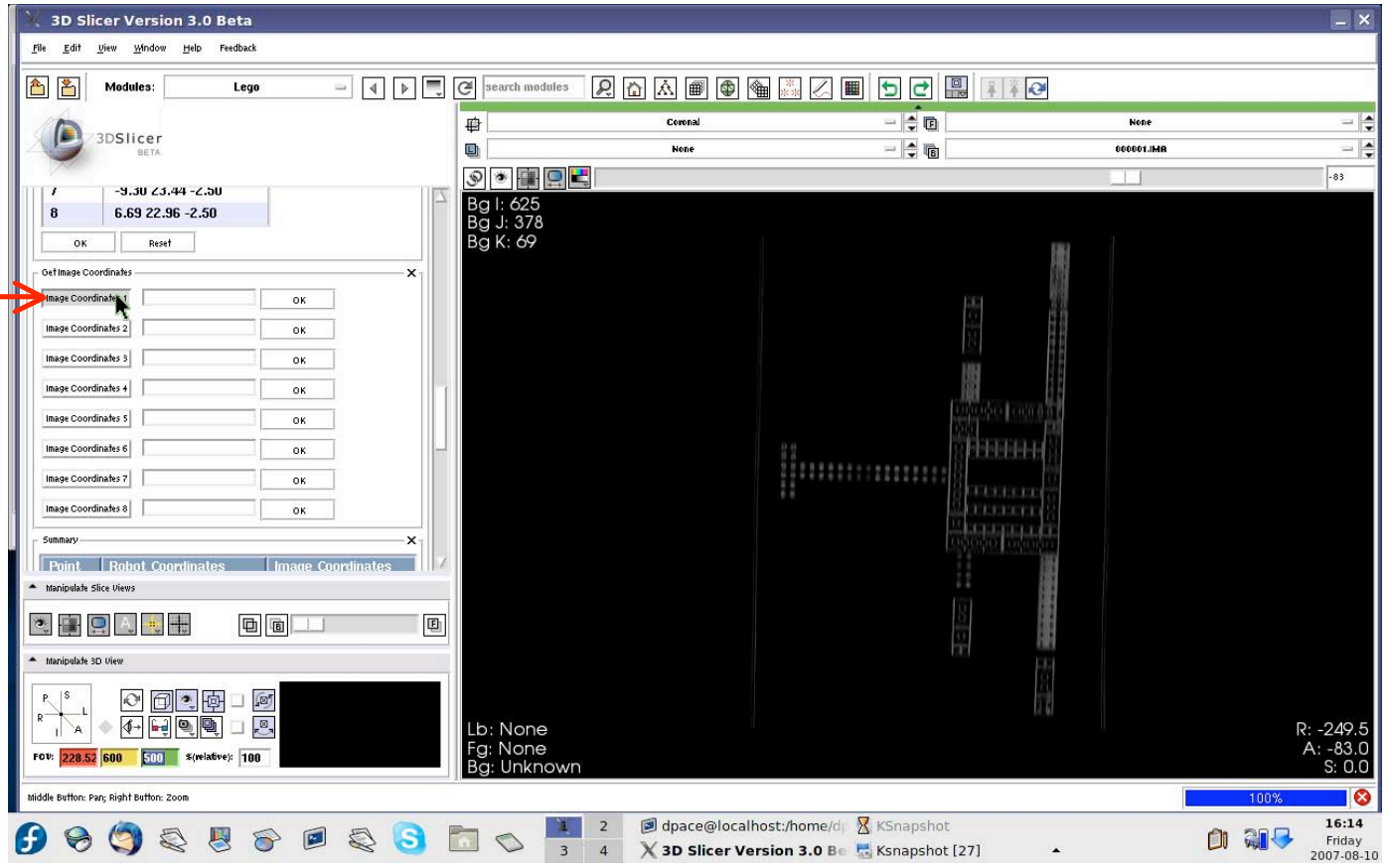


Recall:

- One on the top surface of each pillar (centered on the front side)
- One on the top surface of each corner of the central box

