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# COMPARISON OF TELEOPERATOR CONTROL ARCHITECTURES FOR PALPATION TASK

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## ABSTRACT

This work focuses on the design and testing of teleoperation controllers which are required to discriminate changes in compliance, addressing the question of which controller architecture performs the best in the high fidelity application of telesurgery. Three teleoperator controller architectures are compared for their ability to detect objects in compliant environments. These architectures are: position error based force feedback (PERR), kinesthetic force feedback (KFF), and position and force feedback (P+FF). The gains for each controller are chosen based on stability, tracking performance, and fidelity of the system. Stability is determined by a robust stability criterion. A sensitivity function is used to determine a tracking criterion. A new fidelity measure is introduced which looks at the sensitivity of the transmitted impedance to changes in the environmental compliance. Experiments are conducted to determine which control architecture allows the operator to most easily determine a change in compliance. This experimental task is designed to mimic palpation of soft tissue performed in medical procedures. The results suggest that the hybrid controller (P+FF) outperforms both PERR and KFF.

## INTRODUCTION

One of the most important recent advances in surgery has been the shift from conventional open procedures to minimally invasive surgery(MIS). An example of MIS is laparoscopy, abdominal surgery performed by making small incisions into the body, normally no more than 10 millimeters, and inserting long instruments and a camera through cannulas into the operating site. One benefit of MIS is reduced damage to healthy tissue, which results in quicker patient recovery. While the advantages are quite attractive, there are drawbacks to this type of procedure. In open procedures, the surgeon is able to palpate soft tissue. This is useful for tasks such as locating tumors or occluded vessels, as well as locating anatomical landmarks. In MIS, the surgeon manipulates tissue with long instruments, which transmit very little information about the varying stiffness of the tissue. While current tools for MIS are limited in the information they can transmit, telesurgical manipulators allow more information about the environment to be fed back to the operator. Telesurgery can enhance the dexterity and perception in minimally invasive surgery. The added complexity of the instrumentation allows the opportunity to improve upon the haptic information transmitted to the surgeon. Communication channels between the master and slave can transmit important information about the environmental impedance.

While many researchers have studied stability and fidelity in teleoperation, these studies have focused on contact with stiff environments. In hard contact, the key concerns are often stability and good position tracking. The stability concerns that arise from large time delays are not of concern in this system since the time delay is very small. Telesurgery requires a much greater degree of fidelity than previous applications, such as the ability to detect compliance changes in soft tissue.

The key goals of this work are the design and testing of teleoperator controllers in a compliance discrimination task. Robust control theory methodology is used to determine the stability and fidelity of the controllers. Human operator performance is evaluated by experiments meant to mimic palpation tasks performed in surgery, requiring the operator to discriminate changes in compliant surfaces.

## Previous Work

The control algorithms available in the literature can be classified in terms of the trade-off between stability and fidelity (Lawrence, 1993). For example, the passive communication based control algorithms of Niemeyer and Slotine (1991), and Anderson and Spong (1989;1992) are optimized for stability and have poor fidelity (Hannaford, 1993), whereas the control algorithms of Yokokohji (1994) for ideal kinesthetic coupling are optimized for fidelity and have poor stability. In the latter approach, the idea is to achieve perfect position and force tracking between the master and slave manipulators. This type of control is model based, and requires the measurement and transmission of position, velocity, acceleration and force in both directions (Yokokohji, 1994). This control algorithm is sensitive to model uncertainties which results in stability problems.

While stability is essential to the system, an equally important criteria in telesurgical applications is the 'feel' of the system, which is always difficult to quantify. One approach to this type of performance evaluation was investigated by Lawrence (1993), who evaluated the system's transparency, defined as the ratio of the impedance of the environment and the impedance transmitted to the master. Lawrence's design goal was to keep this ratio equal to one over a maximal bandwidth. Other recent work which focused on the human interface was carried out by Daniel and McAree(1998). Their design included a filter which fed back forces from the environment at frequencies important to the stimulation of tactile and kinesthetic receptors. While their filter does provide greater stability, the design needs for a compliant surface may be different than those used for hard contact. In this work, a new measure for the fidelity of the system is introduced.

Robust control theory has been previously used in the literature for different objectives, for example by Kazerooni (1993), Yan and Salcudean (1996), Hu and Salcudean (1995), and Leung (1995).

