Registration graphs: a diagramming and analysis tool for registration in computer-assisted surgery
Jon Lea and Michael Peshkin
13th International Congress on Computer Assisted Radiology and Surgery (CARS '99), ed. H. Lemke, Paris, 23-26 Ju

Registration graphs: a diagramming and analysis tool for registration in computer-assisted surgery

Jon Lea* and Michael Peshkin

Mechanical Engineering Department, Northwestern University,
2145 Sheridan Road, Evanston, IL 60208 USA

We introduce the *registration graph*, which is a visual diagram of the method by which registration of a computer-assisted surgery system is accomplished. The registration graph is useful as a unambiguous qualitative descriptive tool, and also may be used to drive a quantitative error analysis. Both uses are illustrated in this paper.

1. INTRODUCTION

Computer-assisted surgical systems must bring diagnostic images, surgical plans, patient anatomy, surgical tools, robot coordinate systems, and other components into accurate alignment with one another. Diverse registration procedures have been devised, each unique due to the characteristics of the hardware used and the demands of the surgery to be performed. The variety of registration methods makes it difficult to verbally communicate the finer points of any particular registration strategy, and the numerous registration steps typically complicate attempts at rigorous analysis.

A method for diagramming registration strategies makes descriptions straightforward and simplifies analysis. We have developed a notation which uses a graph theoretic framework and can be used to illustrate the architecture of a registration strategy as well as perform a rudimentary error analysis.

2. THE REGISTRATION GRAPH

Many graphical techniques were tested during the development of the registration graph. The only representation we found satisfactory melded the visual techniques of data flow diagrams [1] and Petri nets [2] with the spatial transformation networks commonly used in robotics and computer graphics [3].

* Now with Surgical Insights, Inc., 1840 Oak Avenue, Evanston, IL 60201 USA
This work was supported by Whitaker Foundation Grant RG-94-0436.
The authors can be contacted via e-mail at jonlea@surgicalinsights.com and peshkin@nwu.edu.

Registration graphs as a descriptive tool may be drawn by hand; it is not necessarily a computer-based technique. However for quantitative analysis we have implemented registration graphs as a C++ library and graphical (Microsoft Windows® 95/98/NT) program. The C++ library is simple and efficient, and may be extended easily by programmers. The graphical program provides a means to interactively explore and design a registration strategy via a registration graph.

2.1. Drawing the graph

The registration graph consists of two primary elements: *features* (shown as circles), representing objects or parts of objects; and *links* (shown as lines), representing measurement actions (See Figure 1). Features are grouped logically within *rigid bodies*. Links connect any two features, and are classified as one of two types: *direct* links (shown solid) representing an actual measurement, and *induced* links (shown dashed) representing a measurement derived from a connected subgraph of other links.

Links contain temporal validity markers, called *event tags*, which prescribe the lifespan of the link measurement. These are shown as a number/letter combination, where the number signifies the "time period" when the link becomes valid. A letter *t* denotes that the link is *transient*, that is, valid only for its initial time period, whereas a letter *s* indicates the link's validity is *sustained* throughout subsequent time periods.