4) Get the fiducials in the image coordinate system, continued

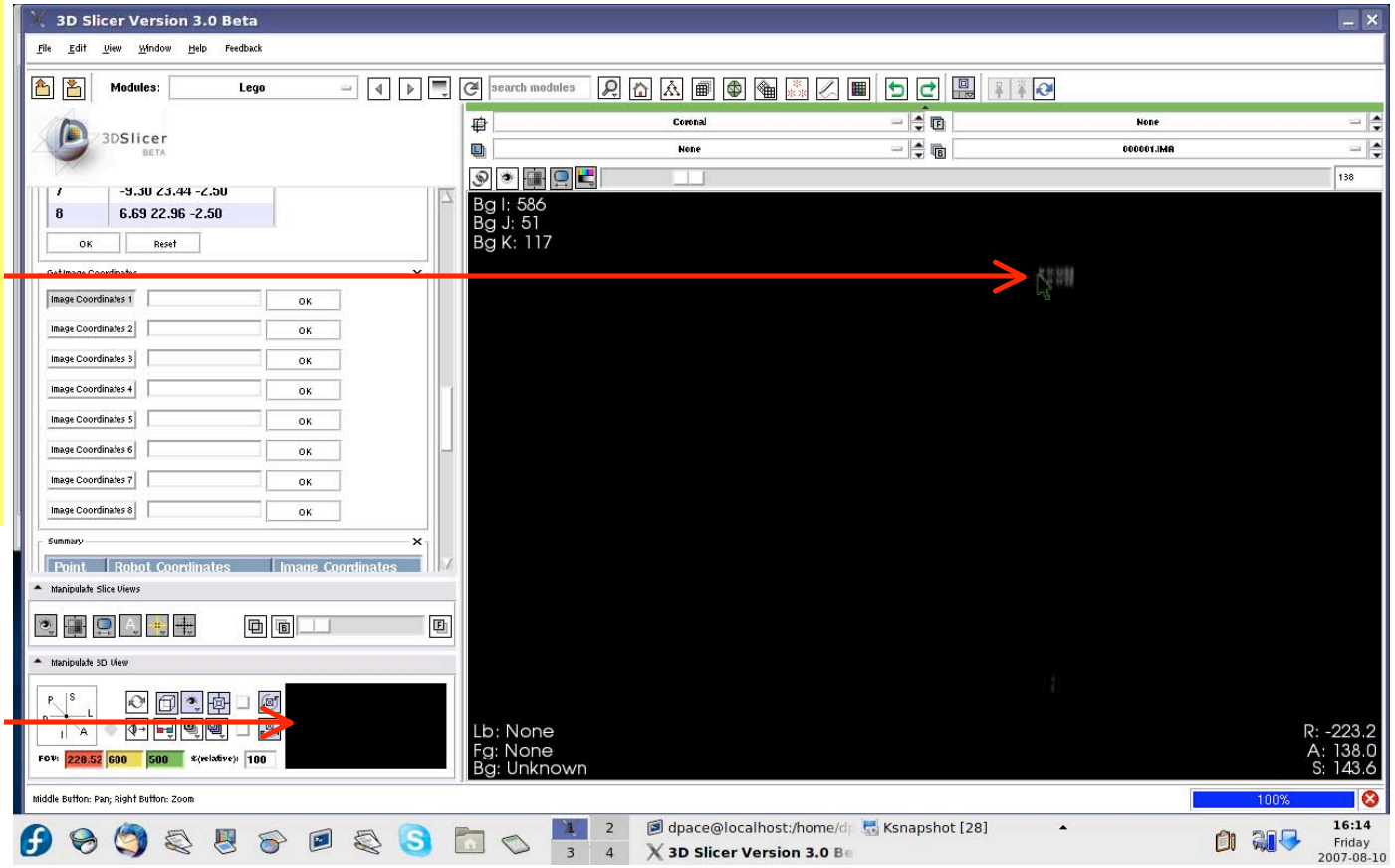
Click on "Image Coordinates 1"



4) Get the fiducials in the image coordinate system, continued

Scroll through the 2D viewers using the sliders until you find the first fiducial point **(#1 on slide 35)**. Click on the fiducial coordinate.

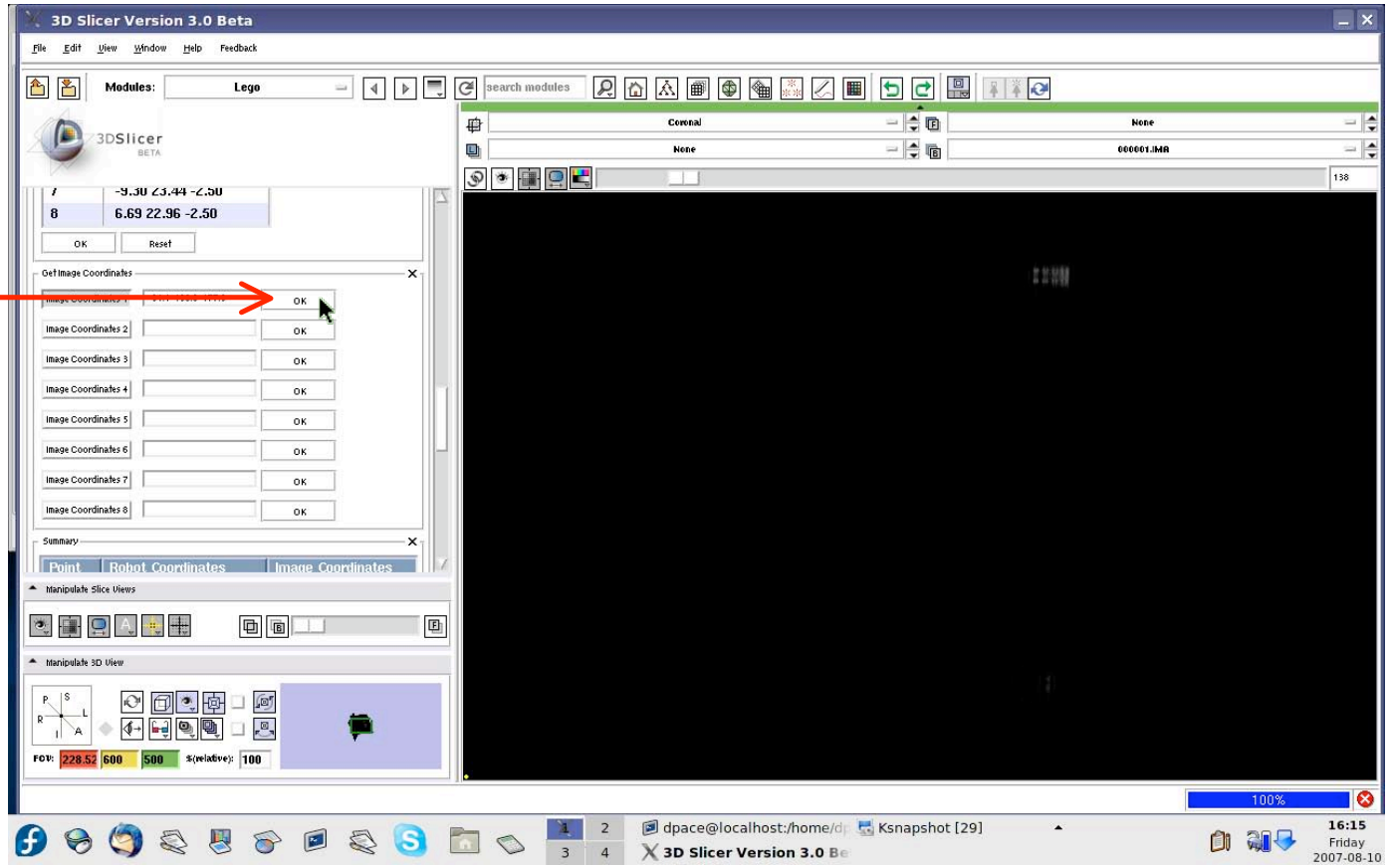
The area around the current cursor position is shown in more detail here.



