Redundant Consistency Checking in a Precise Surgical Robot

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Abstract

Over the past several years, we have developed an image directed robotic system for orthopaedic bone machining applications, aimed initially at cementless total hip replacements in dogs needing such surgery. The fact that our application anticipates a robot moving a tool in contact with a patient has motivated us to implement a number of redundant consistency checking mechanisms. This paper outlines the requirements defined by the veterinary surgeon who will use the system. It provides a brief description of our approach to implementing them and concludes with a few remarks about our experience so far and possible extensions of our work.

Introduction

The precision of image-based pre-surgical planning often greatly exceeds that surgical execution. Typically, precise surgical execution has been limited to procedures (such as brain biopsies) for which a suitable stereotactic frame is available. The inconvenience and restricted applicability of these devices has led many researchers to explore the use of robots to augment a surgeon's ability to perform geometrically precise tasks planned from computed tomography (CT) or other image data (e.g., [1], [2][3] , [4]).

Safety is an obvious consideration whenever a moving device such as a robot is used around a live patient. In many applications (e.g., [1][2]), the robot does not need to move during the "in-contact" part of the procedure. The robot moves a passive tool guide or holder to the desired position and orientation relative to the patient, brakes are set, and motor power is turned off while a surgeon provides whatever motive force is needed for the surgical instruments. Other surgical applications (e.g., [5]) rely on instrumented passive devices to provide feedback to the surgeon on where his instruments are relative to his image-based surgical plan.

We have developed an image-directed robotic system to augment the performance of human surgeons in precise bone machining procedures in orthopaedic surgery, with cementless total hip replacement surgery as an initial application. The present-generation system is suitable for veterinary use and is targeted at clinical trials on dogs needing hip implants. The total system consists of an interactive CT-based presurgical planning component and a surgical system consisting of a robot, redundant motion monitoring, and man-machine interface components. In-vitro experiments conducted with this system have demonstrated an order-of-magnitude improvement in implant fit and placement accuracy, compared to standard manual preparation techniques [4]. Since our applications inherently require computer controlled motion of the robot's end-effector while it is in contact with the patient, we have incorporated additional redundant consistency checks into the system architecture.

This paper describes some of the more important of these mechanisms in greater detail and concludes with a brief discussion of possible extensions.

Requirements

The principal requirements were defined by one of the authors (Dr. Paul) who is the veterinary surgeon who will use the system. They are (1) that the robot should not "run away"; (2) that it should not exert excessive force on the patient; (3) that its cutter should stay within a pre-specified positional envelope relative to the volume being cut; and (4) that the surgeon should be able to intervene at any time to stop the robot. Once robot motion is stopped, he should be able to query the robot's status, to manually guide it, to select an appropriate recovery procedure to continue the surgery, or to completely terminate use of the robot and continue manually.

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Implementation

Robot Controller

The robot controller routinely performs many safety and consistency checks, including such standard features as position and velocity error limits in the joint servos, monitoring of external signals, and a safety timeout monitor which turns off arm power if the controller does not affirmatively verify system integrity every 16 ms. In addition to a basic power-enable relay (external to the controller), controller software provides facilities for disabling manipulator power, for "freezing" motion, for resuming interrupted motions, and for transferring control to user-written recovery procedures.

A large number of conditions (externally signalled consistency checks, force thresholds, pushbutton closures, and the like) interrupt the application program and cause motion to be frozen or (occasionally) power to be dropped. Menus on a gas-sterilized, hand held pendant then permit the surgeon to interrogate system status, to select local actions (such as manual guiding or withdrawal of the cutting tool), to continue the present motion, to discontinue or repeat the present step of the procedure, or to restart at some earlier phase altogether. One very common case is a simple "pause" to allow the surgeon to satisfy himself that all is well or to perform some housekeeping function like refilling an irrigation bottle.

Force Monitor

The microprocessor interface to a wrist-mounted force sensor computes forces and torques resolved at the cutter tip. If any tip force component greater than about 1.5 kgf is detected, the controller is signalled to freeze motion. Forces greater than about 3 kgf cause arm power to be dropped. Experiments in which the a sudden large motion is commanded in the middle of cutting confirm that these checks are quite effective in detecting many "run away" conditions. They are also effective in detecting such conditions as the cutter stalling or hanging up in improperly excised soft tissue.

Motion Monitoring Subsystem

We rely on a separate PC/AT with special input-output hardware to provide an independent check that the cutter tip stays within a defined volume relative to the bone. This is done by checking (a) that the bone does not move relative to the fixator, which is rigidly affixed to the robot base and (b) that the end effector never strays from a defined volume in space.

Bone motion will be sensed by strain gauge sensors attached to the fixator and bone. The mechanical parts are still being fabricated as part of the "final" bone fixator. Experiments with bench versions demonstrated that motions on the order of 0.1mm are easily detectable. Furthermore, experiments with earlier fixators, have indicated that even rather large forces (5 kgf) have produced only a few microns of motion, which would be negligible in the context of this application.

Tracking of the robot's end effector is performed by a Northern Digital Optotrak system, which tracks LED beacons to accuracies of 0.1 mm or better over a 1 meter cube. We fabricated a rigid PC card with eight such beacons and affixed it to the robot's wrist, as shown in Figure 2 Northern Digital-supplied software is used to compute a coordinate system from the beacon locations. The robot-to-camera and cutter-to-beacon transformations were computed by ordinary least squares from data taken with the robot in various known positions, using appropriate linearized models. Constructive solid geometry (CSG) tree "check volumes" corresponding to implant and cutter selection were constructed from primitives bounded by quadric surfaces located a defined distance (now, 1 mm) outside the furthest nominal excursions of the cutter. During surgery, the PC/AT reads the beacon plate coordinates from the Optotrak and computes the cutter location. If this location is outside the check volume, it signals a "out-of-bounds" condition through an optically isolated digital port to the robot controller, which freezes motion and then obtains more detailed information through a serial port.

