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

Part I: Background and Materials

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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 background and materials section

- To provide theoretical background on image-guided therapy and medical robotics.
- To assemble the necessary materials for the basic and advanced tutorial sections.

PART I:
What are image-guided therapy and medical robotics?

Introduction to Image-Guided Therapy (IGT)

Image-guided therapy (IGT) allows us to **see inside the body** so that we can perform medical procedures with **greater accuracy** and using **minimally invasive techniques**.

(Other names for IGT: computer-assisted surgery, computer-aided surgery)

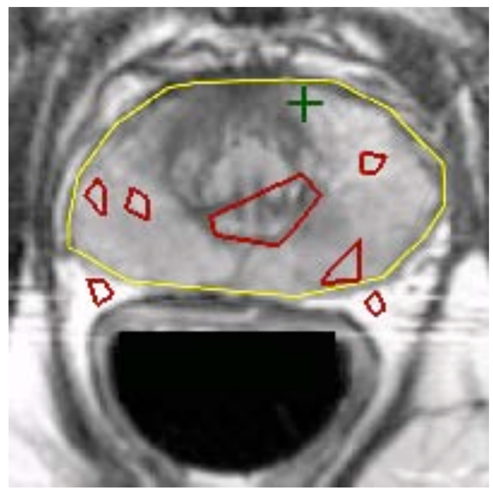
Advantages of IGT

- Enables new minimally-invasive procedures
- Improves postoperative outcomes
- Increases quality and speed of surgical procedures
- Shortens hospital stays
- Decreases long-term health care cost

An Example of IGT in Action: Needle Biopsy

- In suspected cancer cases (such as for prostate or breast cancer) a **needle biopsy** is often performed as part of the diagnostic process.
- A needle is used to extract small pieces of tissue for analysis.

Goal: Hit the tumour so that it can be detected!



(image from R. Alterovitz, K. Goldberg and A. Okamura, Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, April 2005, pp. 1652-1657)

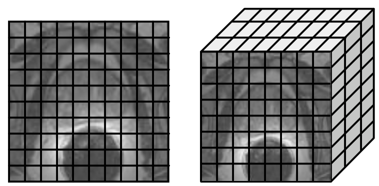
Medical Robotics

- Medical robots are increasingly popular for procedures such as needle biopsy in prostate cancer
- Robots may be passive, semi-active or active
- In medical robotics, we use the same steps as in IGT: imaging, planning, registration, tracking and navigation
- To the right is a prostate biopsy robot that operates within an MRI machine (being tested on a melon!)

(JHU/SPL MRI prostate robot)

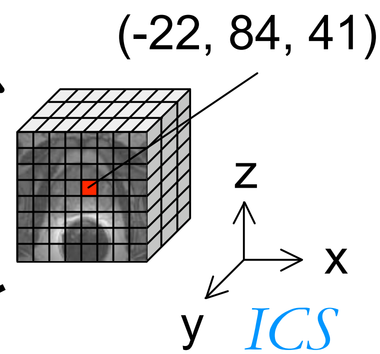
IGT Workflow

Step 1: Imaging



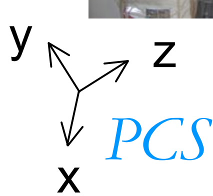
(image modified from S. Haker *et al.*, Top Magn. Reson. Imaging 16(5), October 2005, pp. 355-368)

Step 2: Planning



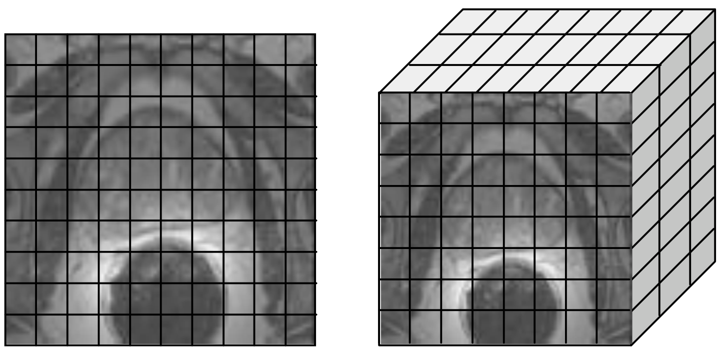
Step 3: Registration

(image from http://www.ncigt.org/ourwork/core_mrguidedtherapy.html)



