An accessible, hands-on tutorial system for image-guided therapy using a robot and open-source software

Release 0.00

Danielle F. Pace[1], Ron Kikinis[1] and Nobuhiko Hata[1]

July 15, 2007

[1]Surgical Planning Laboratory, Brigham and Women's Hospital and Harvard Medical School

Abstract

This paper describes an accessible, hands-on tutorial on image-guided therapy (IGT) using the LEGO Mindstorms NXT, a commercially available robotics kit, and 3D Slicer, an open-source application for medical image processing. Tutorial participants will learn about the typical IGT workflow by using the LEGO robot and 3D Slicer to perform a simulated needle biopsy on a phantom made of traditional LEGO pieces. In addition, this paper describes NXT-USB, a new C++ library that allows direct control of a LEGO Mindstorms NXT robot from a Linux computer via a USB connection.

Contents

1 Introduction **2**

2 Materials and Methods **3**

2.1 Building a Robot and an Anatomical Model using LEGO 3

2.2 Robotic Control using 3D Slicer 4

2.3 The Tutorial Task 4

2.4 Assessment of Targeting Accuracy 5

3 Results **6**

3.1 Accessibility 6

3.2 Assessment of Targeting Accuracy 6

4 Conclusions **8**

5 Acknowledgement **8**

A NXT-USB Functions **8**

B Example Use of NXT-USB 9

1 Introduction

Image-guided therapy (IGT) is a minimally invasive therapy aiming at improved postoperative outcomes, shorter hospital stays and improved quality and speed of surgical procedures. IGT has gained significant interests both in research and in clinics. For example, more than 700 articles have been published in a literature database [1]. Open-source software projects such as ITK[2], VTK[3] and IGSTK[4] are major contributors to this growth, as are multicenter collaborations such as those described by Hata et al. in [5]. The current expansion of the field means that both academia and industry require specialized personnel in order to continue the upward trend. Therefore educational tools that both attract people to IGT and provide them with the necessary knowledge must be extensively disseminated. This goal has been partially accelerated by the introduction of abovementioned open-source software and their tutorials books and seminars (http://wiki.na-mic.org/Wiki/index.php/Training:Main).

However, education on IGT is a challenge because the field's intrinsic reliance on equipment means that tutorials must be hands-on in order to be truly effective. Since tracking devices are expensive and phantoms are time consuming to construct, this requirement directly conflicts with the equally important requirements for educational materials to be open-source, low-cost and widely available for purchase. To the best of our knowledge, there does not exist a sub-$500 USD, practical tutorial system for IGT available today. Instead, the only options available to many students of IGT are to merely read about the subject or, if they are lucky, attend a brief conference workshop that may or may not have a practical component. These educational experiences do not come close to conveying the dynamic and evolving world of IGT: without practical and affordable educational tools, the field of image-guided therapy will fail to capture the best and brightest minds that it needs to continue its rapid growth.

The objective of this paper is to describe an open-source tutorial for image-guided therapy that is both accessible and hands-on. The tutorial uses the LEGO Mindstorms NXT, an inexpensive and widely available robotics kit. The software architecture chosen for this project was 3D Slicer (Massachusetts Institute of Technology Artificial Intelligence Lab and Brigham and Women's Hospital, Boston, Mass), a comprehensive open-source software package for medical image processing and image-guided therapy [6]. 3D Slicer was selected for its extremely unrestrictive license and its extensive array of image processing functions. The LEGO robot and 3D Slicer will be used to perform a simulated needle biopsy with a target (such as that which may be done for breast or prostate cancer) on a phantom created out of standard LEGO pieces. In this way, the user of the tutorial will be exposed to all of the typical steps of an IGT procedure, including pre-operative imaging, registration, target planning, and tracking and navigation, in a hands-on manner.