The protrusions on the pillars of the phantom will help you orient yourself when scrolling through the CT volume.

4) Get the fiducials in the image coordinate system, continued

Click on "OK" to select the coordinate for fiducial 1.



To change the fiducial, click on another point in the CT volume and click on "OK" again.

4) Get the fiducials in the image coordinate system, continued

- Repeat the steps on the previous three slides for fiducials **2-8 in slide 35**:
  - Click on the "Image Coordinates" button
  - Click on the fiducial on the CT volume
  - Click on "OK"
- Remember, the numbering of the fiducials is important!

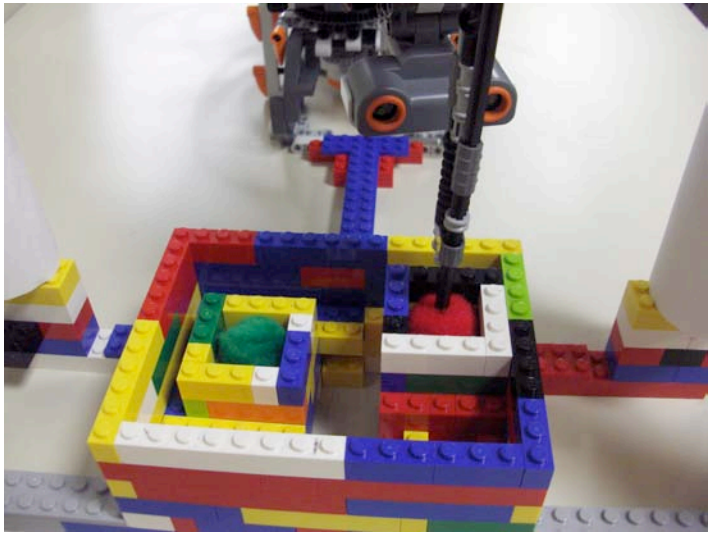
Summary

Point	Robot Coordinates	Image Coordinates
1	-23.03 32.86 19.00	-93.2 138.0 174.5
2	20.95 31.54 19.00	-80.5 136.0 -167.3
3	-17.30 23.68 8.25	-28.6 48.0 131.8
4	14.69 23.73 8.25	-28.6 48.0 -120.9
5	-8.94 35.44 -2.50	-117.7 -35.0 63.6
6	7.05 34.96 -2.50	-113.2 -36.0 -59.1
7	-9.30 23.44 -2.50	-27.7 -37.0 67.3
8	6.69 22.96 -2.50	-23.2 -39.0 -55.5

The fiducials in the image coordinate system will be summarized in the "Summary" table

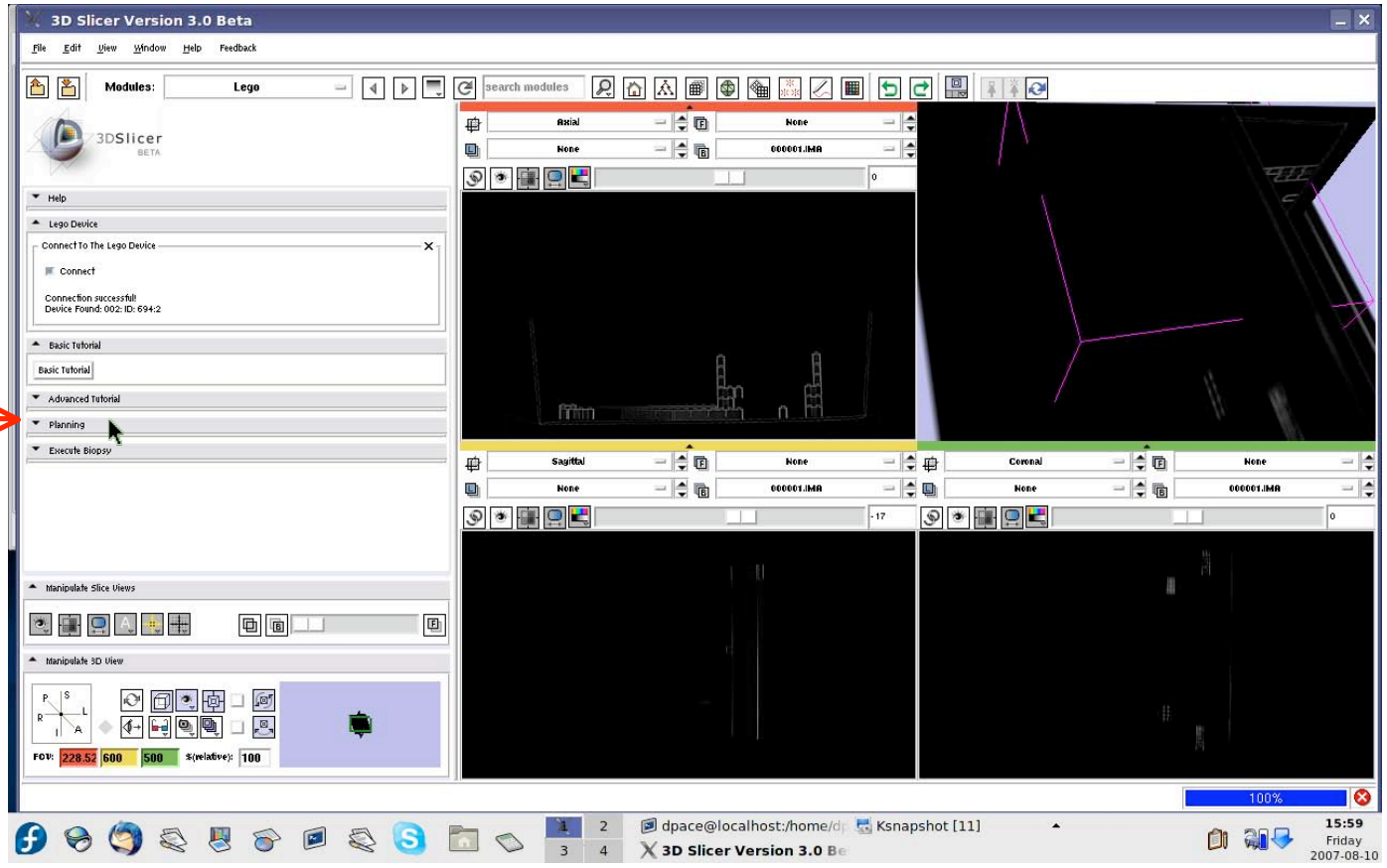
5) Planning - select the target coordinate

