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Registration of Computed Tomography Data to a Surgical Robot Using Fluoroscopy: A Feasibility Study

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Abstract

We present a new semiautomatic method for registering preoperative CT scan data to a robot used intraoperatively for Total Hip Replacement Surgery. Our goal is to utilize anatomical features for registration markers.

We use xray-fluoroscopy images to perform the registration. We developed a novel technique for calibration of these images with respect to the robot, such that a 3D projection line can be fully specified in robot space for each image pixel. The calibration uses an original radiolucent rod with removable metallic beads.

We extract surface models from the CT-scan, define a distance between the surfaces and a beam of 3D lines, and find the pose of the surfaces that minimizes the distance to the lines using a statistically robust method, thus providing a registration. Our new registration method uses surface apparent contours to assign a positive distance to lines intersecting the surface.

We compare our result with the registration obtained when using three metallic fiducial markers, or "pins", corresponding to the clinical protocol, and representing the ground truth for the present study. Using CT scan and fluoroscopic images of a human femur, we measured the error at the pin locations. When one fiducial is used instead of three, the maximum registration error is two mm, which indicates that the new method is accurate enough to be used clinically.

1 Introduction

Computers are increasingly used to plan complex surgeries by allowing to analyze preoperative Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) scans of the patient. In order to execute the plan, it is necessary to *register* the three dimensional preoperative data to the actual location of the anatomical features of interest during surgery. The standard technique for performing the registration is to attach a stereotactic frame or fiducial markers to the patient, and to precisely locate the frame or markers both prior to and during surgery.

In this paper, we propose a new method for the *rigid* registration, i.e., without deformation, of CT data to the operating room theater based upon anatomical features. Our context is Primary (PTHR) and Revision (RTHR) Total Hip Replacement Surgery assisted with the ROBODOC® device, manufactured by Integrated Surgical Systems (ISS) of Sacramento, CA [1]. The operation is total hip arthroplasty: In PTHR, the patient's diseased or damaged hip joint is replaced with a two part implant inserted both in the acetabulum and femur. In RTHR, a failed implant (either in the acetabulum, femur, or both) is replaced by a new implant. The role of the robot is to accurately prepare the femoral cavity for insertion of the implant.

The current registration protocol consists of implanting three metallic markers, or "pins", in the patient's femur, one proximally in the trochanter and two distally in the condyles, near the knee. This insertion requires minor surgery. A CT-scan image of the patient is subsequently acquired. By analyzing CT data, the surgeon decides upon the size and location of the implant that best fits the patient's anatomy. During surgery, the metallic pins are exposed at the hip and knee. The patient's leg is attached to the robot, that must locate the exposed pins. A registration, or coordinate transformation from CT space to robot space, is computed using the locations of the three pins as a Cartesian frame. The accuracy of this registration was measured by ISS to be better than one millimeter. However, the pins are impractical, as they cause significant patient discomfort, and the required operation causes extra inconvenience and cost.

We propose the following method to either replace entirely the pins, or keep only one proximal pin. The differences with the previous protocol are that: At most one pin is inserted before surgery; During surgery, a fluoroscope captures radiographs of the knee and hip regions, at different angles, yielding at least two different views. A calibration rod is inserted in the robot end effector. For each view, the rod is moved by the robot about two different planes. Each time the robot moves, a radiograph is acquired. The radiographic images of the rod are used to produce a calibration of each view. Once the images are calibrated, we extract the profile of the femur in each of the views using deformable contours. Using the calibration, a beam of three dimensional lines is associated to each image profile. We extract surface models of the bony anatomy from the CT-scan. We determine the pose of the surface models that minimizes a distance from the surfaces to the beam of lines. This pose, that can be constrained by the placement of one pin, provides the CT to robot registration.

Our goal is to obtain an accuracy of 2 mm for the registration. As our gold standard is the pin-based registration, we compare it to

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the transformation that we find, by computing the distances between the pins registered by our method and the pins registered with the clinical protocol.