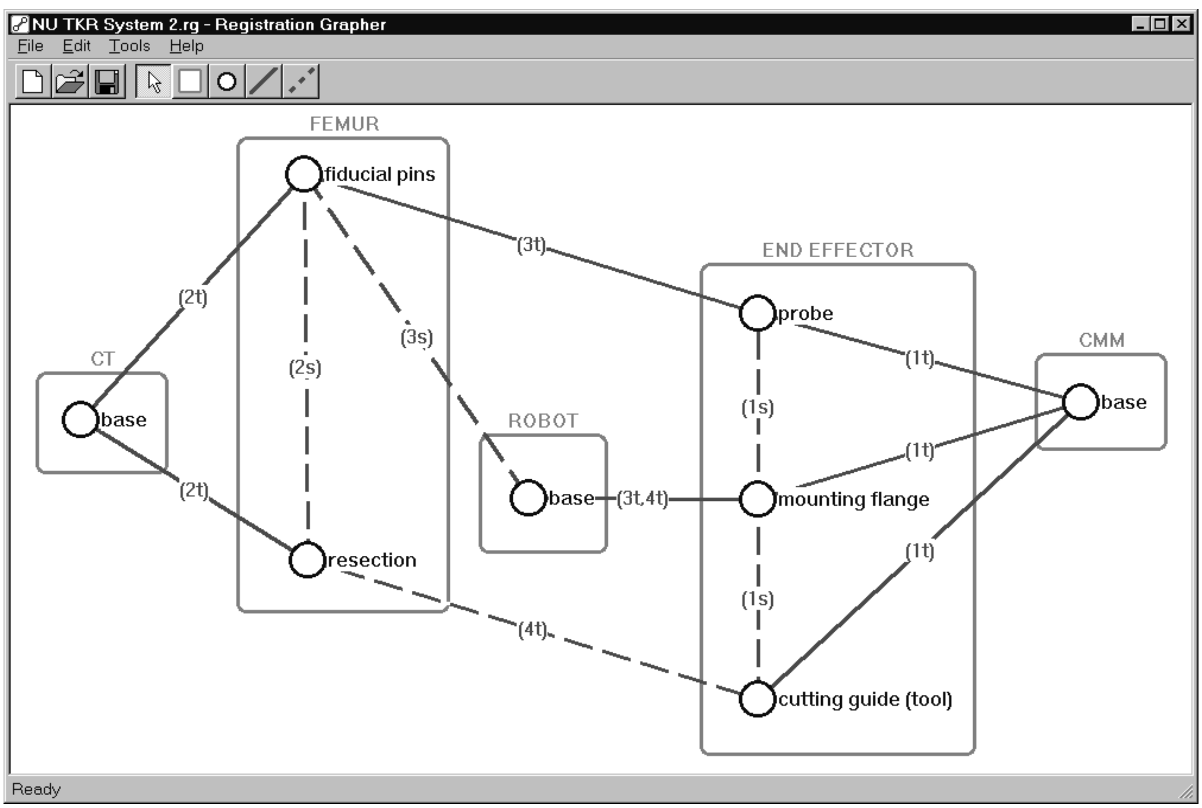

Figure 1. Registration graph of the Northwestern University CT/robotic system.

An induced link's viability is tested by a set of rules governing event tag "summation" and traversal of the link's subgraph. If all links of a subgraph are not co-valid, the induced link is flagged as impassable. In this manner, the feasibility of registration between, for instance, a patient's bone and a surgical tool through both direct and induced links can be determined.

2.2. Computing errors

To provide quantitative as well as qualitative analysis of a registration strategy, a model for propagating measurement uncertainties through links is incorporated into the registration graph. Many techniques exist, notably geometric uncertainties of Taylor [4] and the more common statistical uncertainties. Using the second technique, links then represent the first and second statistical moments - mean and covariance - of a measurement. Direct links intrinsically contain this information since they represent actual measurements. Induced links derive these quantities from the connected subgraph of links that validates the induced link. Computation of an induced link's mean and covariance requires that its subgraph be reduced to a single equivalent mean and covariance.

The methods of Smith and Cheeseman [5] for combining means and covariances both in serial (for links connected end to end) and in parallel (for two links sharing the same start and end features) are used to accomplish this reduction. While the governing equations are rather complex, it is interesting to note that the reduction of a network of covariances behaves similarly to equivalent resistance reduction in electrical circuit theory; covariances combined in serial result in a larger covariance, whereas two covariances combined in parallel result in a covariance smaller than either original covariance.

3. AN EXAMPLE - THE NORTHWESTERN TKR SYSTEM

The registration strategy of a robotic/CT computer-assisted surgery system for total knee replacement [6] is shown in Figure 1. This system bears many similarities to other works, notably the RoboDoc system for hip arthroplasty [7] and a system for knee arthroplasty developed at Rizzoli Institutes [8].