- Planning in the advanced tutorial is the same as planning in the basic tutorial.
- The target coordinate is the location where you would like the tip of the robot's needle to be at the end of the "biopsy".
- Let's try to have the robot biopsy the red pom-pom.
- We need to find the center of the red pom-pom on the CT volume.



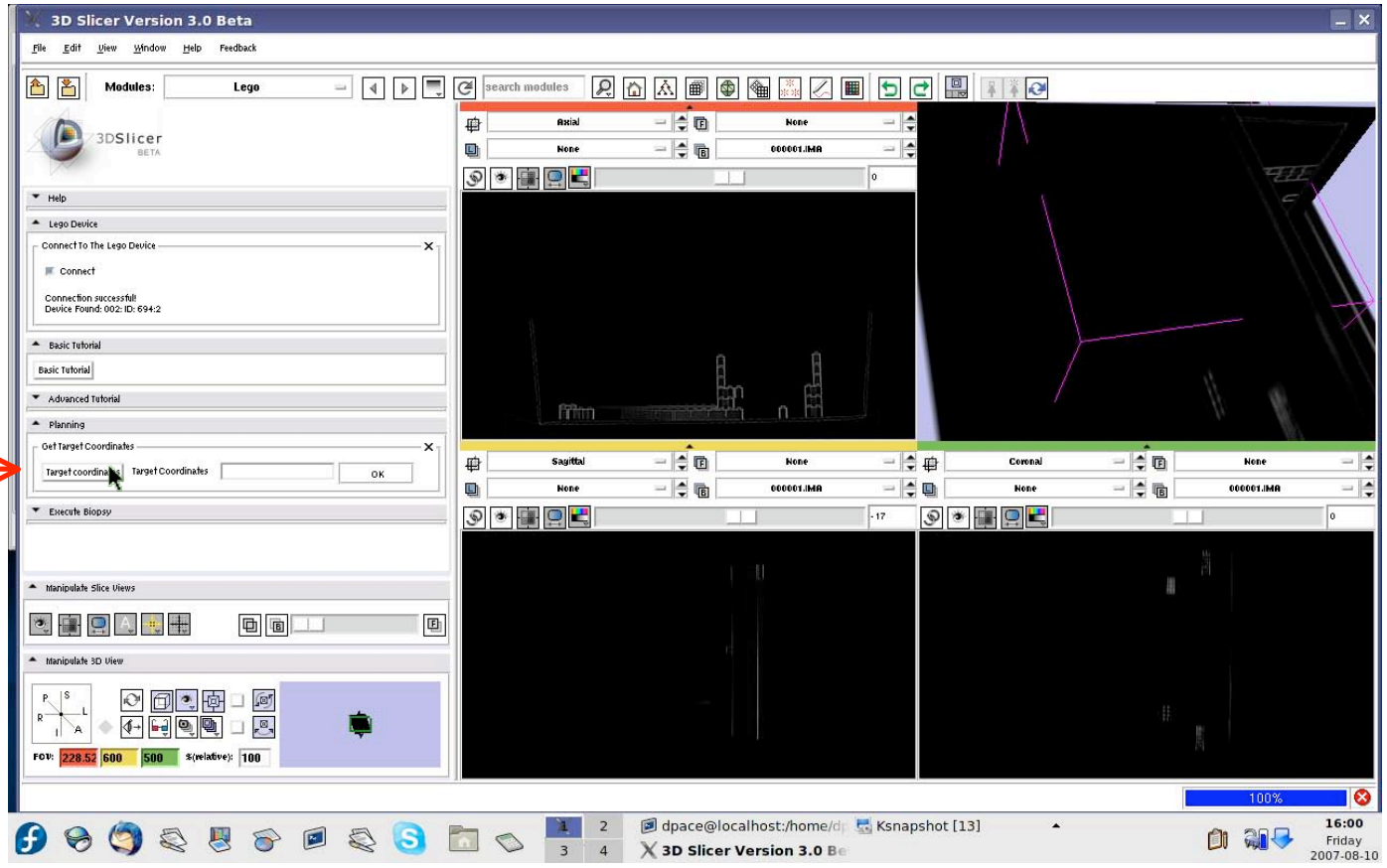
5) Planning - select the target coordinate, continued