2 Overview

We describe an experiment that was used to validate our method. Three pins were inserted in a cadaver femur having undergone a primary hip replacement operation. The femur was subsequently CT-scanned. It was brought to an operating room and attached to the ISS robot. The robot was calibrated and used to locate the pins. Our calibration rod was then fixed to the robot. A fluoroscope was brought to image the proximal and the distal ends of the femur. For each view, the rod was moved by the robot so as to simulate two planar grids of markers, allowing to calibrate the views. The calibrated views were registered to a surface model of the femur obtained from the preoperative CT, ignoring the pins. Another registration was obtained when supposing that the position of one pin was known, using two different initializations. This registration was compared to the pin-based registration, and found to differ by no more than two millimeters at the pin locations.

The paper is organized as follows. Radiograph acquisition and calibration is explained first. In the same section, we describe our method for extracting profiles of the bone as oriented planar polygons. Using the calibration, these oriented polygons are mapped to beams of nearly parallel 3-D lines. We then describe surface extraction from CT data. Our method copes with unequal spacing of the slices and poor contrast within the slices. Registration is explained in the last section. We use surface apparent contours for fast computation of meaningful correspondences between projection lines and the surface.

3 Previous Work

The following related methods have been investigated by other researchers: Lavallee *et al.* [2] use calibrated video images to register a model of a vertebra to its projections. They build a hierarchical volume that is used to quickly query the closest point from anatomical surfaces to projection lines. They define a negative distance to address the situation of lines intersecting the surface. Lee [3] uses stereo pairs of radiographs to track in real time the position of a patient's skull during radiotherapy delivery. He uses localized bony features segmented from a CT-scan. Feldmar *et al.* [4] register surfaces to projected contours, by defining image to surface correspondences and by minimizing a least squares criterion using iterative methods. The criterion incorporates contour and surface normals. Their method accommodates errors in calibration by allowing optimization of the camera parameters. The calibration of distortion free radiographs was investigated by Brown [5].

With respect to these approaches, our work brings the following contributions: We introduce a novel image calibration technique using an original rod design. The principle of the calibration is that of the two-plane method [6]. Our method is particularly simple, and facilitates automatic feature extraction and identification. Our pose estimation algorithm is new; It uses the surface apparent contours for determining correspondences between lines and surface points. Thus, we can treat the case of lines intersecting the surface. The search for correspondences uses an original algorithm that experimentally performs in constant to logarithmic time. We use a robust method for computing the registration of points to lines. For details, see [7]. Also, inspired from the distal pins used clinically, we exploit the rigid structure of the femur, by collecting images of the knee to perform the registration on the proximal femur. This innovative use of image based registration has the advantage that the anatomy of the knee is generally intact for patients undergoing THR, contrary to the proximal part. Using clinically available data, and comparing with a clinical protocol for registration, our results show a significant step toward the clinical validation of anatomy based registration.

Finally, most of the prior work, with the notable exception of Lee's, uses high quality three dimensional and projection images for experiments, such as high resolution CT scans of dry bones, or simulations of radiographs using video images. Such data are only available in a controlled laboratory test. In contrary, we have used the same data that would be clinically available. The CT slices show soft tissue, present notable artifacts, and are of wide and unequal spacing, to minimize the x-ray dose delivered to the patient. Precise segmentation of such data is a very challenging problem. The fluoroscopic images were obtained with a device widely available clinically, characterized by a narrow field of view, with a maximum of 100 mm, and significant noise and distortion.

4 Radiograph Acquisition and Calibration

In the sequel, we use the term *view* for a collection of radiographs taken in the exact same position of the patient and fluoroscope. By calibration, we mean determination of the perspective camera parameters as well as determination of, and compensation for, the distortion. For fluoroscopic images, it has been shown that the distortion is very significant as well as position dependent, due to the interaction of a magnetic field with the electron beam inside the image intensifier.

The rod used for our validation experiment is made of radiolucent material. It contains metallic spherical beads of 3mm in diameter that are interspaced every centimeter. Each individual sphere is removable, and can be replaced at its exact same location, with an accuracy of one tenth of a millimeter. We used a coordinate measurement device to assess this accuracy of bead placement in comparison with the design.