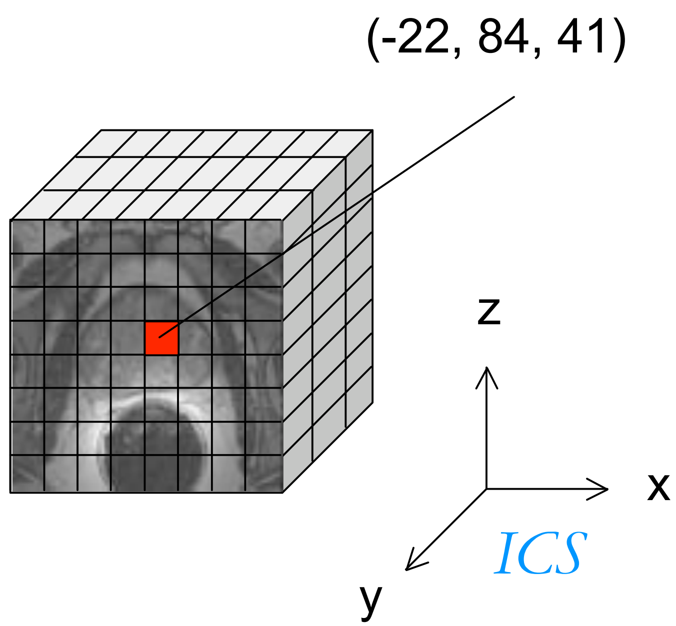
Step 4: Tracking and Navigation

1) Imaging



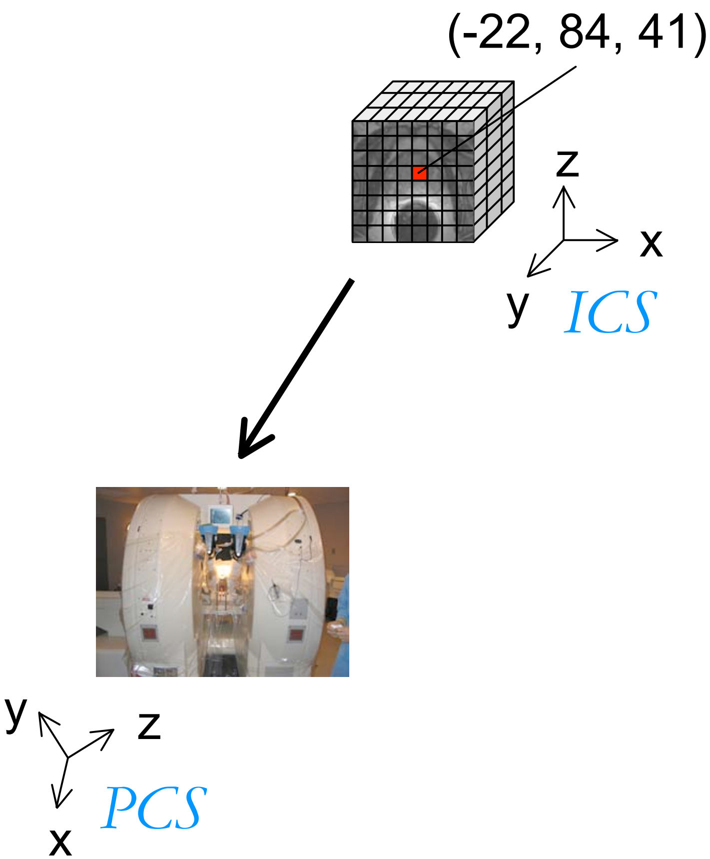
- Can use one or many of CT, MRI, ultrasound, X-ray, fluoroscope, etc.
- May be 2D images or 3D volumes, or both, depending on the image modality(ies) used.
- The imaging may be preoperative, intraoperative or both.

