ROBUST SCANNER - ULTRASOUND IMAGES REGISTRATION FOR
COMPUTER ASSISTED TOTAL HIP ARTHROPLASTY

Agung Alfiansyah *)

ABSTRACT

This paper proposes a robust registration method of computer assisted orthopedic surgery using ultrasound as intra operative data acquisition modality. This method is based on a geometric based rigid registration between segmented CT scan and localized ultrasound images. Ultrasound images segmentation is performed automatically using a type of model deformable (snake) method with integration of regional energy term and posterior points selection. For CT scan, we develop a segmentation based on thresholding value application and largest connected component detection followed by extraction of the bone surface visible by ultrasound probe. Registration process is carried out by finding a rigid transformation that minimizes the sum of squared distance between selected surface issued from CT scanner segmentation and segmented ultrasound contours. A variant of ICP was employed to perform this registration task by determining the closest points pairs using octree to accelerate the calculation. And then continued by minimizing the total energy using Levenberg-Marquardt optimization method. Validated using bone phantom and a female cadaver, we demonstrate that this proposed method enhance the robustness and accuracy of the registration method.

Keywords: Computer Aided Surgery, Orthopedic Surgery, Ultrasound, CT Scanner, Segmentation, Registration.

INTRODUCTION

The emergence of medical imaging technology brings significant influences in medical applications not only for patients diagnosis, but also in surgical intervention room.

Thanks to medical images, ones might obtain the better result by means of minimally invasive surgical procedure, that decrease postoperative recovery needed times and lower overall cost. This technique also allows the surgeon to perform some medical interventions that were considered as too dangerous before.

Using the medical images acquired preoperatively, surgeon can design a planning based on these images. Then, this planning is integrated to the operating room by performing a data fusion process via registration method between intraoperative images data with the preoperative ones.

One of medical domain, where the computer assisted medical intervention is widely applied is in orthopedic surgery. The intra-operative data for this application are generally a points clouds represented the patient’s bone acquired by sliding a three dimensional pointer on the operated bone surface. This method is quiet fast, easy and accurate but it has some mains important drawbacks: this is invasive, its acquisition areas is limited in the exposed part bone surface and in some case cause additional pain postoperatively [1]. In the other hand, lack of information in the non incised areas might affect the overall registration accuracy.

To enhance this acquisitions method, several works have been proposed as the alternatives approach to reach a noninvasive data acquisition for intra-operative application.

X-ray and fluoroscopic [2,3] images are proposed as image modality for 2D/3D registration algorithm between these images and CT scanner. Compared to fluoroscopic imaging that use ionizing radiation, ultrasound is a much less invasive image modality. Furthermore, it is portable, inexpensive, and real time for continuous data acquisition. These advantages make some authors interested to integrate the ultrasonic imagery as intra operative image modality. The main drawback of ultrasound images is its quality, due to the presence of artifacts.
that make it difficult to analyze in order to obtain an accurate feature result. Some authors reported the application of ultrasound for orthopedic surgery, such as: on hip[4,5,6], long structure bones[7] and vertebrate [8,9].

This paper proposes robust registration method to perform a coordinate matching (registration) process between CT scan and localized ultrasound images. We choose a geometric registration method, thus the available data set should be segmented previously. A method to select solely pertinence information in CT scan is elaborated also in this paper to increase the robustness of the method.

In order to be applied in real operating room, the system also needs to be accurate: Target Registration Error (TRE) should be less than 1.5 mm; need simple and minimal user interaction. The method should be also easily customizable for the other applications in ultrasound images based orthopedic surgery.

Method and implementation

This chapter describe firstly the problem formulation of image registration for computer assisted surgery application. Since we applied a geometrical approach of registration, thus we presents our segmentation method for ultrasound and scanner images with a method to select solely the pertinence bone surface in scanner imaged by ultrasound device. Then, the registration method applied to these segmented data set will be presented.

2.1. Problem formulation

Registration is a method to accurately find the spatial relationship between preoperative images and patient’s anatomy in operating room. Once this process has been performed, all of the data set can be matched and the surgical instruments can also be navigated into the correct position and orientation as specified by the preoperative planning.

Registration problem for computer assisted surgery for orthopedic application can be illustrated as Figure 1 that describes the hardware components of this system and their transformation that relate each of them. It consists of: a) optical localizer for position and orientation instrument tracking; b) anatomical attached rigid body, with infrared reflecting markers; c) preoperative CT scan; d) ultrasound probe with attached rigid body for tracking purpose during image acquisition.

