Robot Calibration for Precise Ultrasound Image Acquisition

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Abstract

Roboticsurgery is an area that has evolved greatly in recent years. The use of robots to perform orthopaedicsurgery is an ongoing research field, with applications in various pathologies. There are robotic systems with applications in laparoscopy, neurosurgery, orthopaedics, among others, e.g., the DaVinci robot, ROBODOC, etc. The HIPROB project is based on the development of a robotic system for orthopaedic surgery, e.g., Hip Resurfacing surgery. This project aims to develop a robotic system with navigation through ultrasound (US) images avoiding the fiducial markers used by other orthopaedic robotic systems, which have brought many problems to patients.

The work, presented in this paper, is part of the HIPROB project and describes the process of acquiring ultrasound images with an anthropomorphic robot. Robotized ultrasound image acquisition is an accurate method that can increase the precision of the overall robotic setup, and provide the project with an automatic image acquisition system. In this system the ultrasound probe is rigidly attached to the robot manipulator end-effector, i.e., eye-in-hand system. The calibration procedure for the eye-in-hand system used to estimate the hand-eye and the robot-world transformations, is described in this work. Having the system calibrated, the position and orientation of the ultrasound probe placed in the end-effector of the robot, as well as the relationship between each image pixel and the 3D world coordinates, are accurately obtained. The experimental results presented in the paper show the validity of the approach.

Keywords

Surgical Robotics, Image-guided surgery, 3D Ultrasound calibration, 3D Surface Reconstruction.

Introduction

Image-based computer-aided surgical (CAS) navigation systems are common used in several areas of intervention, helping to increase the accuracy of the surgical procedure and allow the performance of minimally invasive surgery. This is a topic that has been strongly debated in recent years; many researchers have focused on the theme and many contributions have appeared, such as [1] and [2]. Robotic systems need a navigation system in order to assist the surgeon, without making mistakes. Robotic solutions that assist the surgeon in orthopaedic surgery have been presented, such as ROBODOC or ACROBOT systems [4], however the navigation system of these systems is not the most appropriate, because they use fiducial markers to know the position and orientation of the bone related to a known fixed coordinate system in the operating room. Fiducial markers are spikes, attached to the bone through the incision. According to experts, serious problems in patients appear after surgery. There are reports [5] of frequent pain in the incision area of incisions and some locomotion problems. HIPROB project is being developed in order to overcome the limitations of current systems, related to the use fiducial markers. Its aims to create a robot for Hip Resurfacing surgery, with a navigation system based on ultrasound images.

Ultrasound imaging is a noninvasive and low cost medical imaging modality. Adding to that its ease of use, ultrasound systems are useful tools with increasing usage in surgical navigation. More important than the diagnosis through a 2D image, the visualization of a 3D surface transmits to the surgeon a better sense of what is inside the human body. Reconstruct a 3D surface with US images is possible using a 3D ultrasound probe, which is very expensive or through freehand systems, as is the case of this work. In a freehand US imaging system, US probe calibration is typically required to construct a 3D volume of the patient’s anatomy from a set of 2D US images. In the reconstruction process is typically used a spatial localizer, with sensors, passive or active, rigidly attached in the probe. In this work a robotic arm replaced the spatial localizer. The probe is attached to the end-effector of the robot and through the relation of several coordinate systems, is possible to calculate the pose of the US probe and consecutively, the corresponding 3D coordinates of each pixel of the US image in the world.
coordinate system. Besides allowing a reconstruction of a volume from an anatomical surface, this method of using the robot, allows automating the process of image acquisition and is a new support to the medical community.

This paper describes the process known as US calibration by estimating a homogeneous transformation that maps the position of individual pixels from the US image frame to the world reference frame.

This paper is organized as follows. First section, after introduction, describes the theoretical and practical concepts of system calibration process. Next section describes the 3D Ultrasound Calibration phantom and the US probe calibration. Experimental evaluations are presented in the penultimate section. Finally, conclusions and future work are presented.

System Calibration

This section describes the steps followed to calibrate the complete system, including robot, probe tool and the US probe. AIR52C robot was used in this work to move the probe. This robot has 5 degrees of freedom (DOF) and its base is fixed to a linear axis. To estimate the pose of the end-effector on the base of robot, it is necessary to calculate the direct kinematics of the robot, through the Denavit-Hartenberg (DH) algorithm [6]. The direct kinematics problem is concerned with the relationship between the individual joints of the robot manipulator and the position and orientation of the tool or end-effector. The joint variables are the angles between the links in the case of revolute or rotational joints, and the link extension in the case of prismatic or sliding joints.