2) Planning



- We do a preoperative plan on the <u>image</u> (in the image coordinate system, or *ICS*)
- Example: Target selection for needle biopsy in prostate cancer
- Example: Cutting plane for high tibial osteotomy
- Example: Radiation dose plan for image-guided radiotherapy.

3) Registration



- Remember, planning was done on the image - in the image coordinate system (*ICS*).
- We want to execute the plan on the patient - in the patient coordinate system (*PCS*).
- We need to be able to transform the plan in the image coordinate system into a plan in the patient coordinate system so that we can execute it.

3) Registration, continued

- The computational process of registration determines the relationship between two coordinate systems, such as that between the image coordinate system (*ICS*) and the patient coordinate system (*PCS*).
- Registration may also be performed between preoperative and intraoperative images or volumes. Example: between preoperative 3D MRI and intraoperative 2D ultrasound.

3) Registration, continued

Sometimes registration is not necessary! If using a C-arm fluoroscope intraoperatively, knowing the position of the C-arm fluroscope means that we can calculate the relationship between the image and patient coordinate systems using algebra instead of a registration algorithm.

(image from http://www.pemed.com/radsystm/radsystm.htm)

3) Registration, continued

The transformation between the *ICS* and the *PCS* is often assumed to be rigid, i.e. composed of a rotation *R* and a translation *t* (after scaling).

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

Alternative notation:
(more commonly used)

$$\begin{bmatrix} PCS_x \\ PCS_y \\ PCS_z \\ 1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & t_x \\ R_{21} & R_{22} & R_{23} & t_y \\ R_{31} & R_{32} & R_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ICS_x \\ ICS_y \\ ICS_z \\ 1 \end{bmatrix}$$

3) Registration, continued

- Various registration algorithms can work on combinations of sets of points, images, volumes and surfaces
- Many rigid registration algorithms use a point-based approach: select a number of corresponding points in the two coordinate systems and use them to find R and t
- The points used in the registration are called fiducials

3) Registration, continued

- If performing registration between the image coordinate system and the patient coordinate system, one can:
  - Find points in the patient coordinate system using an optical or magnetic camera and a pointing device
  - Select the corresponding points in the image coordinate system either automatically or manually
  - Use an algorithm such as Iterative Closest Points (ICP) to determine R and t.

4) Tracking and Navigation

- Tracking: Precisely localize surgical tools, implants and anatomical structures during the procedure.
- Navigation: Provide visualization of the tracked elements to the surgeon during the procedure.

We use tracking and navigation in order to execute the preoperative plan on the patient

PART II: Assemble Your Tutorial Supplies

Tutorial Supplies

To use this tutorial you will need:

- ✓ One LEGO Mindstorms NXT robotics kit
- ✓ One LEGO Deluxe Brick Box
- ✓ Two pom-poms
- ✓ CT volume of the phantom
- ✓ 3D Slicer LEGO tutorial module
- ✓ A Linux computer with root access
- ✓ Two sheets of white paper and tape
- ✓ Assembly instructions for the robot and phantom
- ✓ Phantom placement guide

✓ One LEGO Mindstorms NXT Robotics Kit

Available at:

http://shop.lego.com/ByTheme/Product.aspx?p=8527&cn=17&d=70

Approximate cost:

$249.99 USD + taxes and shipping

The tutorial robot that you will build will act as the surgeon.

✓ *One LEGO Deluxe Brick Box*

Available at:

http://shop.lego.com/ByTheme/Product.aspx?p=6167&cn=306&d=362

Approximate cost:

$44.99 USD + taxes and shipping

The phantom (anatomical model) that you will build will act as the patient.