2 Materials and Methods

2.1 Building a Robot and an Anatomical Model using LEGO

Tutorial participants will be required to purchase a LEGO Mindstorms NXT kit as well as traditional LEGO pieces. Before beginning the tutorial, participants will use our provided instructions and the LEGO Mindstorms NXT to construct the robot that will perform the simulated needle biopsy. In addition, users will construct the phantom (anatomical model) using the traditional bricks. Although the necessary pieces can be purchased individually from LEGO, the Deluxe Brick Box (#6167) contains all of the bricks needed to build the phantom and is less time-consuming to purchase.

The LEGO Mindstorms NXT is a basic robotics kit commercially available from The LEGO Group. Although originally designed as a toy for children ages ten and up, the potential of the NXT as tool for research and education was quickly taken advantage of by the scientific community. After emerging from research at the MIT Media Lab [7], LEGO robots have been used to investigate prey retrieval in collective robotics [8] and are also useful for rapid-prototyping of interactive robots [9]. In the educational domain, LEGO robots have been integrated into undergraduate computer science courses in artificial intelligence [10, 11] while LEGO robot competitions are popular introductions for children to robotics [12, 13]. In particular, this work was inspired by the Computer-Integrated Surgery Student Research Society (CISSRS), which runs weekend-long CISSRS Surgical LEGO Robot Competitions to expose high-school students to medical robotics [14]. The ease with which robots can be quickly constructed and programmed, as well as the extensive open-source software and documentation provided by The LEGO Group and the extremely active LEGO Mindstorms NXT community, makes LEGO an ideal system with which to build a tutorial for image-guided therapy.

Detailed hardware and software specifications of the LEGO Mindstorms NXT can be found in The LEGO Group's description of the product (available at http://mindstorms.lego.com/Overview/default.aspx) and in several books on the product (such as [15]). Provided in the LEGO Mindstorms kit is the "NXT Intelligent Brick", with a 32-bit ARM7 microcontroller, a 8-bit AVR microcontroller, 4 Kbytes of FLASH memory and 512 bytes of RAM. Also included are four sensors: the touch sensor provides button-press functionality, the sound sensor detects decibels up to 90 dB, the light sensor measures light intensity, and the ultrasonic sensor detects objects by measuring distance. Three servo motors each have an adjustable power setting and a built-in rotation sensor to provide and measure movement. Finally, 519 LEGO TECHNIC pieces form the basic construction material for building a robot, which are usually smaller than 2' x 2' x 2' depending on the design.

The typical way to program the LEGO Mindstorms NXT is to write and compile the code on a computer and transfer it to the robot: the robot then is autonomous from the computer when the program is run. The NXT brick has both USB 2.0 and Bluetooth capability for this file transfer. Although LEGO ships its own graphical programming software with the product, most users with programming experience prefer to use an alternative open-source language. Of particular note is Not eXactly C (NXC, available at http://bricxcc.sourceforge.net/nbc), a C-like language built on top of the affiliated Next Byte Codes (NBC) compiler, and Bricx Command Center (available at http://bricxcc.sourceforge.net), a popular integrated development environment (IDE). Although the official LEGO Mindstorms NXT software runs on Windows and Macintosh systems only, one option for UNIX users is to write NXC code in any text editor, compile using the command line NBC compiler and then transfer the resulting executable using LiNXT (available at http://sourceforge.net/projects/linxt). Finally, The LEGO Group also provides documentation for advanced programmers to send direct commands from a personal computer to the NXT brick for all robotic functions, such as sensor reading and motor control and rotation sensing [16].

2.2 Robotic Control using 3D Slicer

All visualization, target planning, robotic control will be performed using 3D Slicer, and so participants will download, build and install a specialized 3D Slicer module for the tutorial. Thus this tutorial builds upon the work done by CISSRS by integrating an advanced software package and by including more advanced material such as preoperative planning and registration.