## Experimental Comparison of Algorithms in Conventional Teleoperation Tasks

Many criteria have been used in comparing control algorithms experimentally, including task completion time, peak force, sum of squared forces, number of errors, and surveys on the subjective feel of the system. Studies comparing the position control based algorithms (with no force feedback, Remote Site Compliance (RSC), Kinesthetic force feedback with and without RSC, Position Error based force feedback with and without RSC) for peg-in-hole and pick-and-place *type* tasks with variable time delays, have favored KFF and shared modes (Das et al., 1992; Kim et al., 1992; Hannaford et al., 1991). They note that force feedback increases the performance, but causes instability problems under time delay.

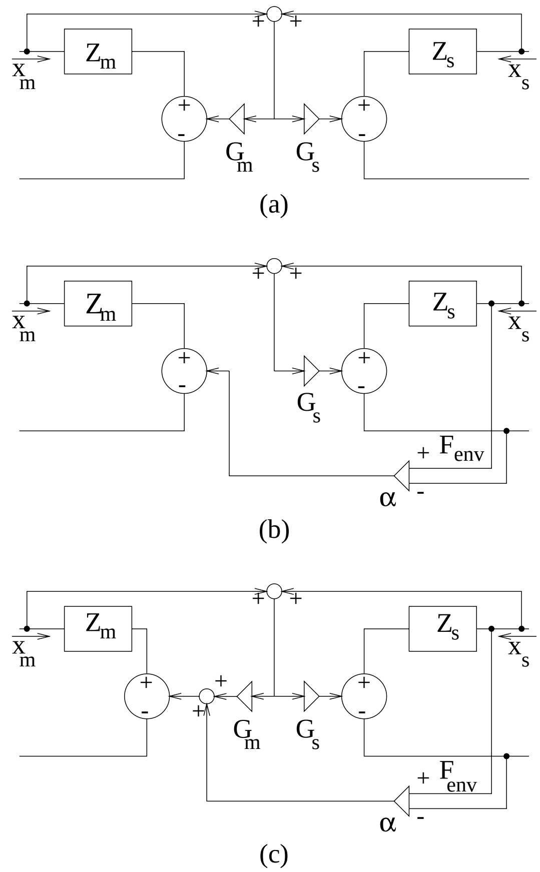

Figure 1. PERR, KFF and P+FF ARCHITECTURES

In Lawn and Hannaford (1993) the tasks used were 1 DOF constant force maintaining, and pointing (simple pointing and pointing under the influence of a non-linear stiffness) tasks. The experiment conditions included simulated communication delays up to 1 sec. Lawn and Hannaford compare position control based algorithms (with no feedback, KFF) and passive communication based control algorithms. They conclude that the passive communication based control algorithm has poor performance at the given tasks (approximately 50% longer completion time compared to the other algorithms, even at no time delay) due to reduced stiffness, and that the performance degrades severely with increasing time delay.

## CONTROLLER DESIGN

The three controller architectures considered in this study are the position error architecture (PERR), the kinesthetic force feedback (KFF) architecture, and the position and force feedback (P+FF) architecture (Fig.1). In PERR architecture, the forces sent

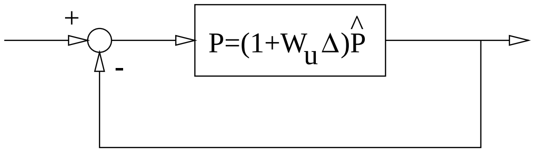


Figure 2. CLOSED LOOP SYSTEM WITH MULTIPLICATIVE UNCERTAINTY

to the master are proportional to the position error between the master and slave manipulators. The KFF architecture uses a force sensor on the slave end to transmit forces back to the master. The P+FF architecture is a hybrid of KFF and PERR. In this architecture, the force fed back to the master is a linear combination of the position error and the interaction force between the slave and the environment. In all three controllers the master position is used to command the slave. There are additional non-position based control schemes such as rate control, remote site compliance, and impedance control, which are not suited for this application because they are designed for situations that will not arise in telesurgery such as manipulating in a large workspace, large time delay, or hard contact tasks. Each of the controllers is analyzed in terms of stability, tracking, and fidelity.

