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Abstract

Steady Hand cooperative manipulation is a hands-on approach that integrates seamlessly in the surgical practice. In steady hand manipulation, the tool is held simultaneously by the user and the robot and the robot complies to forces applied by the user. Steady hand manipulation promises significant improvements in safety, accuracy over conventional practice at minimal cost and training to the user. It also offers a way around the difficult problem of encoding human intelligence, and preserves the benefits from experience and training.

We explore the possibility of encoding/utilizing task descriptions to improve transparency and performance of a steady hand manipulation task. This is done by constructing state space representations of the task. The user's interaction with the robot, tool-tissue interactions, and other sensory and planning inputs can be used to identify the task state and modify the behavior of the robot by using using optimized task and control parameters. Validation experiments for several cooperative tasks with and without augmentation are presented.

Advisor:

Dr. Russell H. Taylor,

Professor, Department of Computer Science

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

As robotic augmentation of surgical tasks role becomes common, its role is being compared with the role of automation in manufacturing. Just as automation helped improve efficiency, lower costs, and improve product quality in manufacturing, augmentation of surgery is predicted to reduce trauma, cost, time, and improve outcomes. This integration of technology is likely to lead to procedures being safer, more widely available, and to introduce new surgical procedures. These modern tools will also provide avenues for quick post-operative evaluation of each procedure, and statistical and comparative analysis of procedures by processing the data generated. Apart from providing better interfaces for training and evaluation of students, this will also allow iterative improvement (process learning), and quality management in surgical procedures.

The realization of this vision will require introduction of augmentation devices and systems in the operating room. These devices will integrate manipulation elements (e.g. active robots, passive braking systems, and other navigational aids), sensing elements (e.g. imagers, localizers and trackers), and visualization devices (e.g. displays, and projectors). They will provide high precision minimally invasive manipulation capability guided by multi-modality sensing and visualization. As the "intelligence" in these devices increases, they are likely to assume roles (what has been termed a "surgical assistant" [Taylor, 1999]) played by humans today.

However, as human integration of dexterity, perception, experience and judgment is currently irreplaceable these highly integrated systems are likely to be preceded by simpler systems performing only some functions. These devices are becoming common now. Robots are being used increasingly to improve accuracy, provide minimally invasive access, and as navigational aids. Examples of these systems include ROBODOC^{TM}([Paul *et al.*, 1992] [Taylor *et al.*, 1996, Taylor *et al.*, 1994]), NEUROMATE^{TM}(Integrated Surgical Systems, CA), MRT Robot (Brigham and Women's Hospital), JHU Steady Hand robot [Taylor *et al.*, 1999a]), JHU RCM/PAKY robot modules [Stoianovici *et al.*, 1998], JHU/IBM LARS System [Taylor *et al.*, 1996], Zeus^{TM}System (Computer Motion Inc, CA), da Vinci^{TM}(Intuitive Surgical Inc, CA), and PINPOINT^{TM}arm (Picker Gmbh.). They represent the next generation of surgical tools, and are not replacements for surgeons.

1.1 Surgical and Interventional Robotics

Robotic assistants are an attractive means of extending human capabilities and removing natural limitations. These limitations are most visible in fine, or dexterous manipulation tasks. Fine manipulation tasks involve high precision micrometer-level positioning accuracy, but only small ranges of manipulation forces and even smaller tool tip forces. Typically, these tasks will be performed by a human operator looking through a microscope while grasping a handle on the instrument or tool being used to perform the task. Performance of these tasks such as microsurgery is seriously affected by the limitations imposed by physical attributes of the sensory motor, muscular and skeletal systems on manual dexterity, precision and perception. These limitations affect the ability to hold an object steady (figure 1.1), the precision and smoothness with which a motion may be made and the scale of forces and textures which may be discerned [Gupta *et al.*, 1999, Cleeves & Findley, 1989, Bolles & Paul, 1973]. Natural factors such as physiologic tremor which occurs in all normal, active muscle, and drift (voluntary hunting and seeking motion of instruments about the desired point)