The main problem to solve in this registration method is finding $T_{\text{REG}}$ rigid transformation that relates the intra-operative data (i.e. anatomical rigid body) to preoperative (i.e. voxel coordinate in CT scan) coordinate frame. Usually this transformation is initialized as a position guess, not so far to the desired final registration to avoid false final solution.

The exact transformation then firstly calculated by determining transformation using a registration method. This transformation will matches the acquired localized ultrasound images to CT scanner volume. This transformations $T$ can be decomposed as consecutive transformations, as:

$$ T = T_{\text{REG}} (T_{\text{RB}})^{-1} T_{\text{US}}^{-1} T_{\text{CAL}} $$

The transformation $T_{\text{RB}}$ and $T_{\text{US}}^{-1}$ respectively denote the transformation of $i$th the attached anatomical rigid body and ultrasound probe relative to the optical localizer camera. While $T_{\text{CAL}}$ is an ultrasound calibration transformation that maps the position of each pixels in ultrasound images relative to rigid body attached probe. Several methods are proposed to determine this transformation, such as [10,11]. During the registration, an optimization method seeks the rigid transformation $T$ that minimizes the dissimilarity measure between localized ultrasound in the scanner.

2.2. Image segmentation

Geometric based registration method that we
employed in this paper needs a feature extraction from the available images. It should be performed in ultrasound images as well as in CT scan data. We applied the different methods for those different data, thus we will presented them in the following part.

A. Ultrasound Segmentation

In general cases, the feature extraction from ultrasound images are very difficult to be performed due to its poor image quality (presence of speckle, delayed echoes, reverberation, etc…). However, process is critical in feature based registration.

To overcome this drawback, we propose in [12,13] an automatic bone surface detection method for ultrasound images based on active contour model. This method including a region based energy for detecting the local contrast in the image and intensity based posteriori point selection of to keep only real bone in image.

Deformable model: The active contours are generally modeled as the sum of internal energy, that imposes the regularity of the curve; and external energy that attracts the contour toward the image significant features. The segmentation process is the achieved by minimization of the following total energy function [14]:

$$ E(s) = \int_{A} \left( \alpha |v'(s)|^2 + \beta |v''(s)|^2 \right) ds + \int_{A} P(v) ds $$

where $v'(s)$ and $v''(s)$ represent the first and second derivative of the curve, and $P(v)$ is an image potential associated with the image force. Usually $P(v)$ is usually the negative of the gradient image.

We proposed an open contour active type model with two free extremities allows the model moving upward, initialized using a simple contour in the bottom of the image, and then let it evolved in vertical direction to find the its minimum energy.

Cohen [15] proposes an additional force and the gradient image term normalization to avoid local minimum.

A. CT scan Segmentation

In CT scan, bone organ is imaged as a high contrast with a dark area around. Then, segmentation in this data can be performed by converting CT scan data to a binary volume. This binary volume is constructed using the thresholding method by applying the Hounsfield unit value for bone, and then keeping the result having large connected component.

In the previous implementation[13], we proposed to directly utilize this binary volume to reconstruct a three dimensional distance for the registration process. Then, the registration method is achieved seeking a rigid transformation that minimize the distance between the features. This method is so sensitive to the minimum local solution, due to the presence of double surface in iliac wing. In that previous method, to increase the method’s robustness, we proposed a method based on transformation perturbation to place the solution in the better minimum energy.

In this paper, we applied another different approach to avoid the local minimum solution by directly selecting the bone surface in CT scanner that visible by ultrasound probe. In fact, since bony organs usually have the ultrasound high absorption rate, thus all of the emitted energies will be absorbed by the fist bone surface that imaged by the probe, and it also generates an acoustic shadow behind them. So, by performing a selection to keep only the bone surface visible by ultrasound probe, we expect that we can remove the local minimum selection comes the presence of double surfaces on the iliac bone area.
Robust Scanner - Ultrasound Images Registration For Computer Assisted Total Hip Arthroplasty

Agung Alfiansyah

ISSN 1858-1633 @2008 ICTS

Figure 3: Double surface effect in iliac area and their influences in energy minimization. a) Ultrasound points clouds situated closer to the interior part of iliac surface, this situation will lead the registration to the false minimum local. b) Ultrasound points clouds situated closer to the exterior part, correct registration might be achieved in this case.