The selection of controller gains for the three architectures is based on both stability and performance criteria. To make the experiment a fair comparison, each controller was required to meet the same stability criterion. A robust stability measure was used to select the subset which were stable. This subset of gains was further narrowed by placing a criterion on the tracking performance of the system. The tracking restrictions are important to avoid large position errors and keep the slave stiff. The final set of gains were selected by optimizing for fidelity over the sets of gains which met the stability and tracking conditions.

Due to space limitations, details of the plant model and controller design is omitted here. These details can be found in Çavuşoğlu (2000).

### Stability

Stability of the system is evaluated using a robust stability criterion. To begin this discussion consider a plant model $P$ with a nominal value $\hat{P}$ and multiplicative uncertainty (Fig.2),

$$P = (1 + W_u\Delta)\hat{P} \tag{1}$$

where $W_u$ is a weighting function and $\Delta$ is the perturbation, defined such that $||\Delta||_\infty \leq 1$. Then the norm of $W_u$ can be expressed in terms of $P$ and $\hat{P}$,

$$\left|\frac{P(j\omega) - \hat{P}(j\omega)}{\hat{P}(j\omega)}\right| \leq |W_u(j\omega)| \ \forall\ \omega \tag{2}$$

The uncertainty model developed in this work focuses on the uncertainty in the environmental impedance. We use two port hybrid parameters of the teleoperator (Hannaford, 1989),

$$\begin{bmatrix} F_m \\ v_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} v_m \\ F_s \end{bmatrix} \tag{3}$$

where $v_m$ and $v_s$ are the velocities of the master and slave manipulators, and $F_m$ and $F_s$ are the forces on the endpoint of the master and slave manipulators. The loop gain, $L$, is given by

$$L = G_{loop} = \frac{-h_{12}h_{21}Z_{env}e^{-st_d}}{(h_{11} + Z_{op})(1 + h_{22}Z_{env})} \tag{4}$$

Separating out the terms containing $Z_{env}$, the nominal and perturbed plant are defined as:

$$\hat{P} = \frac{\hat{Z}_{env}}{1 + h_{22}\hat{Z}_{env}} \tag{5}$$

$$P = \frac{Z_{env}}{1 + h_{22}Z_{env}} \tag{6}$$

Where $\hat{Z}_{env}$ is the nominal environmental impedance, taken to be the impedance of the gel samples used to model soft tissue in the experiments. $Z_{env}$ is the perturbed environment, which in this analysis ranges from 0 to 100 N/mm. Combining equations 2, 6, and 5 yields the relationship between the weighting function, $W_u$, and the environment:

$$\left|\frac{Z_{env} - \hat{Z}_{env}}{\hat{Z}_{env}(1 + h_{22}Z_{env})}\right| \leq |W_u| \ \forall\ \omega \tag{7}$$

$W_u$ is chosen to be a bounding function for the curves created by varying $Z_{env}$ in equation 7. For stability analysis, we have used the robust stability criterion for unstructured uncertainties as given in Zhou, Doyle, and Glover (1996). To satisfy this robust stability it must be shown that:

$$||W_uT||_\infty \leq 1 \tag{8}$$

where $T = \frac{L}{1+L}$. Matlab (MathWorks, Natick, Ma.) is used to compute the set of gains for each of the three control architectures which meet this requirement. To account for the fact that some modeling errors are ignored in this analysis, a stricter criterion is used, requiring that $||TW_u||_\infty \leq \frac{1}{3}$. The set of gains which meet this requirement are then compared based on performance measures.

### Performance

Once the stability criterion is met, the performance of the controller is evaluated. Position tracking and fidelity are the two measures employed to determine the performance of the controllers. Tracking is a measure of how well the slave manipulator can follow the position commanded by the master manipulator. Traditionally transparency, which is defined as the ratio of the transmitted impedance to the environmental impedance (Lawrence, 1993), is used as a fidelity measure. In this work, a different fidelity measure is proposed which focuses on the sensitivity of the transmitted impedance to changes in the environmental impedance. This measure corresponds to the ability of a surgeon to discriminate changes of compliance in the environment. The gains for each controller architecture will be based on meeting stability and tracking requirements, and optimizing fidelity.

**Tracking** The first performance requirement is position tracking in the forward (master to slave) direction. Consider a simple closed loop system in which the slave manipulator is the plant, the input signal is the commanded position of the master, and the output of the system is the position of the slave. The tracking requirements placed on this system correspond to limiting the error between the slave position and the position commanded by the master. The problem of tracking is evaluated in free space, so the interaction between the environment and the manipulator position does not play a role. The sensitivity function will be used to set the boundaries for desired performance.