For each view, we initialize the position of the rod such that we can easily identify the origin marker as well as subsequent markers, and such that the rod appears at the far side of the image. We then alternate between radiograph acquisition and rod translation by a vector perpendicular to the rod axis, as shown in Fig. 1. We repeat the same operation by moving the rod along a second plane that is roughly parallel to the first plane. Finally, we acquire an image without the rod to extract occlusion free anatomical features.

For each of the radiographs where the rod shows, we run an edge detector [8] and select the curves whose shape approximates the circle most closely. Our criterion is very successful: only the markers and the circle marking the field of view are retained, as shown in Fig. 2. This last circle has a considerably larger diameter, approximately ten times larger, than the other circles, and thus can be quickly selected out. We then choose the centroids of the remaining circles as the projections of markers locations.

Each marker is identified with coordinates (u, v) in robot space and (x, y) in image space, as detected with our segmentation algorithm. We use thin plate splines to interpolate the robot coordinates (u_0, v_0), for each calibration plane, of any image point (x_0, y_0) that is not a marker. This yields two positions for each image point, specifying a three dimensional line, which we call *projection line*, as any point along that line would project to the same image pixel.

The thin plate splines compensate for the image distortion. Our experiments show that all computed projection lines are withing a distance of one millimeter from a focal point that can be determined by optimization methods [7]. This is in agreement with the expected extent of the x-ray source. Another experiment performed to assess the accuracy of calibration was to collect an additional image of the rod in arbitrary position and orientation, to localize the markers on the image, to compute the location of projection lines, and to

Figure 1: Radiograph calibration: We show fluoroscopic images of the proximal part of the femur imaged with the calibration rod in two different positions.

compute the distances of these lines to the true marker positions. The distances ranged from .1 to .4 mm.

The advantages of the calibration rod compared with techniques that have been proposed are the following: The rod allows to simulate a calibration grid with all the advantages of the grid, i.e., equal spacing of markers and regular coverage of the images, and none of its inconveniences, i.e., calibration of the grid orientation and error prone detection and identification of the markers. We can simply and automatically identify each visible marker as well as markers that disappear at the image border. The rod is more versatile than a grid, as all of the following choices can be made without a tedious and redundant alteration of the entire grid: individual markers can be removed; the spacing can be doubled or tripled; the origin can be translated. We have practically exploited this versatility and adapted the rod to the available field of view.

In order to extract the profiles of the bone from the radiographs, extending [9], we developed a segmentation tool using a deformable model, attracted with a smoothed image gradient. This tool is interfaced to IBM Data Explorer. A Result is shown in Fig. 3.

5 Segmentation of Bony Anatomy from Computed Tomography Data

We extract a surface model from the CT-scan using a semiautomatic method. In our test CT scan, the slice spacing varies widely, from 1 to 3 to 6 and finally to 120 mm. Such a variation can be expected in practice, to maximize the detail in the critical areas while limiting the x-ray dosage. We rapidly ruled out isosurface algorithms for surface extraction since they suffered from poor contour definition at the slice level and poor surface tiling in between contours.

Instead we developed the following algorithm: For each slice, we use a deformable model to detect the contour of the bone, as was previously done for radiographs. The result is shown in Fig. 3. Contours are approximated to within .1 to .3 millimeters and are tiled together in an optimal fashion, such that the average triangle *compactness*, similar to the area to perimeter ratio, is maximum. This optimum triangulation can be obtained using dynamic programming, and is thus affordable. The resulting surface is an oriented manifold with (typically two) boundaries.