✓ *Two Pom-Poms*

- diameter approximately 2.5 cm (1 inch)

Available at:

http://www.amazon.com/PAC-1859614-Poms-ClassPack-Sizes/dp/B0006HXNRY/ref=sr_1_12/104-9511701-9925562?ie=UTF8&s=office-products&qid=1187791961&sr=8-12

or at a local art or crafts store.

Approximate cost:

$13.49 USD + taxes and shipping

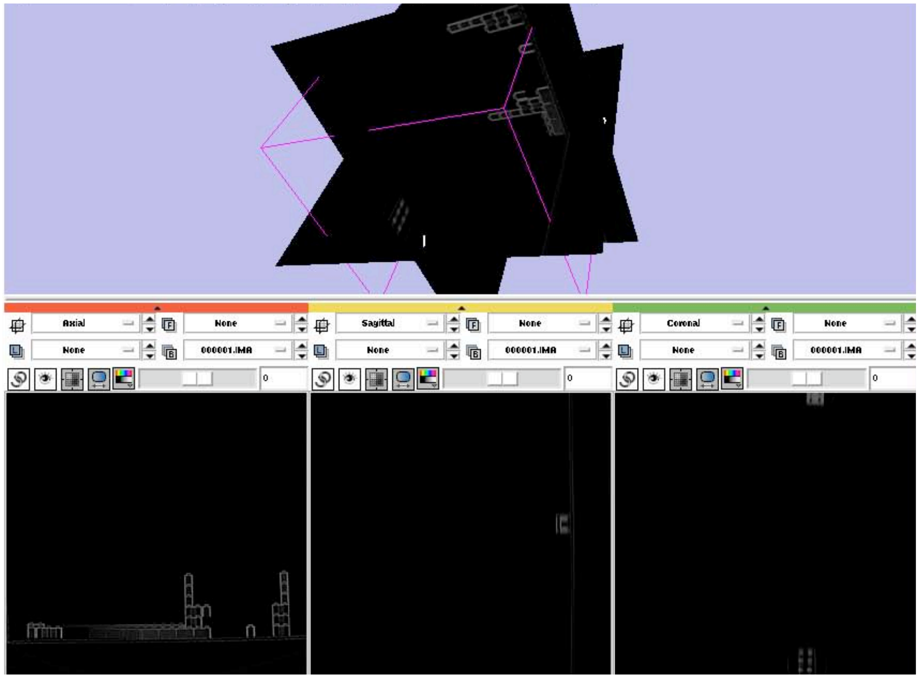
The pom-poms on the phantom will act as the tumour targets.

✓ *CT Volume of the Phantom*

Available at:

<link>

The **three-dimensional** image volume of the phantom will act as the preoperative image.



✓ *3D Slicer LEGO Tutorial Module*

Available at:

www.slicer.org

<link>

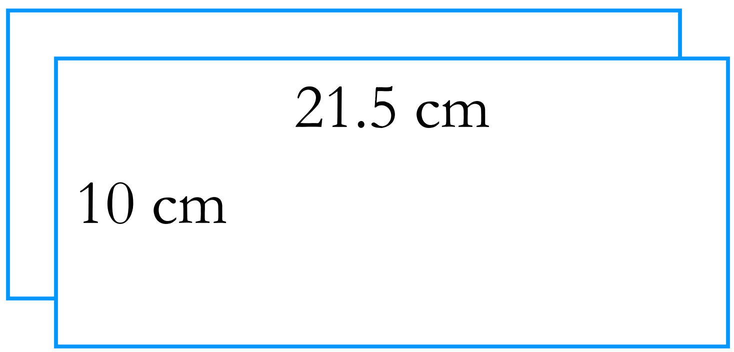
3D Slicer is a comprehensive open-source software package for medical image processing and image-guided therapy. 3D Slicer will act as the IGT software for all steps of the procedure.