The sensitivity function, $S(j\omega)$, is the transfer function from the position commanded by the master to the position error between the master and the slave. Thus, it is desirable to have a system in which $S$ is bounded in a manner which limits the position tracking error between the master and the slave. A frequency dependent boundary function, $b(\omega)$, is chosen such that $S$ is kept small for low frequencies. In this application, we are mostly concerned with the lower frequencies since it is expected that the operator will not move faster than 5-10 hertz. Once $b(\omega)$ is determined, the performance requirement is expressed as:

$$|S(j\omega)| \leq b(\omega) \;\; \forall \; \omega \tag{9}$$

Finally, we introduce a weighting function $W_p(\omega)$ which is related to $b(\omega)$ by:

$$W_p(\omega) = \frac{1}{b(\omega)} \tag{10}$$

This leads to the expression for the sensitivity boundary:

$$||W_p S||_\infty \leq 1 \tag{11}$$

This inequality is used as the second requirement for the set of acceptable gains. Those sets of gains which meet the nominal performance requirement and the robust stability requirement are then evaluated for fidelity.

**Fidelity** There is not a universal measure for fidelity in teleoperation. One performance measure described by Lawrence (1993) is transparency, the ratio between the transmitted impedance to the environmental impedance. The transmitted impedance is defined in terms of the hybrid parameters by:

$$Z_t = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21})Z_{env}}{1 + h_{22}Z_{env}} \tag{12}$$

This fidelity measure allows one to determine the frequency range within which one would expect the system to accurately transmit impedance. Our concern is with the sensitivity of the transmitted impedance to changes in the environmental impedance. In other words, how small can a change in the environmental stiffness be and still be detectable to the user. As mentioned, the telesurgery application has higher fidelity demands than most teleoperated systems. Similar to the analysis for tracking and stability, this analysis is based on the value of the norm of the fidelity measure and a frequency dependent weighting function which will be described below. The fidelity measure used is the derivative of the transmitted impedance with respect to the environmental impedance:

$$\left\| \frac{dZ_t}{dZ_{env}} W_s \right\|_2 \tag{13}$$

The weighting function, $W_s$, is band limited, to emphasize the frequencies of interest. The weighting function is a fourth order filter with a bandwidth of 40 Hz which is based on results of psychophysics experiments evaluating compliance discrimination (Dhruv and Tendick, 2000).

The maximum value of this norm will correspond to the system which is most sensitive. For each combination of gains, the norm, $\left\| \frac{dZ_t}{dZ_{env}} W_s \right\|_2$, is calculated for a range of $Z_{env}$. For each set of gains, the norm corresponding to the worst sensitivity over all the values of $Z_{env}$ is determined. The final set of gains is chosen to maximize worst case sensitivity. The range of $Z_{env}$ for this calculation is $0.1 - 0.4\ \frac{N}{mm}$. As a summary, the optimal set of gains for the controllers are given with the following optimization:

$$\sup \left\{ min_{Z_{env}} \left\| \frac{dZ_t}{dZ_{env}} W_s \right\|_2 \right\} \tag{14}$$

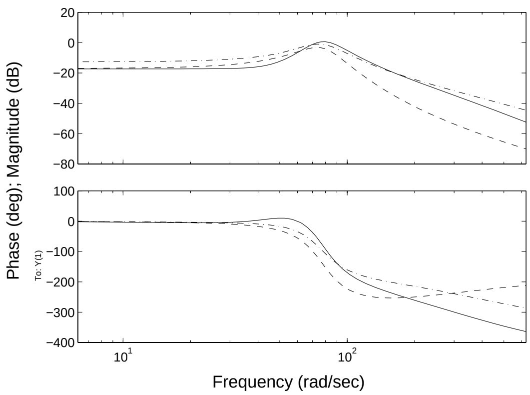


Figure 3. FREQUENCY DEPENDENCE OF (UNWEIGHTED) TRANSMITTED IMPEDANCE SENSITIVITY $dZ_t/dZ_{env}$ AT $Z_{env} = \hat{Z}_{env}$. Solid line:KFF, dashed line: PERR, dash-dot line: P+FF.