3.1. Modeling of the surgery system

The registration graph in Figure 1 can be interpreted as being made up of subgraphs corresponding to three distinct phases: using the coordinate measuring machine (CMM) to measure features of the end effector (right side of graph); using computed tomography (CT) to scan the patient's femur and preoperatively plan the placement of resections (left side of graph), and finally, the intraoperative execution of the surgical plan using a robot (middle of graph).

The means and variances of the direct links are assigned values that represent the setup of the system in practice. The mean values are not discussed here but can be found in [9]. A brief synopsis of the assumed variances is

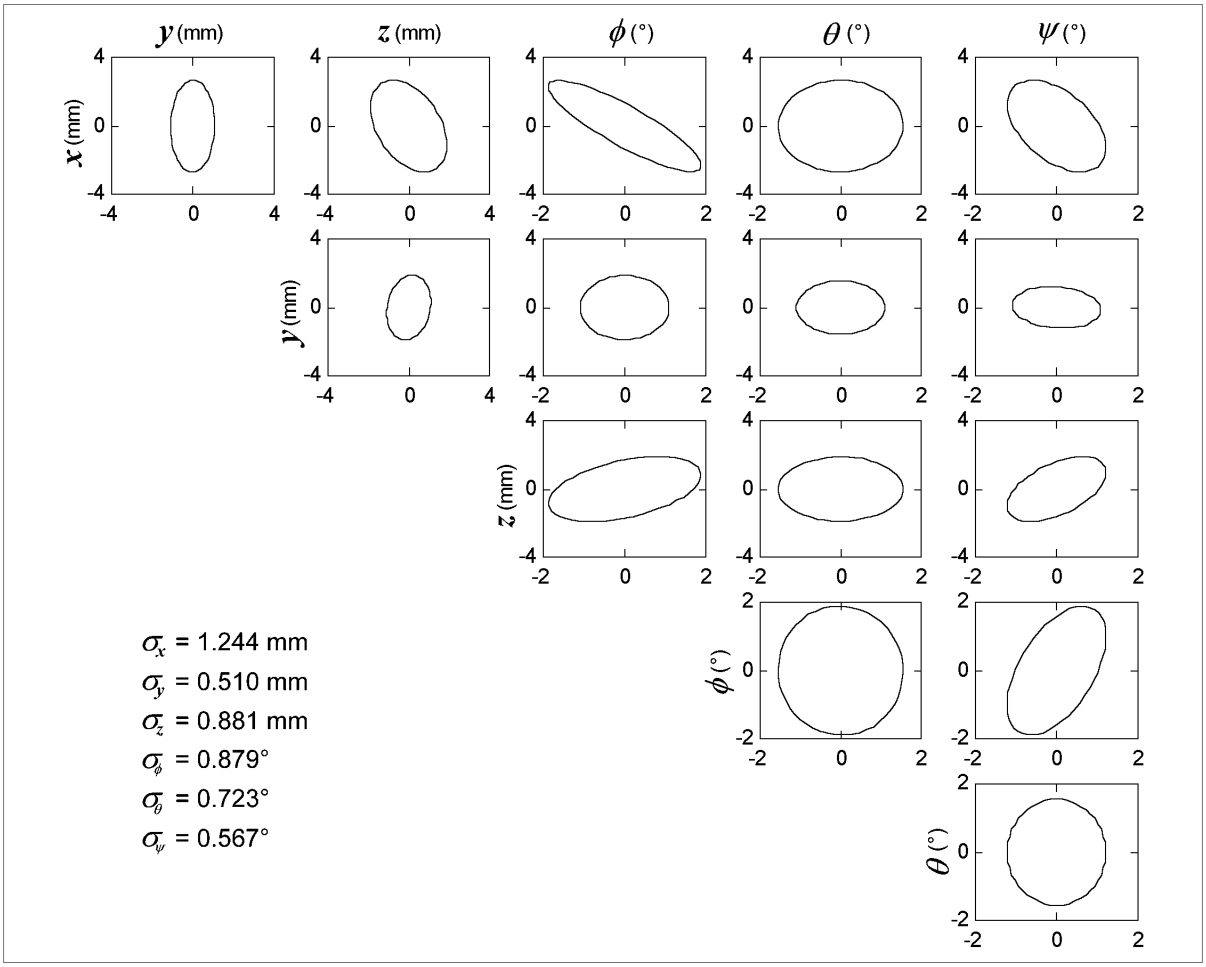

Figure 2. Error ellipses for the final registration link - [FEMUR : resection] to [END EFFECTOR : cutting guide] - of the registration graph in Figure 1.