Open the "Planning" pane



5) Planning - select the target coordinate, continued

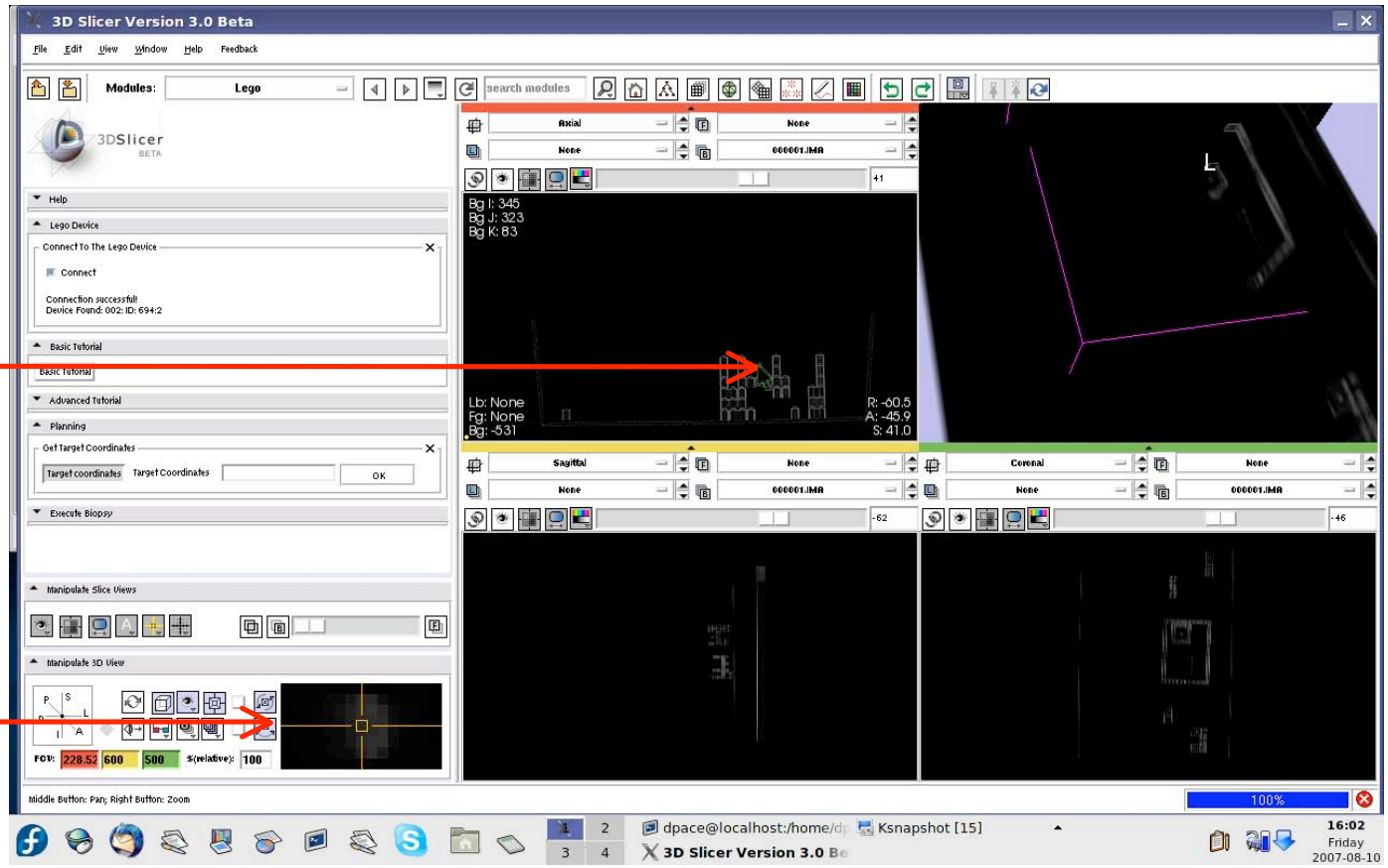
Click on "Target coordinates"



5) Planning - select the target coordinate, continued

Scroll through the 2D viewers using the sliders until you find the center of the red pom-pom. Click on the target coordinate: the **center** of the red pom-pom.

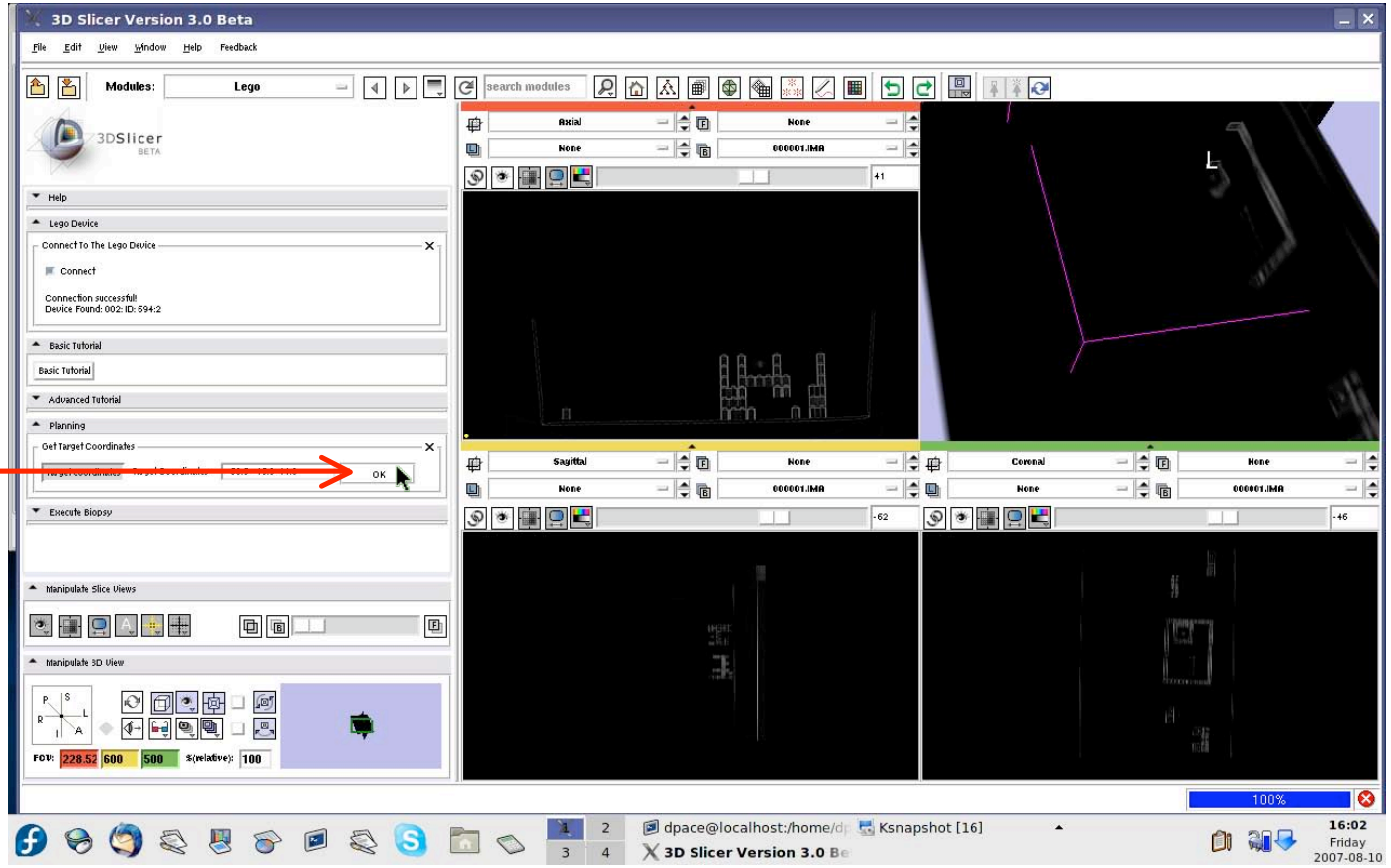
The area around the current cursor position is shown in more detail here.