The contours forming the surface as well as their level of detail

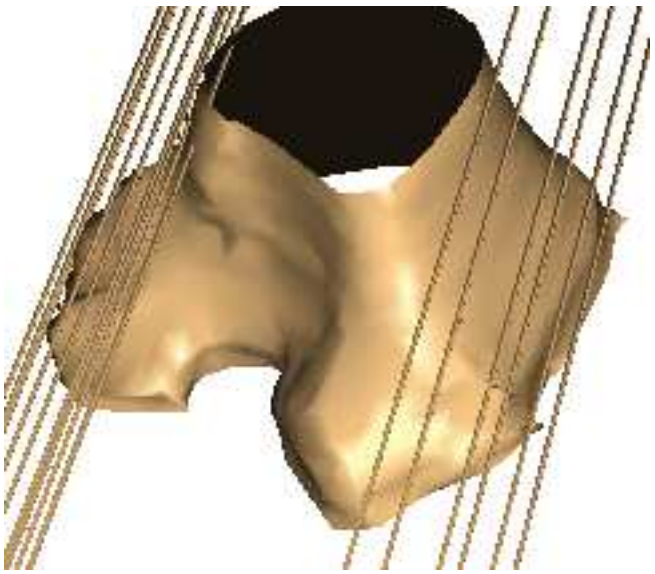

Figure 6: Detail of the distal femur after registration.

are gathered in a script file, that completely determines the surface. The script file can be easily edited for experimenting various levels of details, or adding or omitting particular slices.

The resulting surface was then approximated with a tolerance of .3 mm using a published method [10]. We show the final surface in Fig. 4. Note that both proximal and distal regions are incomplete and that there is a gap of 120 mm between two slices situated distally. The final surface contains 3460 triangles, which is very compact.

6 Registration of Computed Tomography Data with Radiographs

The principle underlying the method is to iterate on the following operations: Determine for each projection line a correspondent on the surface. Using the robust algorithm presented in [7] to determine the rotation and translation that minimizes the sum of distances from

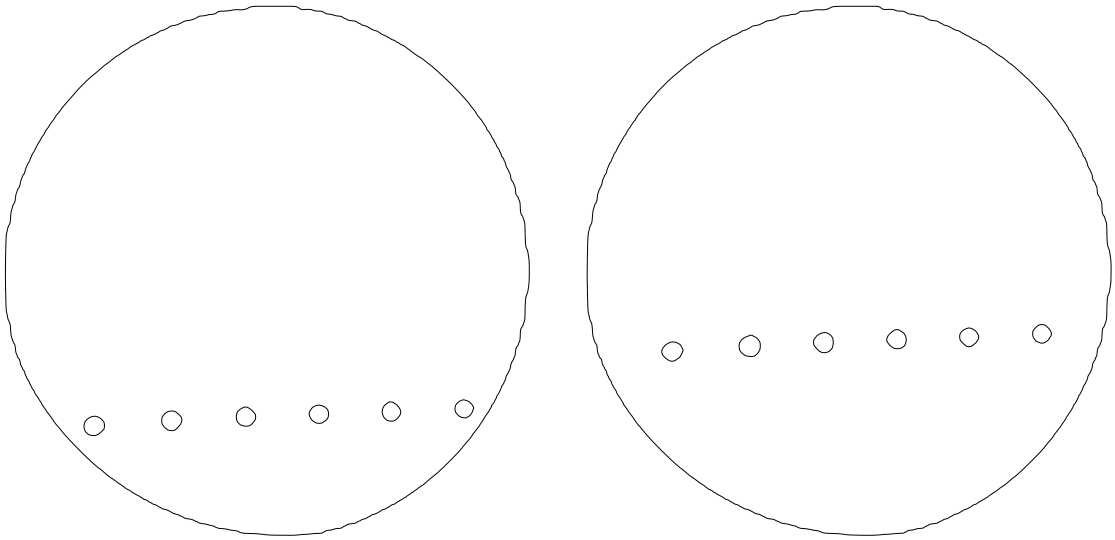

Figure 2: Automatic segmentation of circular shapes in the images of Fig.1. Automatic labelling of the markers is easily achieved