Figure 4. MASTER AND SLAVE MANIPULATORS

Table 1. FIDELITY MEASURE

| Control Architecture | Fidelity Measure |
|---|---|
| P+FF | 3.12 |
| KFF | 2.78 |
| PERR | 1.91 |

over the set of gains satisfying

$$||TW_u||_\infty \leq \frac{1}{3} \tag{15}$$

$$||W_pS||_\infty \leq 1 \tag{16}$$

and stable for nominal $\hat{P}$. The gains resulting from this analysis were used in the experiment with the exception of the P+FF architecture. For P+FF the optimization yielded the same gains as KFF. However, it was possible to achieve superior performance by hand-tuning the P+FF controller while qualitatively maintaining the same amount of stability. This was due to modeling errors, in particular the noise on the force sensor and human operator uncertainty. The fidelity values for each controller are given in Table1.

## EXPERIMENTAL EVALUATION OF CONTROLLERS

The task used to evaluate the feel of each architecture was designed to simulate palpating soft tissue. A simple design to test this ability is to have the subject determine the location of an embedded rod in a soft gel sample. The difficulty of the detection task was varied by using a set of samples which differed in the depth of the inclusion.

### Methods

**Experimental Set Up** The PHANToM haptic interface (SensAble Technologies, Cambridge, MA) was used as both the master and slave manipulators (Fig.4). These haptic devices were controlled by a dual processor Silicon Graphics Octane workstation running IRIX and SensAble Technologies OS Extender as the real time kernel. The end effector on the slave was a rigid plastic hemisphere, 2 cm in diameter. A 6 DOF force/torque sensor (Assurance Technologies,Inc., Gamer, NC) was attached between the shaft of the slave manipulator and the end effector. The contact force records were updated at 540 Hz. The time delay in the F/T sensor was measured to be approximately 6 msec. The master manipulator had a plastic stylus as its end effector, allowing the operator to use a familiar pen grip.

Soft gel molds containing embedded metal rods were used to model soft tissue with an inclusion. Each sample was a wax block with a well containing silicone gel (GE RTV 6166). The dimensions of the well were 1.8 cm deep, 12 cm long and 4.5 cm wide. Each sample contained a 1/4 inch diameter metal rod inclusion running the width of the well. The rod was placed 3 cm from the wall of the well. For the samples used in this experiment the inclusion depths were: 0.8 cm, 1.0 cm, 1.2 cm, and 1.4 cm. To protect the surface of the gel from tearing, a latex glove covered the top surface of the gels.

**Experimental Task** The two alternative forced choice method of testing was used. The subject was asked to determine which half of each sample contained the inclusion. The subject scanned the surface of the gel along the long axis, in a direction normal to the rod. It was necessary to limit the range of movement of the operator to be within the boundaries of the gel. To serve this purpose a cardboard restraint was used on the master's side to limit to range of the operator (not shown in figure 4). On the face of the cardboard restraint were markers indicating the middle of the sample, so that the subject was always aware of which side of the sample they were probing. The slave manipulator was covered by a cloth drape to keep the subject from using visual information from the slave side to aid in decision making. Each trial was limited to 10 seconds, during which time the subject scanned the surface of the sample presented. Auditory cues marked the beginning and end of each trial. For each trial the subject was asked to state which half of the sample contained the inclusion.

Three subjects participated in this experiment. All subjects had over 10 hours of experience using haptic devices. All subjects participated in a training period before beginning the experimental trials. Training was conducted to minimize the effects of learning during the experiment. During training, subjects were able to practice the task using all three controllers and all gel samples. The slave was not hidden from the view of the subject during training so that the subject could understand how the apparatus functioned.

Each subject completed 240 trials, comprising three control architectures with each of the four samples twenty times. Each subject participated in two sets of 120 trials, separated by at least one day. Each set of 120 trials took approximately two hours to complete. For tasks of this nature, fatigue can play an important role in performance. Subjects were given three ten minute breaks during each set. The presentation of the gels was based on a random number sequence generated in Matlab. The subject's responses were collected for each trial. From this data the controller's performance was analyzed and compared.

In addition to the experiment using the teleoperative system, the detection task was repeated using a hand-held probe. The probe consisted of a pen-length shaft with a spherical plastic tip of the same diameter as the end effector of the slave manipulator. Subjects held the probe with a pen grip and scanned the surface of the gel. A cloth drape prevented the subjects from seeing their hand or the sample. Each subject completed 80 trials (20 repetitions on each of 4 samples) with the hand-held probe. This data was used as the control set against which the fidelity of the controller architectures was compared.