The protrusions on the phantom's pillars will help you orient yourself when scrolling through the CT volume.

5) Planning - select the target coordinate, continued

Click on "OK" to select the target coordinate

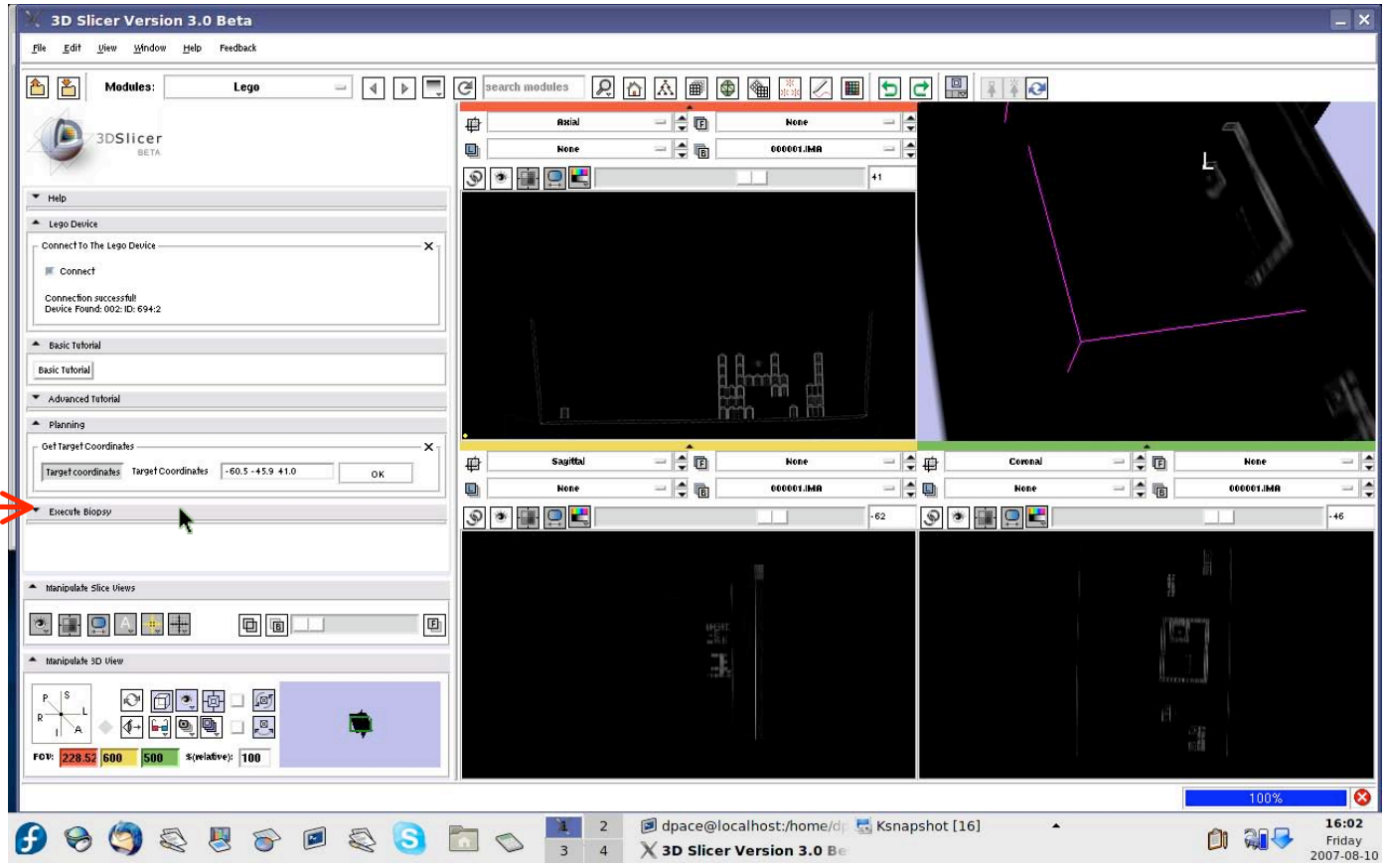


To change the target, click on another point in the CT volume and click on "OK" again.

