Multimodal Correlation and Intraoperative Matching of Virtual Models in Neurosurgery

N95- 15976

Enrico CERESOLE, Michele DAL SASSO and Aldo ROSSI
DIMEG - Department of Innovation in Mechanics and Management
University of Padova
Via Venezia 1 - 35131 Padova - ITALY
Phone: ++39(49)8286820   Fax:++39(49)8286816
e-mail: gaspare@hpdimeg.unipd.it

ABSTRACT

The multimodal correlation between different diagnostic exams, the intraoperative calibration of pointing tools and the correlation of patient's virtual models with the patient himself, are some examples, taken from the biomedical field, of a unique problem: determine the relationship linking representation of the same object in different reference frames. Several methods have been developed in order to determine this relationship, among them, the surface matching method is the one that gives the patient minimum discomfort and the errors occurring are compatible with the required precision. The surface matching method has been successfully applied to the multimodal correlation of diagnostic exams such as CT, MR, PET and SPECT. Algorithms for automatic segmentation of diagnostic images have been developed to extract the reference surfaces from the diagnostic exams, whereas the surface of the patient skull has been monitored, in our approach, by means of a laser sensor mounted on the end effector of an industrial robot. An integrated system for virtual planning and real time execution of surgical operation, that is described in this paper, has been realized at the Department of Mechanical Innovation and Management of the University of Padova, Italy, in cooperation with the Neurosurgical Division of the Hospital of Treviso, Italy.

1. INTRODUCTION

In recent years, systems for surgical planning and intraoperative assistance have been widely used. In these systems a CT or MR exam is used to reconstruct a virtual model of the anatomies of interest. Dedicated software programs allow the surgeon to simulate on the virtual model the approach strategies, to determine and study the target points, the trajectories, etc. Several of these systems allow the correlation among different diagnostic exams. To correlate different diagnostic exams it is necessary to compute the transformation matrix between the reference frames associated to each diagnostic modality. A classical example of it in the neurosurgical field is the stereotactic head frame. Several types of localizers, mounted on the base ring of the head frame, fixed to the patient's skull, produce artifacts in the diagnostic images. Localization of the artifacts in the images allow to calculate the coordinates of each voxel of the scanned volume with respect to the head frame. In this way a correlation can be found, between a diagnostic image and the stereotactic system. Using different types of localizers, this correlation can be established between each diagnostic modality and the stereotactic reference frame, and consequently among the diverse diagnostic exams. In more recent years, newer correlation methods based on artifacts produced by fiducial markers fixed to the patient's skin or implanted in the bone were developed. The data gotten from the planning stage can be used during surgery only if a registration method is found, correlating the reference frame of the "real" patient with one of the diagnostic exams. Such a registration is implicitly achieved if a stereotactic head frame is used, while if fiducial markers are employed it is necessary to use a three-dimensional digitizer to determine the position of the fiducial markers in the real world. A correlation matrix can be computed by surface matching only if equivalent reference surfaces can be extracted from different diagnostic exams. Among all the surfaces, the CT is taken as a reference, because it is characterized by very low distortion. The same procedure can be applied to intraoperative matching, determining, by means of suitable sensors, the real surface to be correlated to the CT. In this paper methods for image acquisition and processing for multimodal correlation and intraoperative matching by means of surface matching techniques are described. These methods are general enough to be applied to the calibration and adjusting of robots in other fields than the neurosurgery.

2. MULTIMODAL IMAGING

The features of each diagnostic exam are due to different physical quantities that are sampled. For instance, the CT provides a great deal of information on the bone tissues, but its spectrum is very narrow for soft tissues (about 100 Hounsfield numbers out of 2001). On the other side, MR images show soft tissues very efficiently, but bones are not visible. Blood vessels are usually detected using Digital Angiographs. Even the most expert radiologist would find hard to mentally correlate the information gotten from all these

most expert radiologist would find hard to mentally correlate the information gotten from all these diagnostic exams. For this reason our research was aimed at finding a non invasive method, which could guarantee high reconstruction precision, easy to be implemented and general enough to be applied to different anatomical districts and different diagnostic modalities.Our work started off using fiducial markers fixed to the patient's skin and visible in all diagnostic exams; in this case the correlation between the different modalities was calculated on the basis of the position of the markers in the various reference frames. Algorithms for 3D-3D and 2D-3D correlation were developed and tested. Then, the surface matching was introduced as a method to minimize the transformation errors. Such a hybrid approach (surface matching + fiducial markers) revealed itself adequate for diagnostic purposes, and can be effectively used also for intraoperative matching.