Solutions using the methods based on “ray casting” method were proposed by Leroy [16], Mozer [17] and Brendel [18, 19] might be interesting to eliminate the local minimum in registration energy due to that double surface in iliac anatomical part. They extracted the ultrasound probe bone surface by scanning the CT scanner according to its coordinate axis, then keeping the first found points represented the bone surface.

The advantage of this method is its possibility to be calculated preoperatively, so the additional time in operating room can be reduced. But unfortunately, the method is difficult to be integrated in computer assisted system, since the ultrasound probe direction is not always parallel to the scanner axes. The ultrasound trajectory and position is also difficult to be predicted, because of the variability in ultrasound images acquisitions in operating room. Furthermore, the method have a tendency to remove certain surface in scanner images that probably important for registration (e.g. iliac crest).

We proposed an novel bone surface extraction approach to detect that visible by ultrasound probe. This method takes into account the position of ultrasound probe during the images acquisition.

Figure 4: Extraction of bone surface that visible by ultrasound probe from CT scan data: a) Oblique slice reconstruction from CT scan on the estimated probe position. b) Segmentation using image thresholding and detection of largest connected components. c) Selection of upper bone surface that represent the visible surface by ultrasound probe.

The process of the proposed method can be broken down in some steps as follows (see figure 4): First, the oblique slice image of preoperative CT scan are reconstructed using the estimation of rigid body parameters and the plane position of each ultrasound slice (figure 4.a.). Then, a thresholding method is applied to this image to extract the bone organ from the others and keeping uniquely the segmentation result having largest connected component to remove the remaining unwanted object (figure 3.b.). To extract the interested surface, we perform a scanning in vertical direction from the top of image, and keep the first point representing the bone surface (figure 3.c.)

We proposed an novel bone surface extraction approach to detect that visible by ultrasound probe. This method takes into account the position of ultrasound probe during the images acquisition.

Figure 5: Extracted visible bone surface using our method (colored in yellow).

This oblique reconstruction and interested surface extraction are not only performed in the estimated ultrasound position in CT scan volume, but also its position around. In our case, we also performed the same reconstruction technique in 45 mm width around the ultrasound probe position, in the same interval value as CT scan thickness. This technique should be performed to keep the correct search space minimization, so that it can achieve the method robustness.

The overall result of visible surface extraction can be observed in figure 5. In this case, the ultrasound data are acquired on the left iliac wing, symphis and the left ischium. The surface colored in yellow represent the visible surface by ultrasound probe.

Once the whole of data sets have been extracted, the registration method can be performed to find the spatial relation between them.
2.3. Registration

In this work, we propose a geometric based registration method. This method is an algorithm that matches the selected geometric features from each of data set by finding a rigid transformation that minimizes the sum of distances between paired features. In general, features might be fiducially implanted points, anatomical landmarks, or surface contour from image segmentation. Several existed approaches can be categorized as: 1) point to point [20]; 2) point to surface [21,22,23]; 3) contour to contour from image segmentation. Our method uses the first approach that registers the localized ultrasound segmentation points to the surface extracted from CT scan image. Formulated mathematically, our objective in this registration is finding a rigid transformation $T$ that minimizes energy defined as the sum of quadric distance over all ultrasound segmented points $p$ to the scanner points cloud $q$.

$$E(p) = \sum_{i=1}^{M_p} [d(T(p), q)]^2$$

We proposed a variant of ICP method [21] to solve this registration problem. This method minimize the registration energy by iteratively determining the corresponding points in the data sets using the closest points between them.

The method can be broken down into some fundamental steps as detailed in following part.

a. Feature pairing to establish correspondences between features of each dataset. This correspondence are determined as two points having the closest distance of each feature in ultrasound data to the CT scan. As we applied pointtopoint registration method, we employed an octree [27,28] to accelerate the calculation of the point’s distance and determine its closest pair.

Octree reconstruction is performed by splitting the CT scan points cloud successively according to plans perpendicular to one of the coordinate system axis. This partition divide points into two sets (left/right or up/down sets), and each with half of the points of the parent node. Their children are again partitioned into equal halves, and this partition procedure is repeated until each point is stored in its own leaf cell.

b. Distance minimization (optimization), to find a rigid transformation that optimally minimizes the squared distance between datasets. We evaluated a method to be applied for this purpose that known as LevenbergMarquardt optimization method [29].