✓ *A Linux Computer with Root Access*

Make sure that you know
the root password!

✓ *Two Sheets of White Paper and Tape*

Cut the pieces of paper so that you have four pieces measuring 21.5 cm by 10 cm (8.5" by 4")



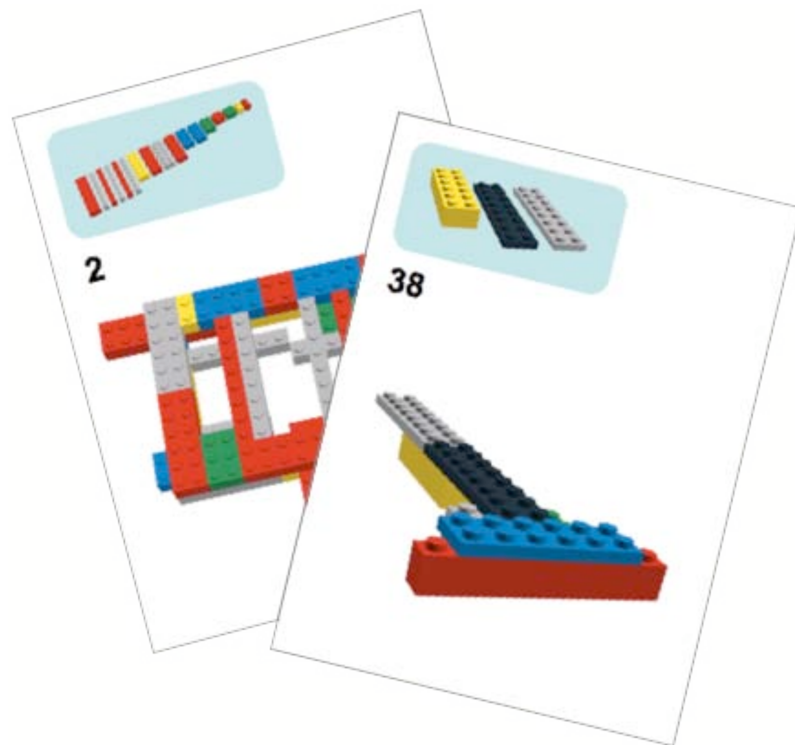
These pieces of paper and the tape will be used as part of the phantom.

✓ *Assembly Instructions for the Robot and Phantom*

Available at:

<link>

These instructions will tell you how to build the tutorial robot and phantom.

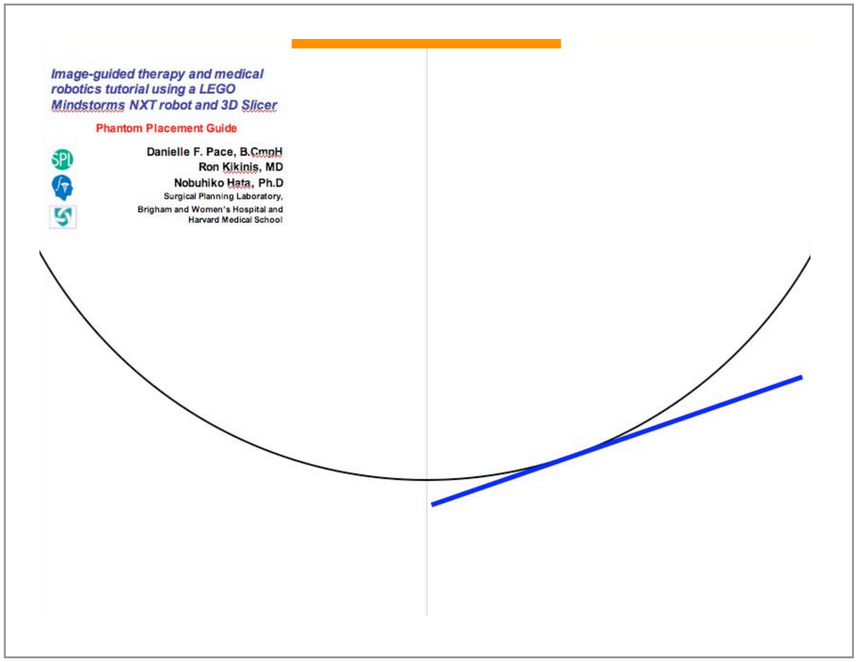


✓ *Phantom Placement Guide*

Available at:

<link>

This guide will help you to to position the robot and the phantom correctly during the tutorial.