3. INTRAOPERATIVE MATCHING AND ASSISTED EXECUTION

The virtual model of the patient is used by the surgeon to define the targets, the approach directions and more generally the surgical tasks to execute thru the robotized system. The system is made of an ASEA IRB2000 industrial robot on which a laser system for distance measurement (by Microepsilon) has been mounted, a robotic simulation software (Robcad, by Tecnomatix), and a three-dimensional digitizer (Surgicom by Faro Tech.). The digitizer is a six d.o.f. passive arm connected to a UNIX workstation thru a serial interface box. The operating room is thoroughly modeled in the robotic simulation environment. The environment is totally structured except the volume occupied by the patient and by the mobile medical devices associated to him. To guarantee the patient's safety, once he has been fastened to the operating bed thru a Mayfield (Ohio Instr.) head holder, the position of the fiducial markers on the patient's skull is determined by means of the three-dimensional digitizer.

Figure 1- Registration of the fiducial markers.

The coordinates of the fiducial markers are transformed from the digitizer's reference frame into the robot's reference frame by means of a transformation matrix which was computed during the cell definition procedure. In fact, the cell has been defined a priori localizing all object inside it, including the digitizer, with respect to the robot's reference frame. This allows to define a bounding security volume that may never be entered by the robot and the instruments associated to it. Moreover, in order to avoid interference between the robot and the devices inside the operating cell, all movements the robot is to make for the registration procedure are simulated before execution. The data of the patient's reference surface are gotten by means of a laser sensor installed on the robot's end effector. This acquisition procedure is firstly simulated utilizing the virtual surface extracted from the diagnostic images as a reference, so that the laser beam is kept perpendicular to the surface itself. Then, during the measurement procedure in the real world, the direction of the laser beam is adjusted on the basis of the previous measurements. Therefore, the measurement procedure in the real world does not correspond exactly to the simulated one, but there are minor differences in the robot's end effector positioning.During the simulation stage, the direction of the first approach to the patient, to begin the measurement scanning, is defined. Knowing then the position of the fiducial markers, computed using the digitizer, an approximated transformation between the patient's and the robot's reference frame can be found. This function is used to limit the number of iterations of the surface matching algorithm, avoid the problem of local minima and overcome the ambiguities due to the symmetry of the skull.
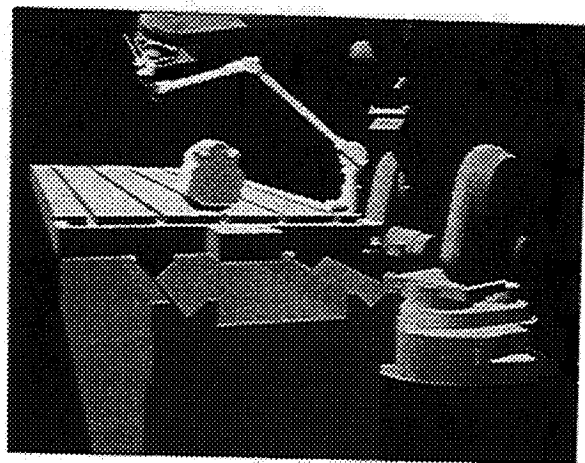

Figure 2 - The operating cell model with the 3D-digitizer, the robot and the CT surface during the registration procedure.