This optimization method is an iterative minimization approach that explicitly combines the steepest descent and Newton method. From the initial position, the method seeks the optimum energy by updating the new position using this update vector $g$ defined as:

$$[H(p_k) + \lambda_k \cdot I] \cdot \delta_k = -g(p_k)$$

where $H$ represent the hessien matrix of the energy, $\lambda$ is the gradient and $\delta_k$ is a constant that determine the searching level in this optimization method.

We propose a two passes minimization with outlier points removal between the passes to enhance the method robustness. This outlier point removal allows the registration method in excluding the false data due to the noisy imaging or remaining false positive points after segmentation process.

We remove the outliers explicitly [22] by keeping only the points nearer than $\mu \pm k \sigma$, where $\mu$ is mean of the distance, $\sigma$ is standard deviation of the calculated distances and $k$ is a constant to that determine the removal sensibility. In our case, we fixed the $k$ in value = 2.0.

A. Initial Positioning

Similar as the other optimization problem, the initial position estimation plays the important role in this registration problem. One method for obtaining a starting estimate position for this algorithm in a real clinical situation is to pick corresponding anatomical landmarks, both in the CT scan and physically using a tracked pointer. As, in comment cases, corresponding anatomical landmarks cannot be located to a high degree of accuracy, this initial positions will almost certainly include relatively large errors.

We defined a data acquisition protocol that include the data acquisition for this estimation. By the assistance of a three dimensional model and three CT scan slices, during preoperative step, the surgeon is ordered to pick these points: both side of anterior superior iliac spine (ASIS), symphis pubian and center of femoral head.

In intra-operative steps, the anatomical points and anatomical direction of operated patient are also need to be acquired. The points might be different according to the patient position. In decubitus supine position, the best initial position method is
achieved by matching two ASIS points and the femoral head center between the patient and the CT. For decubitus lateral position, we find that a triplet of operated side ASIS, femoral head center and patient’s lateral direction is the best choice.

We conducted a validation presented in[13] and it can be concluded that the proposed acquisition points and direction method for this purpose is fast, easy and realistic to be performed in operating room. We also measured the variability intraand interoperator of this acquisition to observe the ergonomic of this initial positioning acquisition. The result showed that the variability of the points and direction acquisitions are small, thus it can be accepted for clinical application in operating room.

Results

To evaluate the performance of this proposed method we perform a validation using phantom from plastic hip bone immerged in the water basin during the ultrasound acquisition, and also a female fresh cadaver. The registration result can be briefly observed in figure 7.

3.1. Bronze Standard

The standard registration measurement that usually utilized for validation purpose is fiducial based registration [23]. For the technical reason, we cannot obtain this data. Thus, we propose to substitute it with a “bronze standard”, obtained from registration of 7200 manually palpated points bone surface and CT scanner. These points are acquired on the both side of iliac wings and the cadaver pubic symphysis.

![Figure 5: Acquired bronze standard for registration validation. The points colored in green are utilized as registration data, and the red ones are considered as outlier points.](image)

We only take into account the very near points to the bone surface, so from all of the points, we only utilized 94% of them for the registration process. The quality of this “bronze standard” can be measured from the distance of the registered palpated points (see table 1).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Mean Distance</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic bone</td>
<td>0.48</td>
<td>0.75</td>
</tr>
<tr>
<td>Cadaver</td>
<td>0.55</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 1: “Bronze Standard” distance of registered points (in mm)

To keep the registration bronze standard accurate the position of the attached rigid bodies should not be moved between the acquisition of the bronze standard and the acquisition of the real data.

We quantitatively measure the performance of the registration method by measuring TRE[30] which represent the distance of predicted position in “bronze standard” of the anatomical target from its actual position. We also calculated the TE (Transformation Error) that measure the different rotation and translation between calculated final result and this bronze standard.

The performance of the registration method was measured from its robustness that deals with the possibility of the method in minimizing the energy and finds the correct registration; and precision that measures the distance between the final registration result and the utilized standard.

3.2. Robustness

Table 2 shows the robustness comparison between the proposed method and generic one validated in plastic bone and cadaver. This table is calculated from 40 different initial position obtained from 4 operators, and robustness rate indicates the percentage of the initial position that reaches the final registration with TRE less than 1 mm for plastic bone and 1.5 mm for cadaver.