## RESULTS

Fig.5 displays the four psychometric curves resulting from the averaged data. These curves compare the performance of the controllers and the hand-held probe at each inclusion depth. The error bars represent the standard error for averaged data. Qualitatively, it appears that P+FF is superior to PERR and KFF. Not surprisingly, subjects performed best using the hand held probe for all but the sample with the deepest inclusion. A logistic regression is used to analyze the data since it is a binomial distribution (Glantz and Slinker, 1990). In this experiment each data point represents one of two possible outcomes: correct or incorrect. To motivate the logistic regression model consider the relationship between the probability of a correct response, $P$, and the independent variables $x_i$.

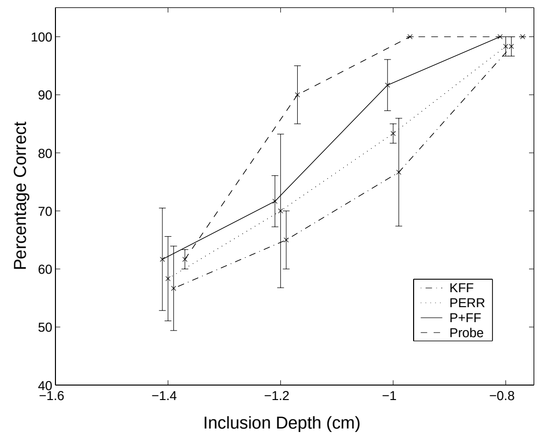


Figure 5. PERCENTAGE CORRECT (MEAN $\pm$ STANDARD ERROR) VS. INCLUSION DEPTH

$$P(x_1,..,x_k) = \frac{1}{1+e^{-(\beta_0+\beta_1 x_1+\ldots+\beta_k x_k)}} \tag{17}$$

A logistic regression equates the natural log of the odds of getting a correct response, $\Omega_C$, to the independent variables, $x_i$. A generalized linear model is given by:

$$\ln\Omega_C = \ln\frac{P}{1-P} = \beta_0+\beta_1 x_1+\ldots+\beta_k x_k \tag{18}$$

From equations 17 and 18 it is clear that large values of the regression coefficient $\beta_i$ correspond to increased probability of an event occurring. In this way, the coefficients $\beta_i$ weight the importance of the independent variables in affecting the probability of a desired outcome. The independent variables in this experiment are inclusion depth, subject, and controller type. Regression coefficients are calculated for each independent variable. An analysis of deviance is then performed on this generalized linear model to test which factors (inclusion depth, controller, subject) significantly effect the outcome ($\ln\Omega_C$). The analysis of deviance is comparable to using an analysis of variance for linear models. This method allows us to see which factors are significant in this model. The results show that inclusion depth, as expected, is a significant factor (Table 2). Controller and subject, although to a lesser extent, also contribute to the deviance in the model. Pairwise comparison between controllers allows us to determine whether one controller has a greater effect on the probability of a successful outcome. To carry out this comparison one controller is taken as a reference in the logistic regression. The coefficients corresponding to the remaining two controllers are compared to

Table 2. THE ANALYSIS OF DEVIANCE OF THE GENERAL LINEARIZED MODEL

| Factor | DF | F value | $P(F)$ |
|---|---|---|---|
| Inclusion Depth | 3 | 32.892 | $< 0.001$ |
| Subject | 2 | 2.637 | 0.091 |
| Controller | 2 | 1.691 | 0.20 |

the reference using a t-test. This analysis is done over the data for all gels. The performance of PERR is not statistically different from KFF or P+FF. However, evaluating the data for all four levels the t statistic for the pairwise comparison of P+FF and KFF is determined to be:

$$t = 2.005 \tag{19}$$

$$0.05 \leq P(|t| \geq 2.19) \leq 0.10 \tag{20}$$

The significance of the difference between P+FF and KFF is not as large as desired. The small t values were due to the large standard error term. A crucial factor in the size of the standard error term is the variation due to subjects. Sources of variance for this experiment are discussed below.

## DISCUSSION

In this work we have developed a new measure for fidelity in teleoperation. This sensitivity function is highly appropriate for the application of telesurgery, where the ability to distinguish small changes in tissue compliance is essential for tasks such as tumor detection. The robust stability analysis can be applied to any teleoperator plant and guarantee stability given an uncertainty model. An experimental protocol has been developed to test the ability of the teleoperator to discriminate changes in compliance.