Our need to send direct commands to the LEGO robot from within 3D Slicer lead to the development of USB-NXT, a C++ library which allows for the control of an LEGO Mindstorms NXT robot over a USB connection (please see Appendices A and B for a list of the functions provided by USB-NXT and a simple example of their use). In particular, USB-NXT allows one to move the motors and read motor rotation and sensor values from within a C++ program. The USB functionality of the LEGO NXT brick was chosen instead of Bluetooth to maximize the reliability of the connection.

USB-NXT was developed based on the open-source projects NXT++ (available at http://nxtpp.sourceforge.net) and Device::USB (available at http://search.cpan.org/~gwadej/Device-USB-0.21). Although NXT++ provides the same functionality as USB-NXT, it was not used in this project because it unfortunately did not work properly on our 64-bit Linux platform. USB-NXT requires the open-source library libusb (available at http://libusb.sourceforge.net) in order to access the USB device. At present USB-NXT is available only for the Linux platform, although support for Windows and Macintosh is planned for the near future. Please note that you must use USB-NXT as root, since root access is required to access USB devices.

2.3 The Tutorial Task

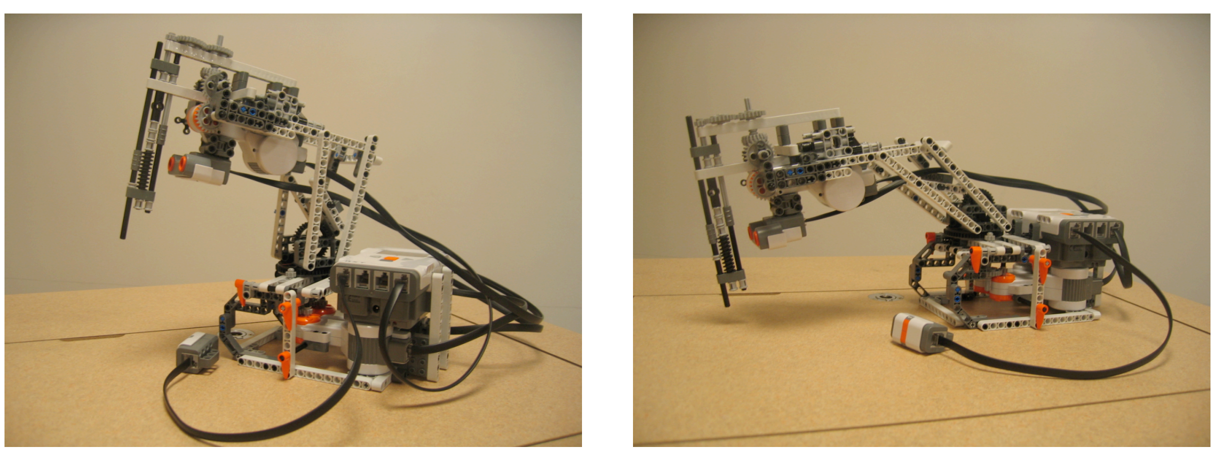


Figure 1 The LEGO Mindstorms NXT robot used in the IGT tutorial. The robot is shown in its initial position at the beginning of the tutorial.

The LEGO robot designed for this tutorial is shown in Figure 1. Although many scientific and educational projects involving LEGO Mindstorms use multiple kits to build a single robot, we constrained ourselves to a single kit in order to minimize cost to the user and satisfy our goal of accessibility. All three motors provided with the LEGO Mindstorms NXT kit are used in the design: one to swing the robotic arm from side to side, one to move the robotic arm forwards and backwards, and one to move the "needle" up and down (please see the provided video for a demonstration of the movement of the robot). In addition, two of the four LEGO sensors are utilized: the ultrasonic sensor measures the distance from the sensor to the nearest object and is useful for registration, while the touch sensor is helpful in development and testing.

