ROBOT ASSISTED REGISTRATION FOR TOTAL KNEE REPLACEMENT

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ABSTRACT

Objective: Registration is a critical step, which links the planning and execution phases of most CAS applications. In this procedure the geometric relationships between the patient's anatomy, the models used for planning and the robotic or sensorized tools employed intrasurgically, are calculated. The registration scheme described in this paper, based on enhanced ICP algorithm, doesn't need any marker implant, thus reducing surgical invasiveness. Points on the bone surface are sampled by the robot which in turn, directs the surgical tool, thus eliminates additional coordinate transformation and increases operation accuracy.

Materials and Methods: The registration technique was tested on an RSPR six degrees-of-freedom parallel robot specifically designed for medical applications. The six axis force sensor attached to the robot's moving platform, enables fast and accurate acquisition of positions and bone surface normals at sampled points.

Results: Sampling with a robot probe was shown to be accurate, fast and easy to perform. The robot alone does most of the registration work, leaving surgeon's hands free. The whole procedure takes about 4 minutes.

Conclusions: The simplicity and accuracy of the proposed registration appears to be sufficient for orthopaedic surgical applications. Robotic registration makes the flawless connection between the preoperative planning and robotic assistance during surgery.

Key words: registration, ICP algorithm, robotic probing, total knee replacement, parallel robot, robot – assisted surgery.

Key links: http://robotics.technion.ac.il/projects/registration.html

Introduction

Since the implementation of joint replacements, the knee has been a popular joint for this procedure because of the high incidence of degenerative disease and problems of malalignment. However, failure rates, for a variety of reasons, have continued to be a concern. In total Knee Arthoplasty (TKA) the distal femoral and proximal tibial compartments are resected and replaced with two prosthetic components. Inaccurate surgical planning and/or execution is the primary reason for a failure. Moreover, prosthesis misalignments of a few degrees/millimeters can seriously affect the post-surgical functionality of the operated limb [10]. About 200,000 cases are performed annually in the US. Progress in implant design and surgical technique led to success rates close to 85% [4]. A robotic assistant integrated with computer controlling system can help carry out procedures with higher accuracy than can be achieved with the free human hand. In orthopedic procedure such as TKA, a robotic assistant can guide the surgeon’s tools along the preoperative planned paths to assure accurate positioning of an implant.

Successful implementation of CAS protocols generally require a coherent integration of spatial data relative to a broad variety of imaging, sensing and actuating devices, each with its own coordinate system. That is why an accurate calculation of the geometric relationship existing between relevant reference frames, which is normally referred to as *registration*, plays a crucial role in almost all CAS applications [10].

Orthopaedic surgery is an ideal field of application for registration-dependent procedures since millimetric accuracies are often required to assure good results. Moreover, bones can be considered as rigid bodies, so that the coordinate transformation to be calculated is equivalent to a rigid transformation between two different views of the same object. Registration sets a link between the pre-surgical planning stage and the actual surgical phase.

The first high accuracy registration protocols employed artificial markers (fiducials), which need to be implanted, before constructing the image. The fiducials are both identifiable in the images on which the preoperative model is based and accessible intrasurgically by means of a digitizer. Registration is then generally performed through fast and robust point-to-point matching algorithms [9]. Following a widespread trend toward a reduction of surgical invasiveness, intensive investigation on non-fiducial registration techniques is currently in progress [10], [13], [14]. All the efforts are focused on avoiding the need for external marker implant. The problem is often stated in terms of matching of spatial data sets embedded in the relevant frames. Non-fiducial registration techniques generally exploit the geometric characteristics of such data sets in order to find a correlation between the two.