Figure 1 and table 1, represent respectively the representation of the coordinate systems of the IR52C robot, according to DH convention and the corresponding parameters.

- \( a_i \rightarrow \) distance between axis origin \( i \) and \( i+1 \);
- \( d_i \rightarrow \) coordinate of axis origin \( i \) along \( z_i \);
- \( \alpha_i \rightarrow \) angle between axes \( z_{i-1} \) and \( z_i \) about axis \( x_i \) to be taken positive when rotation is made counter-clockwise;
- \( \alpha_i \rightarrow \) angle between axes \( x_{i-1} \) and \( x_i \) about axis \( z_{i-1} \) to be taken positive when rotation is made counter-clockwise;

In this case as there are only revolute joints, the variable is \( \alpha_i \).

<table>
<thead>
<tr>
<th>Link, ( i )</th>
<th>( a_i ) [mm]</th>
<th>( \alpha_i ) [rad]</th>
<th>( d_i ) [mm]</th>
<th>( \nu_i )</th>
<th>Ref. [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>( \pi/2 )</td>
<td>285</td>
<td>( \nu_1 )</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>( \nu_2 )</td>
<td>( \pi/2 )</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>( \nu_3 )</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>( \pi/2 )</td>
<td>0</td>
<td>( \nu_4 )</td>
<td>( \pi/2 )</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>( \nu_5 )</td>
<td>( \pi )</td>
</tr>
</tbody>
</table>

The homogeneous transformation relating the tool frame to the fixed base frame is given by:

\[
^0T_E = ^0T_1 \times ^1T_2 \times ^2T_3 \times ^3T_4 \times ^4T_5 \times ^5T_E
\]

The US probe is rigidly attached to the wrist of the robot, through the tool shown in figure 2. When we want to know the position of each pixel in the image on the fixed world coordinate system is necessary to calculate the homogeneous transformations between the various references frame, and also pixel image correspondence in metric units, in this case in mm. Figure 3 helps to understand the transformations needed to obtain the calibration matrix. The direct kinematics of the robot, only describes the relationship between your wrist and base, transformation T1. So it is necessary to calculate the homogeneous transformation that exists between the base of the robot and the referential world, depicted in figure 3 as T0, the relation between the US probe support and the end-effector of the robot, T2 and the relation between the US probe and the support, T3.

\[
T_{ca} = T_0 \times T_1 \times T_2 \times T_2 \times T_3 \times P(u,v)
\]
\( P(u,v) \) is the column vector representing the 2D position of the pixel, according to the coordinate axes \( x \) and \( y \). \( S_x \) and \( S_y \) are the scale factors for the \((u,v)\) pixel coordinates, obtained by the US probe calibration process with the CIRS Ultrasound Calibration Phantom. The next section describes the probe calibration to obtain the scale factors.

Figure 1 – IR52C robot, with the coordinate system

Figure 2 – Probe tool attached to the end-effector of IR52C.

Figure 3–Transformations of the coordinate system for calibration.
3D Ultrasound Calibration Phantom

CIRS 3D Ultrasound Calibration Phantom, model 055, illustrated in figure 4, was used in this work to calibrate the ultrasound probe, and determine the relation pixels / mm, necessary for obtaining the scale factors to volumetric reconstruction. This Model is a volumetric target phantom and contains a small egg and a large egg. There are two scanning surfaces and the targets are centred within the background material. Depending upon what side is scanned, the test objects are located at distances ranging from 2 to 6 cm from the scanning surface. Figures 5, represent, a schematic of what can be seen inside the phantom, with the nominal size of two eggs. As was said before, the phantom has two scanning surfaces, top and lateral, however we can make a cross-scan with the probe, allowing an additional view.
AlokaProsound 2 and a 5 MHz US probe were used to obtain the US images. The US machine allows obtaining images with different spatial resolution and different depth. Different spatial resolutions can be obtained for each level of depth. In this work the images were acquired in the R14 depth, so the scale factors must also be obtained for this depth. The image of figure 6 corresponds to the large egg, at side view of phantom. As seen in figure 5, the egg has an elliptical shape with dimensions of 70 mm by 50 mm, these dimensions correspond respectively to 192 and 139 pixels.

![Image](image.png)

Figure 6 – Large egg, at side view, depth R14.