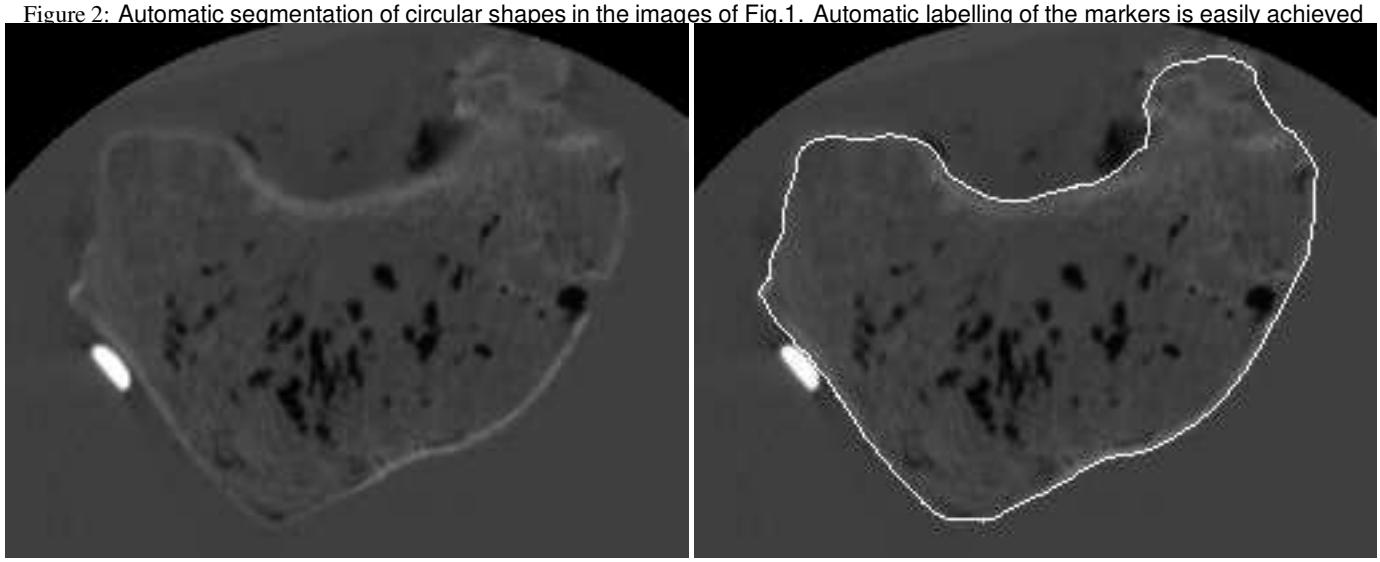

Figure 3: CT segmentation: A slice of the distal femur with artifacts and poor contrast (Left) was segmented yielding a closed outline (Right).

the lines to their point correspondents on the surface, and apply the transformation obtained to the surface. The method can use one or more views. In our experiments, we have used two views.

As observed in [4], a variation of this algorithm, that chooses new correspondents only if their distance to the line is smaller than the current distance, can be easily proven to be convergent. However, such an algorithm might not be optimal, as there are some situations when distances must increase to step out of a local minimum.

One difficulty when defining the distance of a line to a surface is to treat the case of a line intersecting the surface in potentially many locations. Any such intersection could be automatically flagged as a closest surface point to the line, with a zero distance. Ideally, after registration the lines should be tangent to the surface rather than intersecting it. We propose to use the surface apparent contours, which are defined as the boundaries between visible and invisible surface triangles, whereby a visible triangle is such that a ray cast from the focal point of the lines to the triangle centroid will make an obtuse angle with the triangle normal direction. The apparent contours project onto the surface profile in the radiograph, and can be constructed as a set of closed, oriented, non-planar polygonal curves. For their construction, our algorithm uses the surface orientation. The focal point of the lines was determined during calibration. Our data structure encodes the connectivity of the contours and serves to easily prune the shortest ones considered as noise.

Line to surface correspondences are searched for on the apparent contour only. For each projection line, we compute the closest point on the apparent contour using a hierarchical decomposition of the contours. Benchmarks indicate that this method can compute a closest point with a constant or logarithmic complexity in terms of the number of vertices of the polygons, even after incorporating the preprocessing time. The worst case, obtained for particular input lines and polygonal curves, is a linear complexity, which is the complexity of linear probing.

We can constrain the pose estimation such that the transformed location of one point, the remaining pin, is fixed, yielding a rotation only. The difference with the algorithm presented in [7] is that we optimize solely the parameters of the rotation, which is less expensive.