Setup for the tutorial

- Step 1: Install 3D Slicer
- Step 2: Build the LEGO robot
- Step 3: Build the phantom

Step 1: Install 3D Slicer

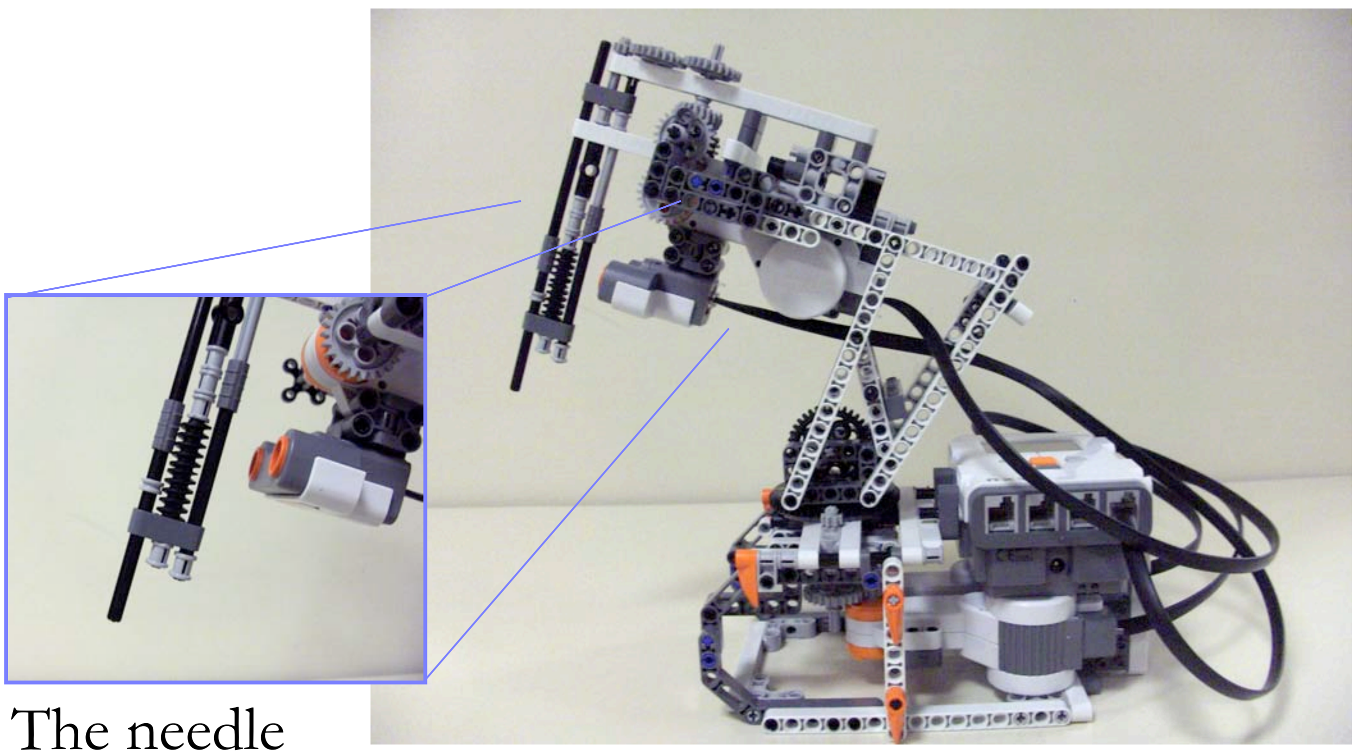
- 3D Slicer is a sophisticated open-source software package for research and development in medical image processing and image-guided therapy
- The image-guided therapy and medical robotics tutorial module was created in 3D Slicer version 3.