The spatial resolution according to the vertical ($\chi_y$) and horizontal ($\chi_x$) axes is obtained using equations 3 and 4.

$$\chi_y = \frac{441 - 272}{50 \text{ mm}} = \frac{2700 \text{ px}}{50 \text{ mm}}$$

$$\chi_x = \frac{424 - 232}{70 \text{ mm}} = \frac{27429 \text{ px}}{70 \text{ mm}}$$

(3)

(4)

In order to have redundant values and confirm those already obtained, the same procedure was done for the small egg of 39 mm by 18 mm, figure 7.
The relation \( \text{pixels/mm} \) obtained in both images tends to the same value, as expected, the method used to acquire the images was the same in both. Through this method is possible to calculate the spatial resolution for the images acquired in R14 depth. To other levels of depth is need to return the same procedure. To work with a calibrated system, all images acquired in the experimental evaluation, were obtained in the R14 depth. The scale factors \( S_x \) and \( S_y \), are calculated by the inverse of \( \text{pixel/mm} \) relationship, to know the distance in \( \text{mm} \) of each pixel.

\[
X_{xz} = \frac{(249 - 199) \text{px}}{18 \text{ mm}} = 2.7778 \frac{\text{px}}{\text{mm}}
\]

\[
X_{xz} = \frac{(358 - 251) \text{px}}{39 \text{ mm}} = 2.7436 \frac{\text{px}}{\text{mm}}
\]

The relation \( \text{pixels/mm} \) obtained in both images tends to the same value, as expected, the method used to acquire the images was the same in both. Through this method is possible to calculate the spatial resolution for the images acquired in R14 depth. To other levels of depth is need to return the same procedure. To work with a calibrated system, all images acquired in the experimental evaluation, were obtained in the R14 depth. The scale factors \( S_x \) and \( S_y \), are calculated by the inverse of \( \text{pixel/mm} \) relationship, to know the distance in \( \text{mm} \) of each pixel.

\[
S_x = \frac{1}{X_{xz}} = \frac{1}{2.774} = 0.365 \frac{\text{mm}}{\text{px}}
\]

\[
S_y = \frac{1}{X_{xz}} = \frac{1}{2.778} = 0.360 \frac{\text{mm}}{\text{px}}
\]
Experimental Evaluation

To validate this calibration method, tests were performed to acquire US images with the robot at different bone structures and 3D surface reconstruction of these bones. An example is the scan of a human femur, where 146 images, were acquired spaced 0.6 mm (robot depth resolution). This test corresponds to the central part of the bone. After image processing, which includes cleaning the images and bone segmentation [7] [8], the 3D surface was obtained by reconstruction of the several 2D ultrasound images. This process was performed in MATLAB to process the data, and MeshLab to visualization. Figure 8, show the result of femur bone reconstruction.

\[ HT_i, \quad \text{and} \quad HT_f \]

represent the homogeneous transformation matrices, referred to the position and orientation of the US probe at the first acquired image and the last acquired image, respectively. In this test the rotation component is equal, because the movement of robot is done along the linear axis, maintaining the same orientation of the probe, however is visible the displacement of 87.8787 mm, along the x-axis. During the 3D reconstruction, after measuring the surface length, a size of 93 mm was obtained, which means a 6.0553 mm error in relation of the probe final position, however this error is not significant, can even be caused by the method of measurement.

![Figure 8 – Femur bone surface reconstruction.](image)

Conclusions

This paper presents an automatic method for moving an ultrasound probe, through an anthropomorphic robot. System calibration and US probe calibration is an important task to precise ultrasound image acquisition, especially when the objective is the 3D reconstruction of surfaces by 2D US images. The homogeneous matrix
obtained in the calibration process allows to know the location of each pixel, in the 3D world coordinates. It is possible to know the coordinates of each 2D image pixel in the 3D space, i.e., knowing its position and orientation in the 3D world. The coordinates of each pixel in mm, were obtained through a phantom with known dimensions, so it was possible to create a relationship between the number of pixels and its size in mm.

In this work, US images of a human leg were acquired using a robot, moving from the direction of the hip to the knee. By the number of acquired images and the trajectory performed by the probe, it was possible to estimate a spacing of 0.6 mm between slices. Having the gaps between images and the location of the pixels was possible to reconstruct a 3D surface of the femur. This reconstruction validated the calibration process to the application, by the comparison between the surface dimensions and the real dimensions of the bone.

Future work

As future work is expected to compare the results obtained through this system, with the results obtained by spatial localizer, POLARIS.

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