The complete registration executed in less than 6 seconds on a RS6000 Model 58K workstation. This timing incorporates the preparation of graphics files shown in Figs. 5 and 6. When fixing

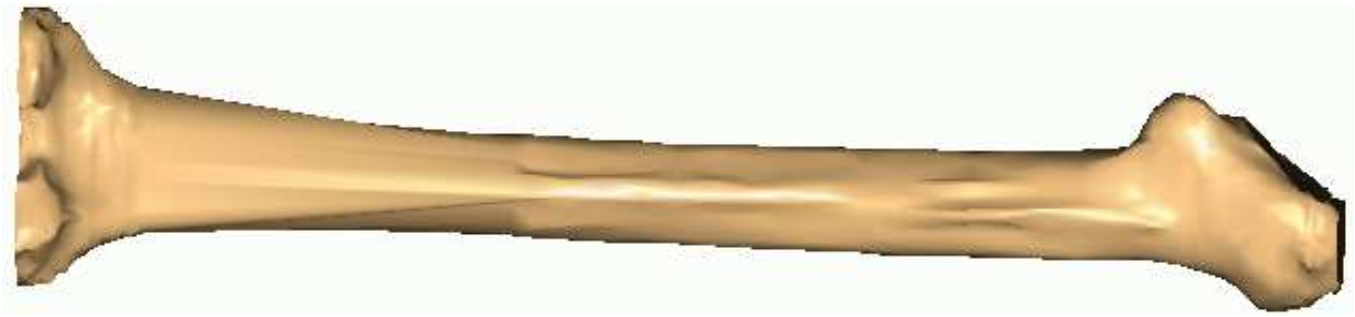

Figure 4: Surface model obtained after optimal

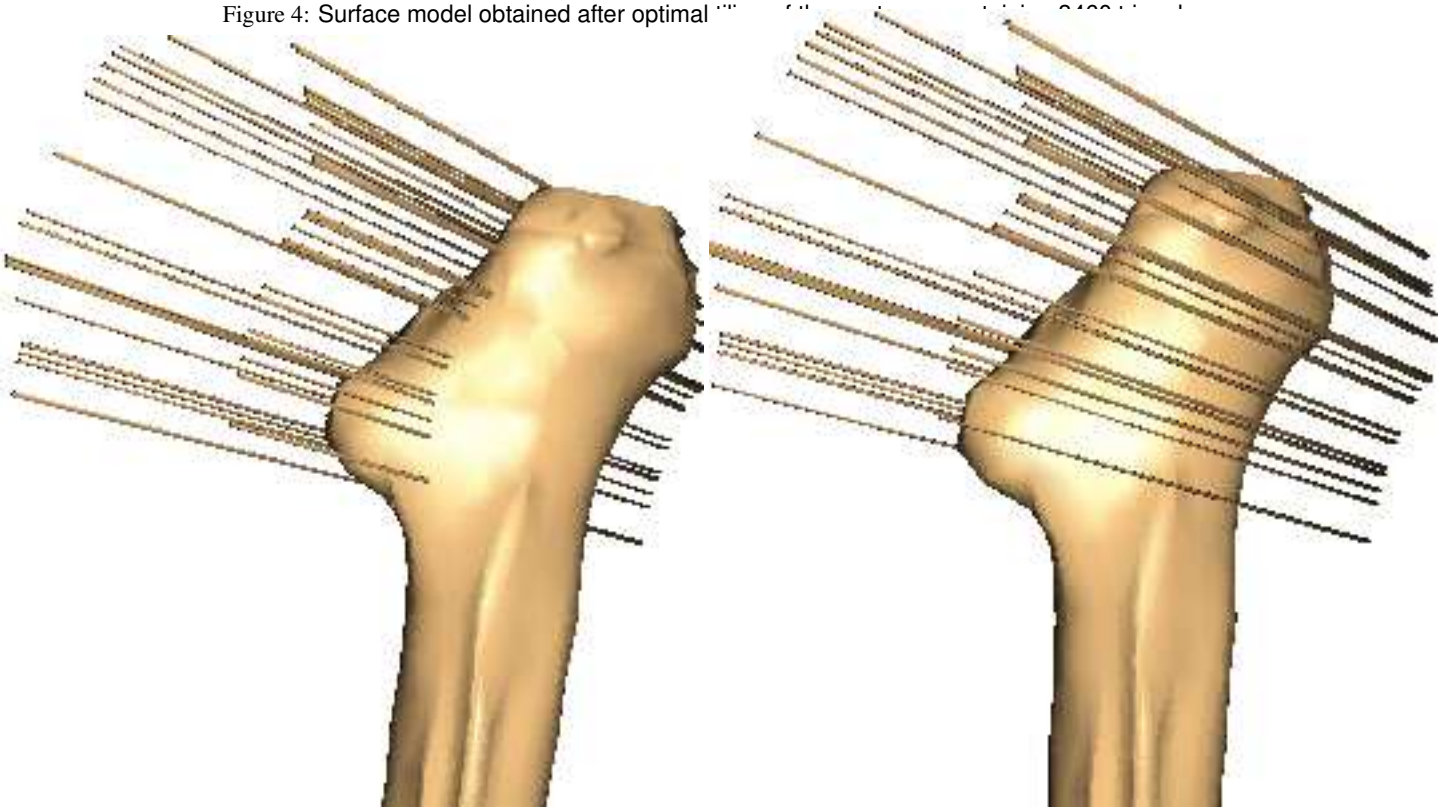

Figure 5: Registration lines-surface: Detail of the proximal part before and after registration.

the location of the proximal pin, we measured errors of 1.70 and 2.36 mm respectively at the two distal pins, starting with two different initial positions of the surface.

7 Conclusion

In robot assisted hip replacement surgery, the current registration procedure starts by implanting three metallic fiducial "pins" in the patient's femur during a first operation. We have described a new method that allows comparable accuracy with a single pin, using two fluoroscopic views of the bone for registration. We might be able to eliminate the remaining pin by using more fluoroscopic views or acquiring more computed tomography data, or acquiring CT data with more contrast.

REFERENCES

[1] P. Kazanzides, B.D. Mittelstadt, B.L. Musits, W.L. Bargar, J.F. Zuhars, B. Williamson, P.W. Cain, and E.J. Carbone. An integrated system for cementless hip replacement. *IEEE Engineering in Medicine and Biology Magazine*, 14(3), 1995.