Although a full characterization study is still to be done, preliminary experiments have demonstrated that the this system can reliably detect when a motion crossed a threshold to about 0.2 mm precision with constant orientation, and about 0.4 mm with cutter reorientation. Checking rates of approximately 3-4 hz are obtained. At typical cutter feed rates, the total excursion before motion is frozen is about 2-2.5 mm, after all latencies are accounted for. This number could be reduced by using faster computers and making certain modifications in the controller software. However, in the hip surgery application, a single aberrant motion (cutting a gouge in a bone) is more readily repairable than an undetected systematic error. We are consequently considering further tightening the tolerance threshold of the checking volumes.

Status and Possible Extensions

Except for bone motion detection, the mechanisms above have all been implemented and integrated with the prototype surgical system. During in-vitro rehearsals on cadaver bone, the most common "error" condition detected has been an excessive cutting force causing a motion "freeze" when the cutter encounters unusually hard bone. Continuation from this condition is almost always easily achieved by backing off 1-2 mm and retrying, and experiments are underway to determine the optimal feed-rate to avoid this condition. A longer term solution will be to implement an adaptive cutting strategy.

We have also been considering a number of possible measures both to reduce the robot's top speed and acceleration and to further increase the redundancy of checking. The former might be accomplished either by mechanical modifications to the manipulator or by electrical limits on motor voltage or current. The latter would include incorporation of redundant position and velocity encoders, which would be monitored by a separate computer, preferably electrically isolated from the robot controller. If an out-of-tolerance or out-of-control condition was detected, this computer would take appropriate action, such as raising a "freeze" signal or turning off power.

In conclusion, the fact that our application anticipates a robot moving a tool in contact with a patient has motivated us to implement a number of redundant consistency checking mechanisms. We believe that this is an important subject even in applications involving less active motions. It is one that will merit considerable attention as robotic devices become increasingly common in operating rooms.

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References

[1] Y. S. Kwoh, J. Hou, E. Jonckheere, and S. Hayati, "A Robot with Improved Absolute Positioning Accuracy for CT Guided Stereotactic Surgery," *IEEE Transactions on Biomedical Engineering*, pp. 153-161, February 1988.

[2] P. Cinquin, S. Levalle, and J. Demongeot, "Computer Assisted Medical Interventions," *Proc. Second Workshop on Medical and Health Care Robots*, pp. 91-101, Newcastle-on-Tyne, Sept. 1989.

[3] R. H. Taylor, H. A. Paul, Brent D. Mittelstadt, et al, "Robotic Total Hip Replacement Surgery in Dogs," *Proc. 11'th IEEE Medicine & Biology Conf.*, pp. 887-892, Seattle, 1989.

[4] Russell H. Taylor, Howard. A. Paul, Brent D. Mittelstadt, William Hanson, Peter Kazanzides, Joel F. Zuhors, Edward Glassman, Bela L. Musits, William L. Bargar, and William Williamson, "An Image-based Robotic System for Precise Orthopaedic Surgery," *Proc. 12'th IEEE Medicine & Biology Conf.*, Phila.: (submitted), 1990.

[5] Y. Kosugi, E. Watanabe, J. Goto, T. Watanabe, S. Yoshimoto, K. Takakura, and J. Ikebe, "An Articulated Neurosurgical Navigation System Using MRI and CT Images," *IEEE Transactions on Biomedical Engineering*, pp. 147-152, February 1988.

Figures

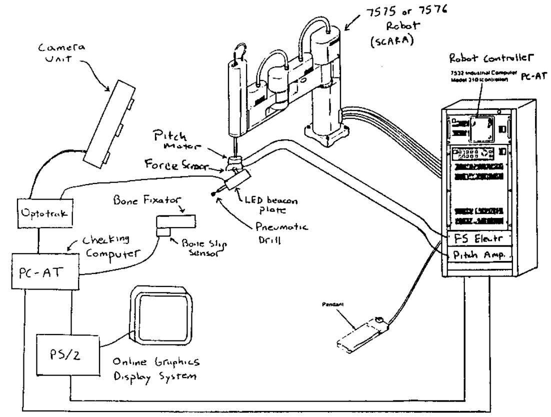

Figure 1: System Architecture

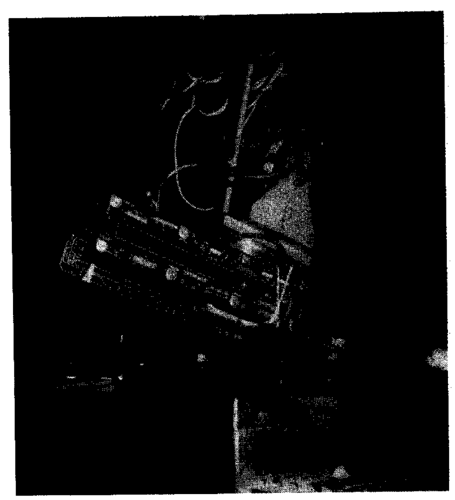

Figure 2: Robot's wrist, showing LED beacon plate and force sensor