6) Execute the biopsy

Now the LEGO robot will try to hit the target

Open the "Execute Biopsy" pane



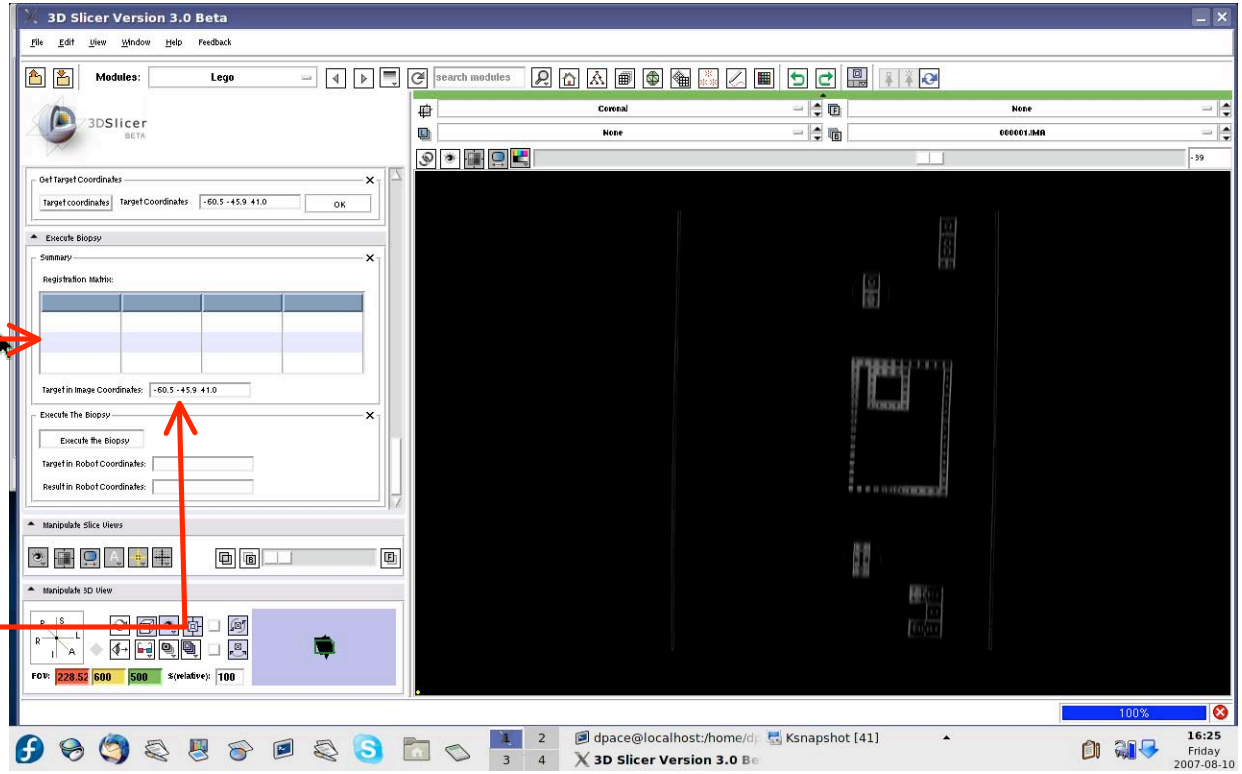
6) Execute the biopsy, continued

Recall:

$$PCS_{3x1} = R_{3x3} \bullet ICS_{3x1} + t_{3x1}$$

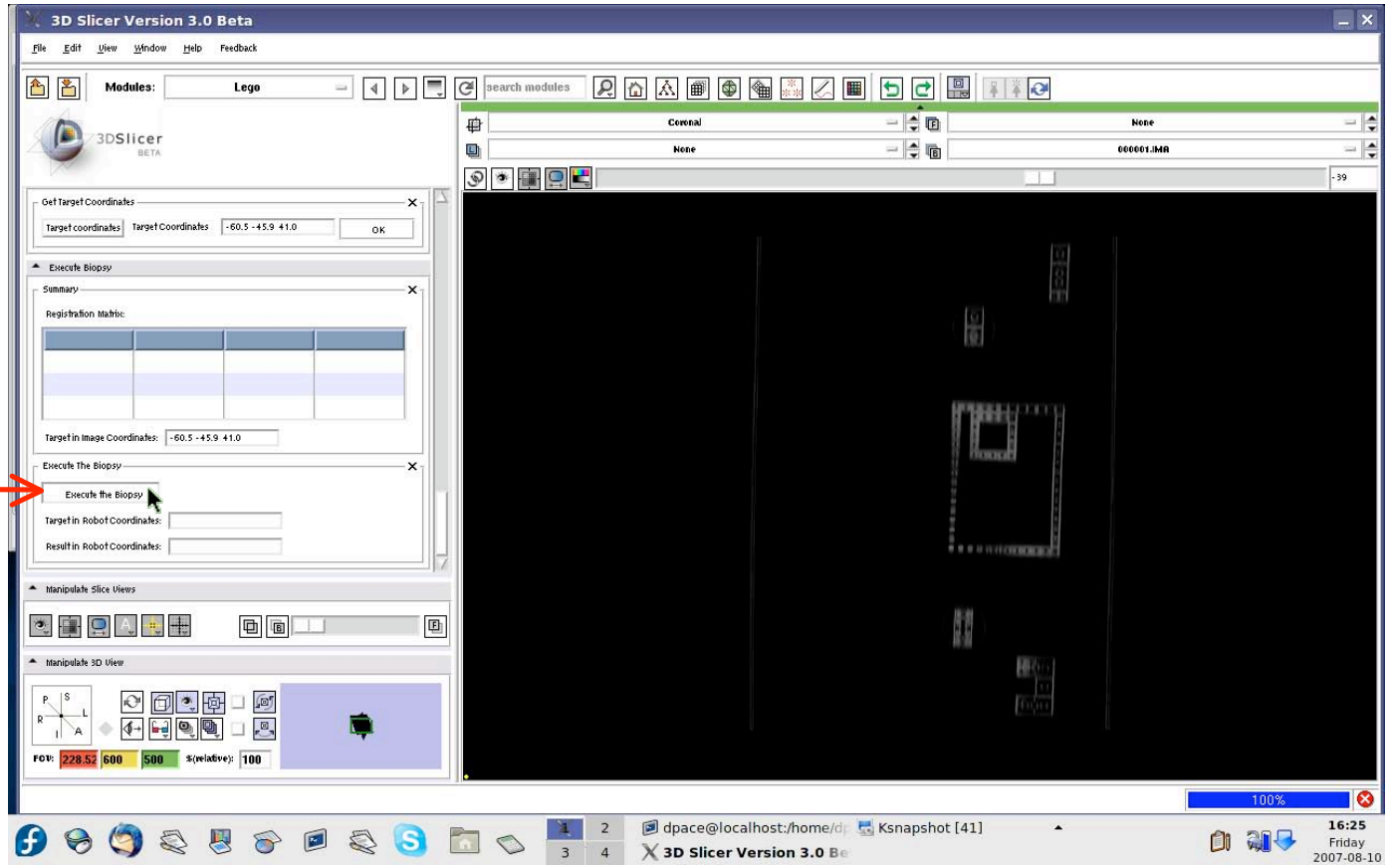
The transformation from the image coordinate system to the patient (robot) coordinate system is unique for each legal position of the phantom

