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An Augmentation System for Fine Manipulation

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Abstract. Augmented surgical manipulation tasks can be viewed as a sequence of smaller, simpler steps driven primarily by the surgeon's input. These steps can be abstracted as controlled interaction of the tool/end-effector with the environment. The basic research problem here is performing a sequence of control primitives. In computing terms, each of the primitives is a predefined computational routine(e.g. compliant motion or some other "macro") with initiation and termination predicates. The sequencing of these primitives depends upon user control and effects of the environmental interaction. We explore a sensor driven system to perform simple manipulation tasks. The system is composed of a core set of "safe" system states and task specific states and transitions. Using the "steady hand" robot as the experimental platform we investigate using such a system.

1 Introduction

Dexterous manipulation is a key element in the speed, safety, and, ultimately, the success of most surgical interventions. The majority of surgical tasks involve hand-held tools operated using both vision and force (including both tactile, and kinesthetic) information. While most interventions use both force and vision at some level, the availability and efficacy of both varies widely. In general, during coarse, large-scale manipulation forces from the tools is an important cue, but visual information improves both the speed and facility of manipulation. In contrast, fine, small-scale manipulation is often almost completely visual, as the interaction forces between the tool and the environment are imperceptible to even a trained surgeon. As demonstrated in the literature [1-5] [6], the lack of tactile information during surgical procedures probably results in them taking longer and being less accurate than if tactile information were present.

Our "steady hand" manipulation approach [7] is intended to provide a safe, intuitive means of addressing such problems by *augmenting* the manipulation capabilities of a surgeon. It is safe, as the surgeon has direction control of the manipulator, and thereby his or her accustomed surgical tools. It is intuitive, as the surgeon not only directly manipulates those tools, but receives direct force-feedback from the manipulator, thus "feeling" the manipulation much as one would during a large-scale surgical intervention. Our approach (compared to conventional tele-manipulation) is also more appealing because of its cost advantages.

While the increasing need for augmentation at micro scales provides a clear opportunity for human augmentation, it also makes it clear that *different levels of augmentation of necessary at different stages and/or scales of surgical intervention.* Thus, open questions in the steady-hand approach (indeed, in any human-augmentation system) include both: 1) How might one develop a framework for human augmentation that varies its behavior in response to both the task context (e.g. scale) and the needs of the human within that context? and 2) Given such a system, does it provide "added value" to the human operator? Clearly, these two questions are closely inter-related and can only be answered through a cycle of engineering and empirical testing. In this paper, we present preliminary results based on a prototype system we have developed.

1.1 Previous Work

Some prior work exists in analogous problems such as automation of assembly tasks and vision guided control. Flexible automation of tasks for assembly [8],[9] has been studied for a long period of time. Taylor [10, 11] also looked at task representations. Some existing work in methods for learning tasks focuses on determining force/position control parameters from a human worker's operation[12, 13]. Analysis of robot systems operating in tandem with humans and extraction of some information from this cooperation is an active topic of research. Kosuge [14-16] has looked at cooperative tasks. Exoskeletons, amplifying user input have been proposed by Kazerooni [17-19]. The vision community also has a body of research (e.g. Dickmanns [20]) in developing similar frameworks for vision guided processes. Similar work also exists in space and planetary robotics, e.g. Lee [21] proposed a sensor based architecture for planetary robotic sampling.

More recently, sophisticated systems have been developed to assist, augment human actions in more unstructured environments, especially in medicine. In medicine, they are often used to reduce humans involved in a task (i.e. to act as tool or camera holder) than for their superior manipulation abilities. However, Davies [22] and Troccaz [23] among others have devised systems that incorporate some level of integration of task information for constrained control.

2 A System For Surgical Manipulation

The following are some of the important requirements of an augmentation system**:**

- **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 be able 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, 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 it performance is likely to be important.