These techniques all use some modifications of *iterative closest point* (ICP) algorithm [2],[17] which provides a simple approach to the solution of the matching problem of two point sets, one of the model and one of the intraoperative scan. The model is composed by points extracted from the preoperative CT images, while the data include the points aquired intrasurgically with some sort of a digitizer. The main disadvantage of these techniques is that they require large number of sampling points to obtain sufficient accuracy, mostly because the high influence of the initial transformation guess. One attempt to solve this problem was, by introducing a preparatory phase called *preregistration* [10], where 3-5 coarse anatomical landmarks are defined on the relevant surface. Intraoperatively, the surgeon first digitizes corresponding points on the patient’s anatomy trying to be as accurate as possible. Once collected, the points are matched with the preoperative ones to get the preliminary estimates of the transformation between the frames.

The other disadvantage is that the digitizer itself is not part of the surgery and adds another reference frame between the bone and the robot. The digitizers such as : precision mechanical digitizer (FARO Arm B06, FARO Tech. Inc., Lake Mary, FL, USA) [10], optical tracking camera e.g. (Northern Digital OPTOTRACK) [7],[11] and laser scanner. Each of these types introduces additional internal error, which influences the overall accuracy of the following surgical procedure.

The system presented in this investigation incorporates features from all the above techniques, whereas the robot itself plays the role of a digitizer. Moreover, the 6-axis force sensor, attached to the robot plate for sampling, gives additional feature information - extracting the normal to the bone at each sampling point. Using the points with their normals requires fewer points to sample because the information is multiplied. The sampling is performed directly by the robot and its attached coordinate system, considerably increases system accuracy, because the robot itself, in turn, guides the surgical tools during surgery. Furthermore, the system doesn't require any additional high cost equipment, such as navigator, for registration.

Materials and methods

The system for the registration consists of a computer system and a surgical robot with attached force sensor and a probe. The robot, force sensor and the bone are shown in Figure 1.

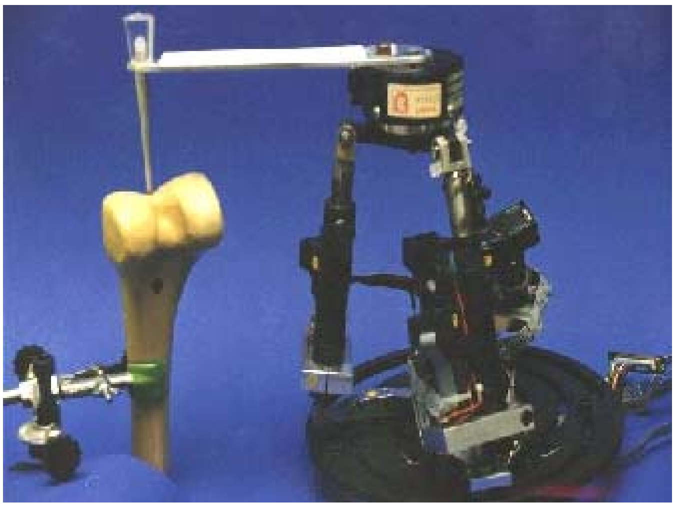

Figure. 1. The robot used for registration.

We use an RSPR six degrees-of-freedom parallel robot introduced in [12] that was developed in the robotic laboratory at the Technion. Parallel robots have several advantages over common serial robots; high payload-to-weight ratio, higher precision and compact size; limited work volume, which provides additional safety factor in medical applications. Also they have smaller inertia which is important for sampling procedure.

The JR[3] universal force-moment sensor, together with the sampling probe, are attached to the moving platform of the robot. We assume that intraoperatively the friction between the probe-attached sphere and the bone in is negligible. Therefore, at each point of contact with the bone we have the coordinates of the contact point and its normal direction.

Any other tools can be easily attached to the robot's moving platform after the registration, so the same robot can in turn, perform the surgical operations.

Registration protocol and algorithm

The registration protocol is based on the ICP algorithm [2][17], which minimizes the distance measured between two point sets. Our addition to the ICP algorithm is the use of normals to the surface at the sampled points.