There are several factors influencing the results of this experiment which are independent of the choice of the teleoperator controller. In pilot experiments, these factors were determined to be familiarity with the task and haptic devices, and, in particular, personal strategy. Pilot experiments revealed a larger variability between subjects than expected and that learning during the experiment was a significant factor. In the pilot experiments, ten subjects completed a more complex detection task which involved scanning a surface in two dimensions. Subjects tended to change their strategy throughout the experiment, and only with extensive training they would converge on one strategy. Thus, to reduce the variation among subjects, it was necessary to have subjects that were highly trained. The final experiment was limited to highly trained subjects with more than ten hours of experience using haptic devices to interact with compliant objects, of which only three were available. The training was completed with a separate set of gels so as not to bias the experiment. Additionally, to reduce the effects of strategy, the task was simplified by requiring subjects to scan along only one axis. Although we were successful in eliminating the strategy changes and training as factors in the final experiment, the small subject pool led to results that were not as significant as hoped.

It is important to note that it is undetermined how much of the subject variability is inherent to variability of human perception. Psychophysics experiments could be used to elucidate the limits of perception involved in detecting objects through haptic interfaces. Collaborators in our group are now performing experiments to elucidate the frequency dependence based on tactile and kinesthetic receptor and haptic display characteristics (Dhruv and Tendick, 2000). This will provide information to adjust the weighting function for the teleoperator fidelity metric. Future work will explore the question of which strategies are most useful in a detection task. In particular, the effects of the amount of force used and the scanning velocity, will be explored.

The results from the experiment suggest that the fidelity is best for P+FF, followed by PERR and KFF. The fidelity measure used in this experiment predicts that the performance ranking of the three controllers would be: P+FF, KFF, PERR. Although the analysis correctly predicts that P+FF would have higher fidelity, it was incorrect in its prediction that KFF would be superior to PERR. One reason for this difference is that the model used does not include the noise inherent in the force sensor. Adding a noise term to the force gain would penalize KFF more than P+FF since the force gain is considerably larger in KFF, and would have no effect on PERR model.

The future direction of the experimental work will include testing the differences between controller architectures for tasks that are more dependent on high frequency information where the difference between the controllers is most significant (see Fig.3). One such task would involve detecting features with varying spatial frequency. Another example of a task which would be more dependent on high frequencies is needle insertion. In this task, the vibration of the needle being inserted gives information about tissue consistency. Algorithms employing the force sensor would likely be superior to PERR at these tasks.

On the analysis side, we plan to develop a more detailed model of the system which will include the dynamic characteristics of the force sensor and the human operator uncertainty. A major topic of interest is to determine the utility of additional sensors in teleoperation control architectures, with an emphasis on the specific needs of MIS applications. Further, the advantages of small scale, perhaps compliant, manipulators for MIS tasks will need to be explored.

There has been great change in surgical technology in the past two decades. As the direction of surgery moves towards less invasive procedures, the need to manipulate in compliant environments will become increasingly important. While stability and fidelity for teleoperators have been widely studied, none of this previous work is directly applicable to the needs in telesurgery. Tasks such as palpation and needle insertion require a much greater degree of fidelity than previous teleoperator applications. New technology will allow for the design of small scale manipulators, yet the question of how to control these teleoperated systems, especially when trying to achieve high fidelity, has not been previously addressed. This study presents a new metric to quantify the fidelity of a teleoperator controller for soft tissue manipulation. The design methodology and analysis can be applied to future systems to determine the advantages of different types of manipulators, sensors, and algorithms for compliant environment manipulation.

## CONCLUSION

In this work, we have created a methodology for designing teleoperator controllers which incorporates stability, fidelity, and experimental analysis. Robust stability is used to take into account the uncertainty in the stiffness of the environment. A new metric for fidelity was created which evaluates the sensitivity of the transmitted impedance to changes in the environmental impedance. Finally, an experimental protocol to test teleoperator controllers with an object detection task has been created. We will use this theoretical analysis to guide the design of innovative manipulators using integrated sensors and novel control algorithms. It is important to emphasize that while theoretical analysis can be used to design and optimize new controllers, it is essential to do experimental evaluation of the controllers to truly judge their performance.

## ACKNOWLEDGMENT

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