There are sufficiently large number of generic manipulation actions in surgical procedures that may be augmented by a single surgical assistant. Some of these also find analogues in industrial automation that have been well studied. Examples of such tasks are camera holding, tool guidance, tool positioning, constrained and guarded motions (force constraints are especially hard to implement without augmentation and very common in practice). There are however significant differences between assembly and surgical environments. Safety is critical and the environment is unstructured and very dynamic (hence the controller more complex), Unlike assembly environments, augmentation must seamlessly integrate with existing processes and environment

2.1 Our Approach

We demonstrate our approach by choosing a sample task that involves both fine and coarse manipulation, and imitates a minimally invasive task. The task of placing a tool through a port (small incision or hole) at a surgical site is composed of the following steps: a) positioning the tool at the port, b)orienting it such that it can be inserted, c) insertion of the tool, d) adjusting the orientation of the tool towards the placement site viewing through the visual feedback device (microscope in the eye, video feedback in laparascopy etc), e) approaching the site, and f) achieving contact.

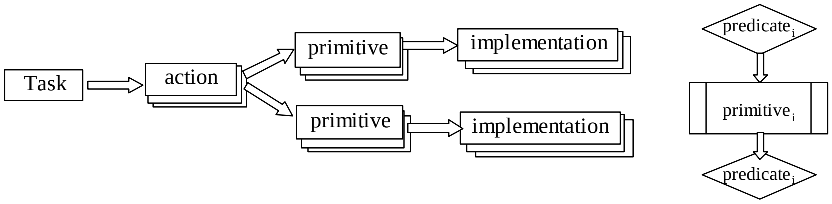

Figure 1: Tasks are made of simpler parts explicitly arranged in a graph by the user.

This task has both coarse manipulation (positioning and orientation leading to the port) and fine manipulation inside the organ. In our approach, each step of the **task** is called an **action.**

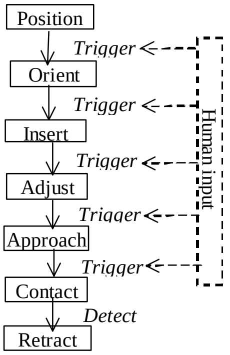

Figure 2: Task graph for the example task, triggers between states are provided by user by pressing a foot pedal.

Actions are themselves more complex than a motion that can be directly coded. They are represented as chains of high-level subroutines (**primitives**) that are linked together by **predicates**. Primitives are composed of functions implementing sensing and manipulation routines. Predicates serve as conditions for transitions in the state graph composed of **basic system states** (for manipulation and safety), and task specific states. Predicates include both automatic sensing (e.g. contact detection) and explicit user input.(e.g. input from buttons or foot pedals).

Implementations of sensing and manipulation subroutines are the basic building blocks. These subroutines perform well defined tasks, that are robust to errors. Manipulation subroutines are move to specified position, move relative distance, move with specified velocity, and sensing subroutines such as get current value, filter raw values, get biased value, resolve values with respect to a given Cartesian frame are examples of basic routines used here.

Primitives are the next higher level entities. They are composed from sensing and manipulation routines. The primary primitives in “steady hand” manipulation are those that support compliant motion. A “move in compliance to forces” primitive is composed of sensing primitives to obtain resolve value of the sensor, a control law (e.g. velocity proportional to force error), and manipulation primitives that receive the output of the control law.

Actions are composed from primitives by specifying sensing primitives (predicates) that initiate the execution of the action. These predicates form the conditions that must be met before the primitive is executed. In the above example, the actions are composed of a single “move in compliance to forces” primitive with different parameters. Position uses the translation stages of the robot to provide XYZ positioning where as the rest of the actions(orient, insert, adjust, approach, retract) use two rotational degrees of freedom (about X,Y) and Z insertion degree of freedom about a mechanically constrained remote center of motion(RCM). In the sample task, the contact action serves only as placeholder for manipulation actions that might follow in a real task.