We can observe from that table that the proposed registration with surface selection capable in significantly enhancing the robustness of the registration method. Selecting the bone surface uniquely to the visible one can remove the presence of local minimum in the registration energy, thus these false solution trap can be avoided.

Table 2: Robustness comparison of generic registration method (without surface selection, point pairs using distance map, and LevenbergMarquard optimization) and its proposed enhancement. Method robustness (in %),
indicates the percentage of the initial positions that find the correct final position. While time (in s) indicate the intra-operative registration needed time, including surface selection on Intel Pentium 4 processor, 1.90MHz and 1 GHz of RAM.

<table>
<thead>
<tr>
<th></th>
<th>Generic Method</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Robustness</td>
<td>Time</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic bone</td>
<td>32.5</td>
<td>31.0</td>
</tr>
<tr>
<td>Cadaver</td>
<td>17.5</td>
<td>27.8</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic bone</td>
<td>22.5</td>
<td>27</td>
</tr>
<tr>
<td>Cadaver</td>
<td>10</td>
<td>28.7</td>
</tr>
</tbody>
</table>

It should be note that the needed time for intra-operative registration are also increased significantly. This time is so critical for real application case in operating room. Although some of these needed time is hard to be accepted (more than 2 minutes), but we believe that with programming optimization and multithreading method, we can reduce the needed time execution for this application.

### 3.2. Precision

For method precision study, we classified the final registration result of cadaver subject on decubitus lateral position in three categories: Good (when final TRE is less than 1.5 mm), Moderate (between 1.5 mm and 3.0 mm) and Bad (more than 3.0 mm). Table 3 shows the recapitulation of this registration precision according to their final TRE and TE.

<table>
<thead>
<tr>
<th>Table 3: Registration method precision.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Good(avg)</td>
</tr>
<tr>
<td>(mm)</td>
</tr>
<tr>
<td>Moderate(avg)</td>
</tr>
<tr>
<td>(mm)</td>
</tr>
<tr>
<td>Bad(avg)</td>
</tr>
<tr>
<td>(mm)</td>
</tr>
</tbody>
</table>

From this table, we can observe that the majority of the initial positions lead to a minimum solution with a good precision. The positions categorized as "Good" have an acceptable enough TRE and TE to be applied to real computer assisted hip surgery application. The second class is still reasonable although less effective to be used for surgical navigation. We can notice that it occurs much less frequently. So does the "Bad" category. From this precision study, we can conclude that the method is acceptable in computer assisted surgery, especially in orthopedic application.

In operating room, due to the lack of the standard during surgery, the precision of the registration result can be verified by picking some points using three dimensional tracker in the different anatomical points. The positions of these points are then visually compared to the CT scan slices and three dimensional model reconstructed previously. Our developed application is also capable to visualize the distance between the picked point to the bone surface in real time.

### Conclusion

In this paper, we presented an enhanced approach to perform a registration between localized ultrasound images and CT scan data for total hip athroplasty applications. The method is a feature (geometric based) registration that minimized the sum of squared distances of the segmented feature of ultrasound images and CT scan. We employed a an ultrasound image segmentation based on deformable model with the integration of a regional based energy and posteriori selection of the final contour. For CT scan, a method based on image thresholding and maximum object connectivity is applied before a with a selection of the bone surface that visible by ultrasound probe. To accelerate the calculation registration, we used an octree to calculate the closest distance (assumed as pairing points) between the feature. Then, Levenberg-Marquart algorithm is employed to search a rigid transformation that minimize the registration energy. Despite of the intra-operative additional time for surface selection, the method capable of reduce the presence of local minimum energies due to the double surface in iliac wing area.

In this research, we found that the registration robustness is significantly enhanced by the surface selection in CT scan with the precision level that acceptable for clinical purpose. It is strongly possible to reduce the needed time for surface selection, not only by optimizing the method implementation and perform a parallel processing programming method, but also performing the method in pre-operative manner. We also need to perform more validation for the other subject in real
operating room application in order to better measure the method performance in multi-subject and multi-operator.

ACKNOWLEDGMENT
This research was partially supported by ANRT (Association Nationale de la Recherche Technique of French Research and Technology Ministry) in the framework of CIFRE convention between Praxim-Medivation and LSIS laboratory. We used Surgetic® station from Praxim-Medivation for our navigation system.

REFERENCES