The image-guided therapy tutorial will be composed of two parts, with an estimated time to complete both sections being approximately one hour. In the basic tutorial, participants will place the LEGO phantom containing two tumour targets in a particular position and orientation with respect to the LEGO robot. The user will then follow the tutorial outline to move through the typical IGT workflow. He or she will:

- upload a provided CT volume of the phantom
- establish the USB connection between the LEGO robot and 3D Slicer
- select a target coordinate on the image
- instruct the LEGO robot to perform the simulated needle biopsy

Registration is not required since the spatial relationship between the phantom and the LEGO robot is known. During the execution of the biopsy, 3D Slicer will show the current position of the needle overlaid in real-time onto the CT volume of the phantom.

In the advanced tutorial, the concept of registration will be introduced. The user will be instructed to position the phantom relative to the LEGO robot such that a target is within reach and so that specialized vertical pillars on the phantom will be in view of the ultrasonic sensor as the robotic arm swings around. The robotic arm will swipe from side to side several times and at several different vertical positions so that a profile of the distance between the ultrasonic sensor and the registration pillars can be generated. This profile will be used to identify landmarks on the phantom in the robotic coordinate system. The landmarks will be widely spread over the phantom in order to maximize the quality of the registration [17]. Using 3D Slicer, tutorial participants will identify the corresponding landmarks on the image volume, and a rigid landmark registration algorithm will be used to calculate the registration transformation. The LEGO robot will again be used to execute the simulated needle biopsy.

2.4 Assessment of Targeting Accuracy

There are two possible sources of error in the ability of the robot to accurately move its needle actuator to a specified target in the robot's coordinate system. Firstly, the geometrical solution to the robot's inverse kinematics problem is based in part on physical measurements of how the rotation of each motor changes the final actuator position. A cubic polynomial was fit to these measurements using Matlab's `polyfit` function and therefore some error in the relationship between motor rotation and final actuator position is inevitable. Secondly, when instructing the robot to rotate a motor by a certain number of degrees, the motor usually rotates more than instructed because braking causes the motor to slow down somewhat gradually. Therefore it is essential to test the accuracy of the robot's ability to target a specific location.

In order to test the targeting accuracy of the robot, a Lego Mindstorms NXT kit was purchased and the IGT tutorial robot described above was built. Ten target points within the range of motion of the robot were randomly selected. Starting from the initial position shown in Figure 1, the robot was instructed to target each of these points, and the final actuator position was approximated by visual inspection using LEGO pieces as measuring devices. Finally, the distance between the target coordinate and the final actuator position in each of the X, Y and Z coordinates was determined.

3 Results

3.1 Accessibility

One of the most important requirements of this IGT tutorial is accessibility, as it will not be widely used if the materials needed for the tutorial are not affordable. Table 1 shows a breakdown of the costs of the materials required, namely the LEGO Mindstorms NXT kit and the LEGO Deluxe Brick Box. Since the total cost is less than $300 USB (without any applicable taxes or shipping charges), it is clear that the tutorial remains accessible to students, surgeons and any other individuals interested in IGT.

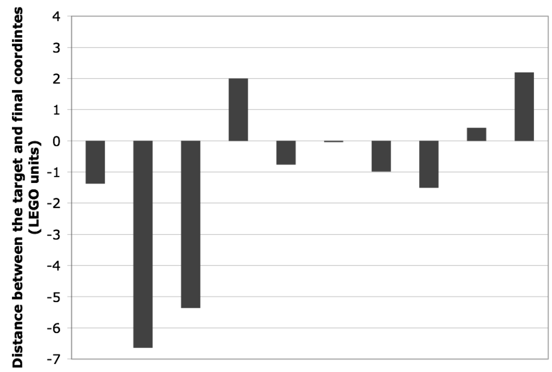
Item	Approximate Retail Price (USD)
LEGO Mindstorms NXT (Item #8527)	$249.99
LEGO Deluxe Brick Box (Item #6167)	$44.99
Total	**$294.98**

Table 1 IGT tutorial expenses. All prices are in USD and exclude any applicable taxes and shipping charges. All prices were obtained from http://shop.lego.com.