A Task representation is generated by first identifying distinct parts in the conventional procedure. Given that “steady hand” manipulation imposes a sequential ordering on *planned* task execution (user only performs one action at a time with the manipulator), each of these parts can be implemented as an action. The conditions that need to be met before each action are identified. They form the predicates for that action. If the actions are composed of several primitives, the process of identifying primitives is repeated for the actions. Finally the user identifies safety requirements, such as limits on motion, sensory values etc for each action. This

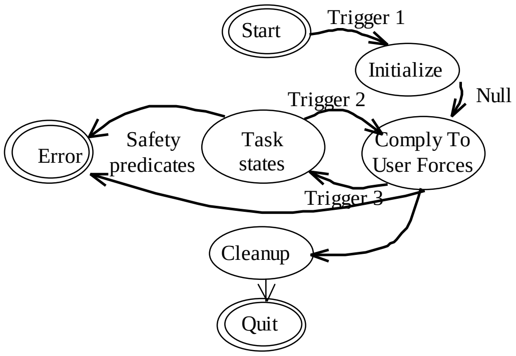

Figure 3: Simple System Graph. System States are composed of Basic States (initalize, cleanup, manipulate, error) and task specific states. Triggers Between task specific states, and initialization are user interface actions performed by the user. Data Collection is not shown.

serves as a skeleton for the task graph. The task graph is then executed in a training enviornment. During execution the user may identify redundant or additional states, predicates that modify the task graph.

The System maintains a basic set of states, and predicates. These include initialization and cleanup, a manipulation set, data collection set, and safety and error checking predicates. The system basic states are sleep, and move in compliance to forces, and error states. The data collection set includes a single Dump state. Safety Predicates include workspace and force limits, and hardware and software errors.

3 Preliminary Experiments

We have begun to experimental studies to evaluate the effectiveness of using task-graph enhanced "steady hand" augmentation in comparison to simpler augmentation and un-augmented free hand performance. The task chosen is a constrained needle placement task that presents many of the fine manipulation difficulties encountered in eye surgery. This task is a modified version of the peg in hole task, a common task used for performance evaluation [24],[25],[26].

3.1 Experimental Environment

The experimental environment [7] consists of software and hardware components. The software consists of the machine level robot control software and the framework specific to this work. The JHU Modular Robot Control (MRC) library provides the machine level robot control functionality. The hardware consists a cooperative manipulator and augmented tools required for selected tasks. The cooperative manipulator used is the "steady hand" robot.

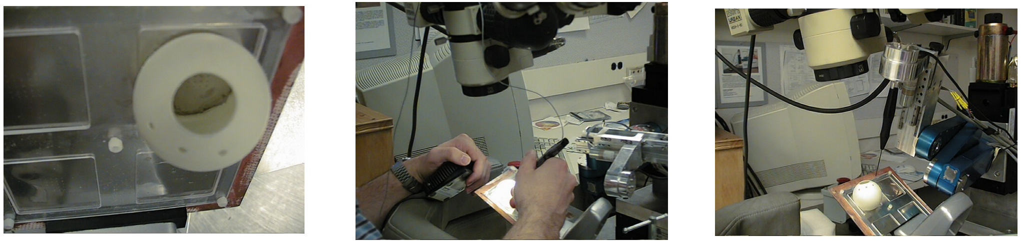

Figure 4: Experimental Setup: The ball with access ports and data grid, a user performing free hand experiment (middle) and setup with the robot (right).

This experimental setup appears in Figure 4. To construct the target a ball was sliced and ports constructed to reflect distances similar to the eye. This ball was attached to a data surface containing 100 micron holes separated by 2mm. An ergonomic tool handle was mounted with a 1 mm shaft and 50 micrometer tip wire for the tool.

The goal of the experiment is to touch the bottom of the hole without touching the sides. Electrical contact sensing is employed to detect contact between the bottom of the holes(success) or the sides of the hole or elsewhere on the plate(error).