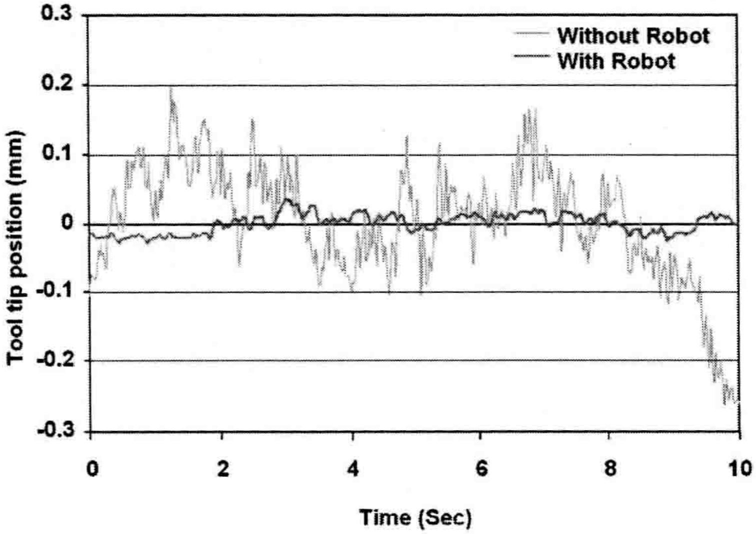

Figure 1.1: Tremor reduction by a cooperative paradigm. A common microsurgical tool is held by a user, and by a user and the steady hand robot together. Tremor is significantly reduced even though no filtering is used.

are some of the factors in establishing these limitations. Tremor further increases with stress, anxiety and following physical exertion. Robotic systems are inherently unaffected by these factors.

Most prior work on robotic micro-manipulation systems has emphasized traditional master-slave [Charles *et al.*, 1989, Hunter *et al.*, 1993] and tele-robotic manipulation [Jensen *et al.*, 1997]. These systems consist of two separate subsystems, a master manipulator at the task site, and a slave manipulator removed from the task site. The slave robot tries to faithfully reproduce the actions of the master, often scaled to suit the application. Combinations of position/velocity/force control are used depending upon the requirements of the task. Bilateral control approaches have also been explored.

The alternative, hand held or steady-hand[Taylor *et al.*, 1999a] manipulation, is a hands-on approach. In steady hand manipulation, the tool is held jointly by human user and the robot. The robot is equipped with a sensor for user interaction and moves in compliance to user forces. It still acts a slave to user motions but because the user is manipulating the robot as he would the tool, there is no scaling of motion. The sensory input driving the motion can be scaled appropriately instead. Various position/velocity/force based controllers can be used depending upon the task requirements.

There are advantages and drawbacks of both approaches discussed above. The advantages of teleoperation approach include a better, more comfortable operating field for the surgeon, and scaling of sensory information, motion commands. The disadvantages include cost and complexity involved due to two manipulators, loss of kinesthetics and changes to existing practice, extra training etc.

The advocates of steady hand manipulation approach cite the simplicity, closeness to conventional procedures and therefore ease of use, reduced cost (due to a single manipulator), and improved kinesthetics among the advantages. The drawbacks include lack of ability to scale motion, and lack of remote operation.

For micro-manipulation, the benefits of steady hand far outweigh the disadvantages. The drawbacks are certainly important abilities but they are not crucial (or even not applicable) in micromanipulation tasks. Further, in applications like microsurgery, surgeon acceptance is crucial and approaches that do not require a complete re-engineering of the surgical workstation are much easier to introduce into practice.

1.2 Supervisory Control

In both approaches discussed above, the operator has direct control of the manipulator and its motion. This is desired, since autonomy of a robot is often seen as reducing safety by surgeons (e.g. What if the patient sneezes?). However, there are actions in any augmented task that are better performed by robots alone, or by robots under limited guidance from the user. This calls for a hybrid system, where the human maintains overall control, and monitors the execution of some portions of the task performed by the robot autonomously.