3.2 Assessment of Targeting Accuracy

The results of the targeting accuracy tests for the LEGO robot are shown in Figure 2. The average distance between the target coordinate and the final needle position was 2.13 LEGO units in the X direction, 1.76 LEGO units in the Y direction, and 1.84 LEGO units in the Z direction. Although not idea, this targeting accuracy is sufficient for large enough targets.

A:



B:

C:

Figure 2 Results of the targeting accuracy tests of the LEGO robot. In each graph, the x-axis shows the results from each of the ten targets. The y-axis shows the distance between the target coordinate and the final needle position in the x, y and z directions for figures A, B and C, respectively.

4 Conclusions

In this paper we have described an accessible and hands-on tutorial on image-guided therapy using the Lego Mindstorms NXT robotics kit and 3D Slicer. We have also described NXT-USB, a new library that allows communication between a LEGO Mindstorms NXT robot and C++ code over a USB connection. The targeting accuracy of the tutorial robot was also evaluated and was found to be adequate for the tutorial purposes.

5 Acknowledgement

This publication was made possible by Grant Number 5U41RR019703, 5P01CA067165,and 5U54EB005149 from NIH. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH. This study was also in part supported by NSF 9731748 and CIMIT. Thanks also to Steven Canvin of The LEGO Group, G. Wade Johnson, Cory Walker, Haiying Liu, Dr. Junichi Tokuda, Christoph Ruetz, and Philip Mewes.

A NXT-USB Functions

Below is a list of the public functions offered in the NXT-USB library. More extensive documentation on the use of these functions has been included with this submission.

```
// Constructor and destructor
vtkLegoUSB();
~vtkLegoUSB();

// Open and close the USB connection to the LEGO robot
int OpenLegoUSB();
int CloseLegoUSB();

// Setup the sensors
void SetSensorLight(int port, bool active);
void SetSensorTouch(int port);
void SetSensorSound(int port, bool dba);
void SetSensorUS(int port);
void SetUSOff(int port);
void SetUSSingleShot(int port);
void SetUSContinuous(int port);
void SetUSEventCapture(int port);
void SetUSContinuousInterval(int port, int interval);

// Read from the sensors
int GetLightSensor(int port);
bool GetTouchSensor(int port);
int GetSoundSensor(int port);
int GetUSSensor(int port);

// Move and stop the motors
void SetMotorOn(int port, int power);
void SetMotorOn(int port, int power, int tachoCount);
void MoveMotor(int port, int power, int tachoCount);
```

```
void StopMotor(int port, bool brake);

// Read the motor rotation from the motors
int GetMotorRotation(int port, bool relative);
void ResetMotorPosition(int port, bool relative);

// Play a tone on the LEGO robot
void PlayTone(int frequency, int duration);

// Get the connection status of the LEGO robot
char * GetStatus();

// Get information about the LEGO robot
char * GetDeviceFilename();
int GetIDVendor();
int GetIDProduct();
```

B Example Use of NXT-USB

```
#include “NXT_USB.h”

int main (int argc, char* argv[])
{
    // Create the NXT_USB object
    NXT_USB* legoUSB = new NXT_USB();

    // Open the connection to the LEGO robot
    int open = legoUSB->OpenLegoUSB();

    // Return if we cannot open the connection
    if (open == 0)
    {
        std::cerr << “Could not connect: ” << legoUSB->GetStatus() << std::endl;
        return 1;
    }

    // Setup:  the touch sensor should be attached to input port 1
    legoUSB->SetSensorTouch(IN_1);

    // Move the motor attached to output port A (for 180 degrees at +50% power) once
    // the button on the touch sensor has been pressed
    while (!legoUSB->GetTouchSensor(IN_1)) {};
    legoUSB->SetMotorOn(OUT_A, 50, 180);

    // Close the connection to the LEGO robot
    legoUSB->CloseLegoUSB();
    delete legoUSB;

    return 0;
}
```

References

[1] Search by keywords "Image Guided Therapy" OR "Image-guided Therapy" OR "Image-guided surgery" OR "Image Guided Surgery" Databases=MEDLINE, WCI, Web of Science; Timespan=All Years]

[2] L. Ibanez and W. Schroeder. *The ITK Software Guide*. Kitware, Inc. ISBN 1-930934-10-6, http://www.itk.org/ItkSoftwareGuide.pdf, 2003.