3.2 Task and Experimental Protocol

The selected task can be performed free hand and with the "steady hand" robot. It has two parts, coarse manipulation outside the ball(eye), and fine manipulation inside. This is also essentially a peg in hole task in a minimally invasive environment.

Two sets of augmentation parameters can be used, one using just constant gain compliant motion (Comply), and another using non-linear gains (Augment). With non-linear gains (Figure 5), the gains to each action are modified as a function of distance to the target. For coarse manipulation actions this is the port on the ball, and for fine manipulation a selected hole. The port and hole locations are taught to the robot by hand guiding it to both locations.

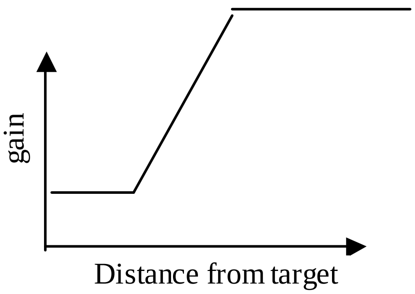

Figure 5: A typical non linear gain profile, the target is at zero.

The users are allowed unlimited training time till they are comfortable with the experimental protocol, both free hand and with the robot. The users execute each task 5 times. In both robotic, and free hand experiments, transition between actions are explicitly signaled by the user (by pressing a button/pedal). Each user also evaluates the setup subjectively on ease of operation, seating comfort, and ease of viewing the target.

3.3 Results

From the current data, the success rates for this experiment (number of errors per try) improve significantly free with the robot, augmentation adds to the improvement. The total time for the task also decreases when the robot is used. Data for three users appears in the table below. User 1 had the maximum training time and experience with the system, and user 2 and 3 are familiar with the system. Training time clearly affects the performance, but further evaluation is needed to confirm this.

Users	Task Mode	Coarse(outside), sec.	Fine(inside), sec.	Err/try
User 1	Free Hand	5.14	47.58	2.5
	Comply	5.5	17.46	1
	Augment	6.88	14.05	0.5
User 2	Free Hand	7.83	45.616	3
	Comply	2.87	27.38	2.4
	Augment	5.25	17.1	0.8
User 3	Free Hand	3.42	35.93	1.2
	Comply	8	22.45	1.8
	Augment	7.2	20.73	0.8

Table 1: Average Times for the experiment. Errors and total time for the experiment decrease significantly with the robot, and further when non-linear gains are used. The time for coarse motion does not change significantly.

Users find the experiment challenging free hand. The seating conditions are reported as comfortable, and visibility of the target good. The use of foot pedal to determine state transitions was considered non-intuitive, but not difficult by the users. This has been replaced with an observer pressing the button instead at the request of the user. The tip wire would bend and touch the side (when touching the bottom) of the hole with very small forces, this may have inflated errors. While this is a problem with all flexible instruments, we are working on improved apparatus/experimental protocol to reduce this problem.

4 Discussion and Conclusions

Our system utilizes the sequential nature of the execution of augmented tasks. Note that since the manipulation uses the "steady hand" approach, this is inherent. The sample task chosen above in not too different from several common tasks in surgery, one example being placing a micro-pipette in an blood vessel to deliver therapy. However, experimentation is needed with skilled users in conditions even more closer to clinical conditions to validate any results . These experiments are also scheduled.

We do not describe the mechanisms for specification of tasks here. The user describes the task in a high level specification being developed. The detailed discussion is beyond the scope of this paper.

A foot pedal was described as non-intuitive by the users in this experiment. However, clinicians routinely use foot pedals and their response to the pedal may be different. Alternative mechanisms for state transitions (pause in motion, automatic detection by comparison of change in state <force,position, velocity>) are available but they are yet to be evaluated.

5 Summary

We report on a sensor driven system for augmentation. Every surgical procedure under this approach is driven by a surgeon, as in conventional procedures. However, portions of the procedure are automated at surgeon's initiation. The system is described in detail. And an implementation is discussed. A preliminary experiment and some preliminary experimental results are reported.

Acknowledgements

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