Step 1: Install 3D Slicer, continued

- <Instructions for how to install 3D Slicer go here, once we know how it will be distributed - exactly where the website will be, links, etc>

Step 2: Build the LEGO robot

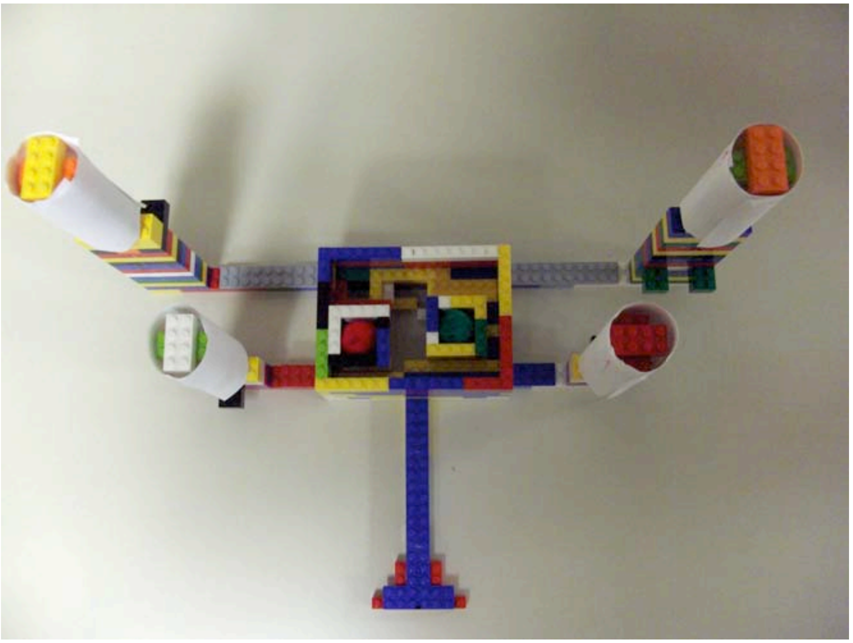
Build the LEGO robot according to the instructions provided. **It is very important that you use new batteries or a freshly charged battery pack - otherwise results are very unpredictable!**



The needle

Step 3: Build the phantom

- Build the phantom according to the instructions provided.
- Wrap the pieces of paper around the top halves of the phantom's pillars and secure with tape.
- Place two pom-poms into the small boxes on the phantom.



After completing this tutorial section

- You have learned about the steps of a typical image-guided therapy or medical robotics procedure.
- You have learned about needle biopsy, the example procedure used in this tutorial.
- You have assembled all of the tutorial supplies and ready to begin the basic tutorial.

Additional references

- Image-guided therapy is common in orthopedic (bone and joint) surgery. You can investigate this exciting field and learn more about the steps used in IGT and medical robotics by reading:
  - N. Sugano. Computer-assisted orthopedic surgery. *Journal of Orthopaedic Science*, 8(3):442-448, 2003.
  - N.W.L. Schep, I.A.M.J. Broeders, and Chr. van der Werken. Computer assisted orthopaedic and trauma surgery: State of the art and future perspectives. *Injury*, 34(4):299-306, 2003.
- Learn more about how medical robots have been used by reading:
  - K. Cleary and C. Nguyen. State of the art in surgical robotics: Clinical applications and technology challenges. *Computer Aided Surgery*, 6(6):312-328, 2001.

Thanks to

- Terry Peters, Ph.D (Robarts Research Institute, University of Western Ontario)
- Steven Canvin (The LEGO Group)
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- G. Wade Johnson (Device::USB Developer)
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- 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