[2] S. Lavallee, R. Szeliski, and L. Brunie. Matching 3-D smooth surfaces with their 2-D projections using 3-D distance maps. In *Geometric Methods in Computer Vision*, volume 1570, pages 322–336, San Diego, July 1991. SPIE.

[3] B. Lee. *Stereo Matching of Skull Landmarks*. PhD thesis, Stanford University, 1991.

[4] Feldmar J., Ayache N., and Betting F. 3D-2D projective registration of free-form curves and surfaces. Technical Report 2434, INRIA, Sophia-Antipolis, France, 1994.

[5] Lisa M. Brown. Registration of planar film radiographs with computed tomography. In *Mathematical Methods in Biomedical Image Analysis*, pages 42–51, San Francisco, CA, June 1996. IEEE.

[6] H. A. Martins, J. R. Birk, and R.B. Kelley. Camera models based on data from two calibration planes. *Computer Graphics and Image Processing*, 17:173–180, 1981.

[7] A.P. Guéziec and J. Funda. Evaluating the registration of 3D points to 3D lines with application to the pose estimation in a projective image. submitted to CVRMEDII-MRCASIII.

[8] IBM Healthcare Management Solutions HomePage. Anatomy based registration of medical images. www.research.ibm.com/hc/REGISTER/register.html.

[9] Michael Kass, Andrew Witkin, and Demetri Terzopoulos. Snakes: Active contour models. In *International Conference on Computer Vision*, pages 259–268, London, June 1987. IEEE.

[10] André P. Guéziec. Surface simplification with variable tolerance. In *MRCASII*, pages 132–139, Baltimore, MD, November 1995.