The surface matching algorithm computes the patient-robot transformation minimizing the distance between the reference surface extracted from the diagnostic images and the real surface measured by means of the

laser sensor. This matrix is then used to transform into the robot's reference frame al the geometric entities defined in the planning stage with respect to the CT reference frame. In this way the real operating cell is completely described in the simulation environment, where the patient, the target points, the trajectories, etc. are defined. Thus, the robot's movement to execute the planned tasks can be simulated and the simulation sequence is shown to the surgeon on a monitor located in the operating room; if the sequence is correct, the execution stage can be started.The transformation matrix is exact as long as the patient is not moved by any surgical procedure executed on him. Should this happen, it is necessary to recalibrate the system using three reference points located on the head holder, which is assumed to be fixed with respect to the patient's head. In this case too, the approximate position of the calibration points is measured using the three-dimensional digitizer so that the laser sensor can be positioned near them.

4. PROCEDURE FOR MEASUREMENT OF THE REAL SURFACE

In this work a technique for measuring the real surface of the patient's skull for intraoperative matching has been developed, which utilizes a laser sensor and a 6 d.o.f. industrial robot.The laser sensor uses a triangularization method allowing to measure its distance from a surface characterized by a diffuse reflection. The precision of the measurement is independent from the type of material constituting the surface. Furthermore, the system is totally non invasive for the patient.
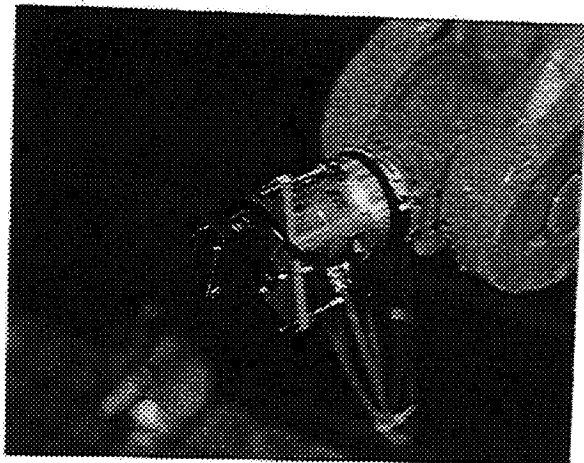

Figure 3 - The laser sensor mounted on the robot's end effector.

The sensor is characterized by a midrange distance about which there is a displacement range where the output signal vs. distance characteristic can be considered linear.The sensor is a Micro-Epsilon opto NCDT series 1605-100 whose main characteristics are:
Midrange   220 mm
Displacement range   ± 50 mm

Non-linearity   300 mm
The sensor guarantees accurate readings if the measured surface presents a ± 15°angle with an axis of the sensor and ± 30°with an axis perpendicular to the former. This limit makes necessary to orient the sensor during the measurement of curve surfaces to guarantee as much as possible that the laser beam be perpendicular to the surface in the measurement point.Since the skull's surface does not have a defined shape, it is necessary to introduce a measurement procedure that adjusts the direction of the laser beam on the basis of the previous readings. Thus, the sensor has been mounted on the robot's end effector: in this way the sensor can be positioned and oriented in whatsoever direction in the whereabouts of the skull. This guarantees a repeatability of ± 0.1 mm and a precision of ± 0.1 mm. As it has been described above, the measurement procedure starts with a coarse calibration of the robot with respect to the skull in order to define the workspace.When the patient has been positioned on the operating bed, the approximate position of the skull is determined by reading the fiducial markers with the three-dimensional digitizer. This provides an approximate transformation matrix that allows to begin correctly and safely the measurement procedure.A midrange surface is generated in the virtual model of the skull; this surface has an average offset equal to the sensor's midrange. The midrange surface must be external to the bounding security volume, that is the volume that may not be entered by the robot.Then, the robot positions itself in that point of the midrange surface which corresponds approximately to the top of the skull, with a direction perpendicular to the modeled surface. Thus, the first measurements with a fair precision can be made, allowing a self calibration of the system, that will be now described. Three readings are made on the vertices of an equilateral triangle, described on the midrange surface in the whereabouts of the point that has been determined on the top of the skull. These three readings allow to calculate the normal to the real surface in the center of the same triangle. The measurement sequence proceeds with a series of points located along a spiral on the surface. At each further step the reading direction is determined on the basis of the last three measured points. These three points are chosen in such a way to guarantee a good approximation in the determination of the local normal. However, the reading procedure is not critical because the skull's surface is regular enough. The result of the measurement is a set of points describing the patient's head surface in the robot's reference system.