[3] W. Schroeder, K. Martin, and W. Lorensen. *The Visualization Toolkit: An Object-Oriented Approach to 3D Graphics, 2nd ed*. Kitware, Inc. ISBN 1-930934-12-2. Prentice-Hall, Old Tappan, N.J., 1998.

[4] K. Gary, L. Ibanez, S. Aylward, D. Gobbi, M.B. Blake, and K. Cleary. IGSTK: An open source software toolkit for image-guided surgery. *Computer*, 39(4):46-53, 2006.

[5] N. Hata et al. Software Engineering Methods for Multicenter Clinical Application of Computer-enhanced MR-guided Therapies. In *Proceedings of the 10th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI'07)*, 2007. To appear.

[6] D. Gering, A. Nabavi, R. Kikinis, N. Hata, L. Odonnell, W. Eric L. Grimson, F. Jolesz, P. Black, and W. Wells III. An Integrated Visualization System for Surgical Planning and Guidance Using Image Fusion and an Open MR. *Journal of Magnetic Resonance Imaging,* 13(6): 967-975, 2001.

[7] M. Resnick. Behavior Construction Kits. *Communications of the ACM,* 36(7):64-71, 1993.

[8] T.H. Labella, M. Dorigo, and J.L. Deneubourg. Efficiency and Task Allocation in Prey Retrieval. In *Proceedings of the Frist International Workshop on Biologically Inspired Approaches to Advanced Information Technology*, Lecture Notes in Computer Science, 3141:274-289, 2004.

[9] C. Bartneck and J. Hu. Rapid Prototyping for Interactive Robots. In *Proceedings of the 8th Conference on Intelligent Autonomous Systems (IAS-8)*, 2004.

[10] F. Klassner. A Case Study of LEGO Mindstorms'™ Suitability for Artificial Intelligence and Robotics Courses at the College Level. *ACM SIGCSE Bulletin,* 34(1):8-12, 2002.

[11] A.N. Kumar. Using Robots in an Undergraduate Artificial Intelligence Course: An Experience Report. In *Proceedings of the 31st Annual ASEE/IEEE Frontiers in Education Conference*, 2001.

[12] D. Opplinger. Using First Lego League to Enhance Engineering Education and to Increase the Pool of Future Engineering Students. In *Proceedings of the 32nd Annual ASEE/IEEE Frontiers in Education Conference*, 2002.

[13] H.H. Lund and L. Pagliarini. RoboCup Jr. with LEGO MINDSTORMS. In *Proceedings of the IEEE International Conference on Robotics and Automation*, 1(1):813-819, 2000.

[14] O. Gerovich, R.P. Goldberg, and I.D. Donn. From Science Projects to the Engineering Bench. *IEEE Robotics & Automation Magazine*, 10(3):9-12, 2003.

[15] B. Bagnall. *Maximum Lego NXT: Building Robots with Java Brains*. ISBN 0973864915. Variant Press, Winnipeg, M.B., Canada., 2007.

[16] The LEGO Group. *LEGO Mindstorms NXT Direct Commands*, 2006. (Appendix 2-LEGO MINDSTORMS NXT Direct commands.pdf of http://cache.lego.com/upload/contentTemplating/MindstormsOverview/otherfiles/2057/LEGO%20MINDSTORMS%20NXT%20Bluetooth%20Developer%20Kit_58CE458E-5292-4CB0-93D2-4BEC821C13C2.zip)

[17] 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.