The ICP algorithm

Suppose that we have two independently derived sets of 3-D points, which corresponds to a single shape. We will call one of these sets the *model* set M and the other the *data* set D. Assume that for each point in the data set, the corresponding point in the model set is known. The problem is to find a 3-D transformation which when applied to the data set D, minimizes a distance measure between the two point sets. The goal of this problem can be stated more formally as follows:

$$\min_{R,T} \sum_i \left\| M_i - \left(\mathbf{R} D_i + \mathbf{T} \right) \right\|^2$$

(1)

where **R** is a 3x3-rotation matrix, **T** is a 3x1-translation vector, and the subscript *i* refer to corresponding elements of the sets *M* and *D* as shown on Figure 2(a). Efficient, non-iterative solutions to this problem, both employing quaternions, were presented in [5],[16].

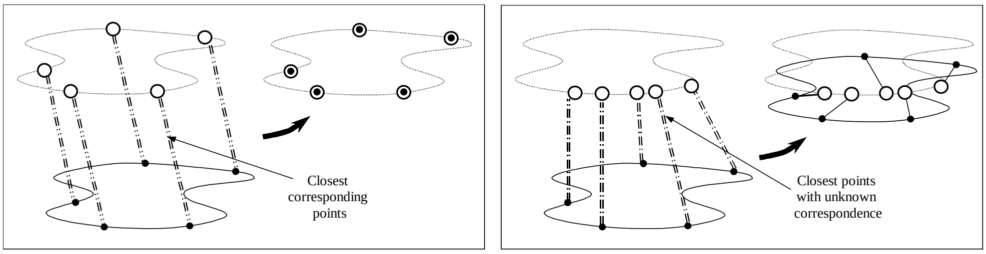

Fig. 2. (a) Corresponding Points Set Registration. (b) Closest Point Set Registration

The general 3-D shape registration problem that we address here, however, differs from the corresponding point set registration problem in three important regards. First, the point correspondence, which was assumed to be known in the above problem, is unknown in the general case. Second, since the data may not lie exactly on the model because of the sampling error, it is not necessarily equivalent to the model. Third, general 3-D shapes to be registered are not necessarily represented as point sets [2].

Suppose that we are again given two sets *M* and *D* corresponding to a single shape, where *D* is a set of 3-D points and *M* is a triangular faceted surface. Assume that the correspondence between points in the two sets is initially unknown. As seen in Figure 2(b), for each point D_i from the set *D*, there exists at least one point on the surface of *M* which is closer to D_i than all other points in *M*. This is the *closest point*, M_i. Figure 2(b).

The basic idea behind the ICP algorithm is that under certain conditions, the point correspondence provided by sets of closest points is a reasonable approximation to the true point correspondence. Besl and McKay [2] proved that if the process of finding closest point sets and then solving (1) is repeated, the solution is guaranteed to converge to a *local* minimum.

Even though the ICP algorithm must converge monotonically to a local minimum from any given rotation and translation of the data point set, it may or may not converge to the desired global minimum. How well the algorithm performs is a function of the initial pose estimate and the characteristics of the shape being registered.

Instead of trying all possible initial guesses, we use the preparatory***???*** phase called *preregistration* introduced in [10] and used in [7]. 3-5 points are preoperatively selected on the model of each involved bone, taking into account accessibility during surgery, identifability of anatomical structures and maximization of the 3-dimensionality of point arrangement – this being highest when the points are located at the vertices of a regular tetrahedron and lowest when they are coplanar [7]. At the beginning of the intrasurgical data collection phase, the selected points are displayed in sequence on a 3-D view of the bone model and the surgeon brings the robot probe close to the shown point, then the robot takes one sample. While the robot is in tracking mode and follows the force exerted on the probe, the surgeon just draws the robot probe to the shown area. The surgeon then leaves the probe and gives the robot order to sample. There is no strong requirement for these points to be extremely exact, the sampling must be just in the area of the predefined point, and it used only for initial condition guess.