5. CONCLUSION

Surface matching is a suitable non-invasive registration method for multimodal correlation and intraoperative matching. It guarantee, with the minimum discomfort for the patient, registration errors compatible with the required precision. It can be successful applied to multimodal correlation of diagnostic exams in which reference surfaces can be extracted thru interactive

segmentation programs. The same surfaces can be used for the intraoperative matching by means of a laser sensor mounted on the end effector of an industrial robot for the "real surface" detection.

REFERENCES

[1] S. Bodice, R. Caracciolo, M. Giovagnoni, A. Rossi, "An On-Line Adjusting System for Assembly Robots", Proc. of the Second International Symposium on Measurement and Control in Robotics, Tsukuba Science City, Japan, November 1992.

[2] N. T. S. Evans, "Combining Imaging Techniques", Clin. Physiol. Meas., vol. 11, Suppl. A, pagg. 97-102, 1990.

[3] R. Dann et al., "Evaluation of Elastic Matching System for Anatomic (CT, MR) and Functional (PET) Cerebral Images", Journal of Computer Assisted Tomography, 13(4): pagg. 603-611, July/August 1989.

[4] P. T. Fox, J. S. Perlmutter, and M. E. Raichle, " A Stereotactic Method of Anatomical Localization for Positron Emission Tomography", Journal of Computer Assisted Tomography, n.1, January/February 1985, Raven Press, New York.

[5] T. M. Peters, J. A. Clark, et al., "Integrated Stereotaxic Imaging with CT, MR Imaging, and Digital Subtraction Angiography", Radiology, 1986; 161: 821-826.

[6] D. J. Hawkes, D. L. G. Hill, et al.,"Preliminary Work on Interpretation of SPECT Images with the Aid of Registered MR Images and MR Derived 3D Neuro-anatomical Atlas", NATO ASI Series, Vol. F60, 3D Imaging in Medicine, 1990, Edited by K.H.Hohne et al.

[7] B. J. Erickson and C. R. Jack, "Correlation of Single Photon Emission CT with MR Image Data Using Fiduciary Markers", AJNR 14:713-720, May/June 1993.

[8] P. Clarysse, D. Gibon et al., "A Computer-Assisted System for 3-D Frameless Localization in stereotaxic MRI", IEEE Transactions on Medical Imaging, vol.10, n.4, December 1991.

[9] D. N. Levin, "MR and PET data merge in 3-D images of brain", Diagnostic Imaging International, 28:33, January/February 1990.

[10] C. A. Pelizzari, G. T. Y. Chen et al., "Accurate Three-Dimensional Registration of CT, PET, and/or MR Images of the brain", Journal of Computer Assisted Tomography, 13(1): 20-26, January/ February, 1989 Raven Press, Ltd., New York.

[11] C. A. Pelizzari, G. T. Y. Chen, "Image Correlation Techniques in Radiation Therapy Treatment Planning", Computerized Medical Imaging and Graphics, vol. 13, n. 3, 235:240, 1989, Printed in the U.S.A.

[12] B. L. Holman, R. E. Zimmerman et al., "Computer-Assisted Superimposition of Magnetic Resonance and High-Resolution Technetium-99m-HMPAO and Thallium-201 SPECT Images of the Brain", The Journal of Nuclear Medicine, vol.32, n.8, August 1991.

[13] D. N. Levin, C. A. Pelizzari et al., "Retrospective Geometric Correlation of MR, CT, and PET Images", Radiology 1988; 169: 817-823.

[14] W. Zhao and T. Y. Young, "A new approach to three-dimensional reconstruction with application to autoradiographic images", Computers in Medicine, vol. 13, n. 3, 1991.

[15] S. Lavallée, P. Cinquin et al., "IGOR: Image Guided Operating Robot. Metodology, medical applications, results", Innov. Tech. Biol. Med.,vol.13, No 4,1992.

[16] D. Glauser, P. Flury, "Conception of a Robot Dedicated to Neurosurgical Operations", Proc. of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 1991.