The target in the image coordinate system that you selected



6) Execute the biopsy, continued

Click on "Execute the Biopsy"

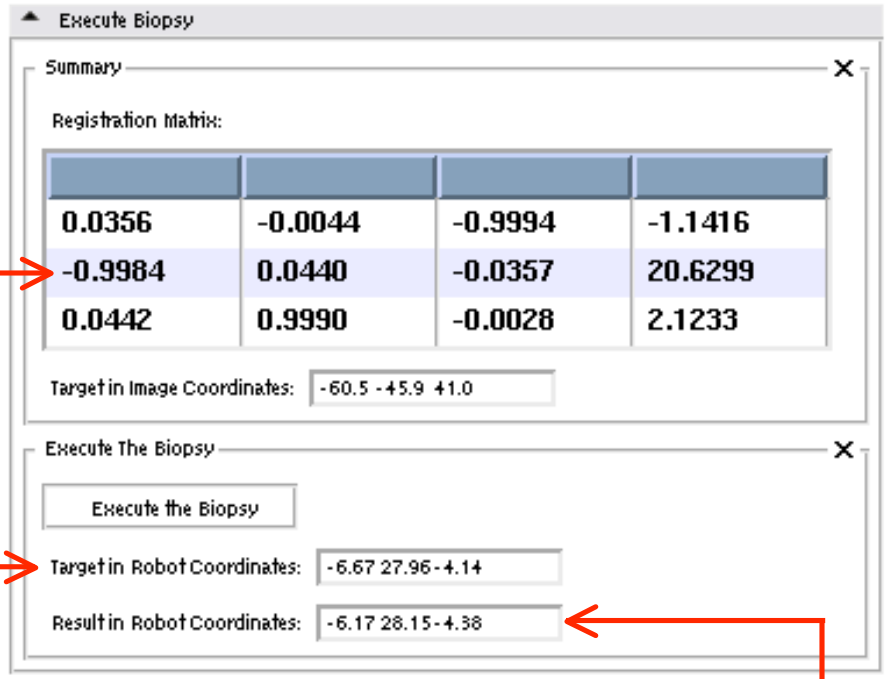


The LEGO robot will move to hit the target!

6) Execute the biopsy, continued

The transformation from the image coordinate system to the patient (robot) coordinate system is unique for each position of the phantom

The target in the patient (robot) coordinate system



Tracking is done through targeting during the robot's movement

The display of the final needle position in the *PCS* provides **Navigation**

The final needle position in the patient (robot) coordinate system. This coordinate is calculated using rotational information from the robot's motors and knowledge of the robot's structure, and is not completely accurate.

To select additional targets:

- If you would like to try additional targets, simply go back to the "Planning" pane, select another point on the CT volume and click "OK". Then go back to the "Execute Biopsy" pane and click "Execute the Biopsy".

If the LEGO robot does not return to the initial position (centered and all the way back), reset it before selecting another target.

To use a different phantom position:

- If you would like to repeat the biopsy with a different phantom position:
  - Select "Reset" in the "Advanced Tutorial" pane to clear the old fiducials in the *PCS*.
  - Click "Scan for phantom coordinates".
  - You may or may not want to select new fiducials in the image coordinate system.
  - You may or may not want to select a new target.

If the LEGO robot does not return to the initial position (centered and all the way back), reset it before selecting another target.

After completing this tutorial section

- You have learned about the following steps in IGT and medical robotics in a hands-on manner:
  - ✓ Imaging
  - ✓ Preoperative planning
  - ✓ Targeting and tracking
  - ✓ Navigation
  - ✓ Registration

Additional references

- Learn about image registration by reading:
  - B. Zitová and J. Flusser. Image Registration Methods: A Survey. *Image and Vision Computing*, 21:977-1000, 2003.
- Brainstorm about the components of the total error that occur from the selection of the target to the final position of the robot needle tip. How could you measure those errors?
  - Start by learning about error in registration by reading: J.B. West, M.J. Fitzpatrick, S.A. Toms, C.R. Maurer, and R.J. Maciunas. Fiducial Point Placement and the Accuracy of Point-based, Rigid Body Registration. *Neurosurgery*, 48(4):810-817, 2001.

Thanks to

- Terry Peters, Ph.D (Robarts Research Institute, University of Western Ontario)
- Steven Canvin (The LEGO Group)
- Cory Walker (NXT++ Developer)
- G. Wade Johnson (Device::USB Developer)
- Steve Pieper, Ph.D (Surgical Planning Laboratory)
- Haiying Liu (Surgical Planning Laboratory)
- Junichi Tokuda, Ph.D (Surgical Planning Laboratory)
- Christoph Ruetz (Surgical Planning Laboratory)
- Philip Mewes (Surgical Planning Laboratory)
- The entire LEGO Mindstorms community