illustrative: the CMM is accurate within 0.1 mm and 0.1°, scanning the patient is accurate within 0.25 mm and 0.15°, 0.15°, 0.25° about the x, y, and z axes (differences in angular variances are due to the coordinate frame assignment method), the robot is accurate within 0.25 mm, 0.5°, and the [END EFFECTOR : probe] to [FEMUR : fiducial pins] operation is accurate within 0.1 mm and 0.1°.

3.2. Interpretation of errors

Figure 2 lists the standard deviations (square roots of the variances) and shows the covariance ellipses for the final registration link - [FEMUR : resection] to [END EFFECTOR : cutting guide]. Although all direct links in the graph contain only independent variances (i.e., covariances are zero), the combined variances of this induced link's subgraph yield significant covariances, whose degree of cross-dependence is indicated by the angular slant of the error ellipses. The results also show that the registration graph analysis is consistent with the registration accuracies observed in practice (approximately ±1.0 mm, ±1.0°).

4. CONCLUSION

The registration graph is an effective tool for understanding current registration methods as well as investigating new ones. It proves to be useful for analyzing the accuracy of a computer-assisted surgery system, and is complementary to detailed analysis of registration algorithms [10][11] used to correlate image data with anatomy intraoperatively.

The library and graphical program as well as further documentation are available online at the website of the Laboratory for Intelligent Mechanical Systems, http://lims.mech.nwu.edu.

REFERENCES

1. T. DeMarco. *Structured Analysis and System Specification*. Yourdon, Inc., New York, NY, 1979.
2. F. Dicesare, et al. *Practice of Petri Nets in Manufacturing*. Chapman & Hall, London, 1993.
3. R. P. Paul. *Robot Manipulators: Mathematics, Programming and Control*. MIT Press, Cambridge, Mass., 1981.
4. R. H. Taylor, V. T. Rajan. 'The Efficient Computation of Uncertainty Spaces for Sensor-based Robot Planning.' Research Report RC 13998 (#62814), IBM Research Division, 1988.
5. R. Smith, P. Cheeseman. 'On the Representation and Estimation of Spatial Uncertainty.' *International Journal of Robotics Research*, 5(4): 56-68, 1986.
6. T. C. Kienzle III, et al. 'A Computer-Assisted Total Knee Replacement Surgical System Using a Calibrated Robot.' *Computer Assisted Surgery*, R. H. Taylor, S. Lavallée, G. Burdea, R. Mösges, eds., MIT Press, Cambridge, Mass., 1995.
7. R. H. Taylor, et al. 'An Image-Directed Robotic System for Precise Orthopaedic Surgery.' *IEEE Transactions on Robotics and Automation*, 10(3):261-275.
8. M. Fadda, et al. 'Computer-Assisted Knee Arthroplasty at Rizzoli Institutes.' *Proceedings of the First International Symposium on Medical Robotics and Computer Assisted Surgery*, 26-30, Pittsburgh, PA, September, 1994.
9. J. Lea. 'Registration Graphs: A Language for Modeling and Analyzing Registration in Image-Guided Surgery.' Doctoral dissertation, Northwestern University, December, 1998.
10. D. A. Simon, et al. 'Techniques for Fast and Accurate Intrasurgical Registration.' *Journal of Image Guided Surgery*, 1:17-29, 1995.
11. W. E. L. Grimson, et al. 'Evaluating and Validating an Automated Registration System for Enhanced Reality Visualization in Surgery.' *Proceedings of the First International Conference, CVRMed '95*, n. Ayache (ed.), Springer-Verlag, Nice, France, April, 1995.