The degree of autonomy given to the robotic system can be dynamic and decided by the human expert. This paradigm is referred to as supervisory control by Sheridan [Sheridan, 1988, Sheridan, 1998] and can form the basis of augmenting surgery. He describes supervisory control to mean one or more human operators setting initial conditions for, intermittently adjusting, and receiving information from a computer that itself closes a control loop in a well defined process through artificial sensor and effectors.

How does a supervisory control framework deal with augmented surgical tasks? Surgical tasks impose stringent requirements on an augmentation system. Goals for designing a good system include:

- Safety: includes identification of critical portions of the controlled task, ability to identify and/or correct faults, and redundancy to some extent. In medical procedures, the criticality of the task puts safety as the most important design consideration.

- Stability: performance meeting specifications over time, state/condition and over the range of inputs possible

- Efficacy/Accuracy/Functionality: ability to perform useful function identified by users, and to perform the function without significantly modifying existing processes.

- Ease of Interaction: ability to interact with the user with conventional tools used in the process and without imposing significant training or restrictions on existing practice.

Interaction with the planning process, possibility of learning/teaching, and accounting/process learning are other desirable attributes. It is difficult to design an optimal solution for tasks in such a dynamic environment and the flexibility of the system to allow tuning of its performance is also important.

1.3 Problem Statement

Steady hand manipulation is very well suited for supervisory control. Just as in conventional manipulation, the tool held by the manipulator performs a single function at any time, and the sequence of these actions defines the surgical task. However implementation of other requirements of supervisory control requires augmentation of compliant control with additional sensory information.
The core issues in this problem are

1. understanding the motions being made (or specifying them in some way)

2. designing task strategies and control strategies for efficient augmentation,

3. integrating non-sensory information (planning information, constraints etc.),

4. evaluating human performance with and without augmentation.

Each of these problems is large in its general form and beyond the scope of this work. A more time bound and tractable formulation of the problem is the following:

> *Generate a set of generic robust primitives, and ways to combine them to transparently implement explicit specifications for simple manipulation tasks.*

This reduces the core issues to:

1. creating robust primitives for common motions (and ways to compose them),

2. *implementing* control strategies for augmented tasks,

3. integrating *explicit representations* of non-sensory information,

4. evaluating human performance with and without augmentation for *implemented tasks.*

The domain of this problem is motions made by a surgical robot under direct surgeon guidance. A subset of motions made during surgery are similar to assembly analogues, such as positioning a tool to the surgical site (to the peg in hole problem) thus some inferences could be drawn from work in assembly environments. However, due to complex interactions with the environment and increased safety requirements only limited help is available from assembly tasks where the problem may be a little easier due to limited cost of an error and constrained environments.

Further, we are primarily interested in manipulation tasks with a degree of contact compliance between the tool and the environment being manipulated. Usually, these are relatively low information bandwidth tasks with moderately small force ranges. The environment interaction (i.e. tool tip) forces require special instrumentation, but this is available as part of the experimental platform.

We develop a system for executing explicit task level specifications of microsugical tasks, and validate them with experiments. Section 2.3 lists the contributions from this work in greater detail.

1.4 Organization of this document

This section provides an introduction to interventional robotics and discusses the importance of task level augmentation in computer-integrated surgery. A supervisory approach to task level augmentation is discussed and finally a workable problem statement is presented.

The **overview** section provides context to the problem of task level augmentation. A large body of research is available for task level programming and this is briefly outlined. The tasks under consideration are broadly classified into groups. This section also provides a basic definitions and overview of our approach. Finally we point out the contributions from this work and its applications.

The **system description** section details the organization and parts of the experimental environment. Both hardware and software components are described. The steady hand robot on which the experimental platform is based is described in de-