After the preregistration points are sampled, the initial condition to the algorithm is well established, the bone approximate location is known. Then the robot continues sampling alone, another 5 or more points based on the required accuracy. The whole procedure takes about 3-4 minutes. After the registration is finished, the bone is shown on the computer screen at a registered position relative to the robot. The results may be verified by assigning a robot to touch some test points on the bone.

Experiments and Results

Experiments with the surgical robot constructed at the robotic laboratory at the Technion were performed on a plastic model of a femoral bone. The model was scanned on a Cyberware 3-D laser scanner, building a regular mesh 152x133, Figure 3.

Figure 3. Sampled bone surface

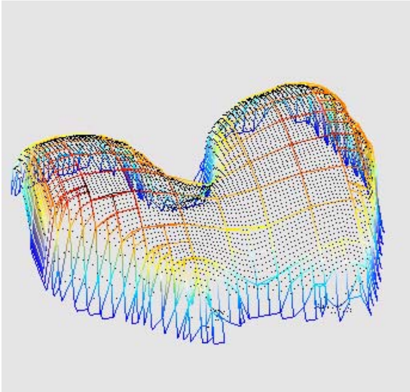

Figure 4. Created multiresolution model of a bone.

Four points were selected on the model and used for preregistration, Figure 4.

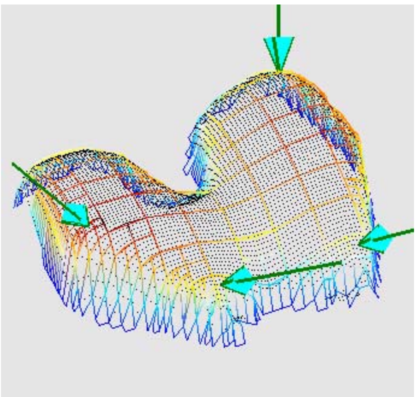

Figure 4. Selecting preregistration points.

These points are well identified on the model since they where selected by different features on the bone surface. Usually, there will be enough number of such feature points on a pathological bone.

After the preregistration step, the bone position relative to the robot is well established and the robot can continue the registration alone. It samples automatically another 5 points on the bone surface. The bone model together with the robot is then shown on the screen, in the registered position, Figure 5.

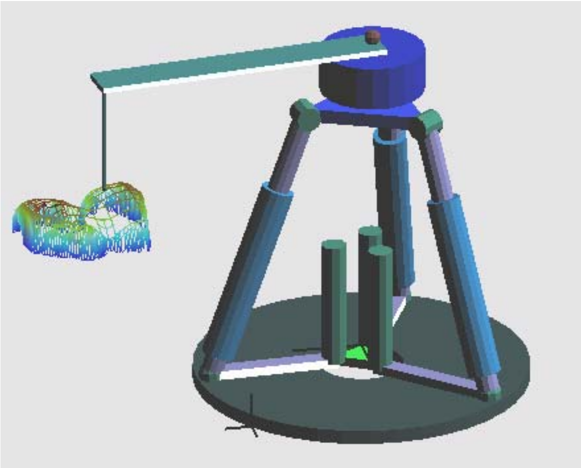

Figure 5. Robot and the bone relative to each other.

To test the accuracy of the results, the robot is required to touch in sequence the predefined marked points.

Conclusion

The registration proposed in this investigation requires only small surgeon interaction to approximately indicate 3-4 coarse anatomical landmarks; the rest is performed automatically by the robot. Performance examinations of the algorithm indicate that the coarse landmarks can be located by the surgeon to within ±1cm of the accurate position, which leaves a good safety zone for error due to soft tissue obstruction of landmarks or the difficulty in locating landmarks on the smooth anatomical surfaces.

The proposed method doesn’t require any high cost digitization hardware; it uses the same robot for registration that performs also the surgical procedure.

Future work is concentrated on finding the number and position of points to be sampled to get the best registration accuracy.

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