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Bilateral Controller Design for Telemanipulation in Soft Environments

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Abstract

Previous research on teleoperation has focused on manipulation of hard objects. However, the design constraints are different in applications that involve manipulation of deformable objects, such as robotic telesurgery. In this paper a new measure for fidelity in teleoperation is introduced which quantifies the teleoperation system's ability to transmit changes in the compliance of the environment. 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 bilateral teleoperation controller design problem is then formulated as the optimization of this new metric with constraints on free space tracking requirements and robust stability of the system under environment and human operator uncertainties. The robust stability analysis can be applied to any teleoperator plant and guarantee stability given an uncertainty model. The analysis is also extended to evaluate effectiveness of using a force sensor in the teleoperation system.

Keywords — Bilateral Control Design, Haptics, Telemanipulation of Soft Objects, Teleoperation

1 Introduction

Previous research on teleoperation has focused on manipulation of hard objects. However, the design constraints are different in an application which involves manipulation of deformable objects. The stability-performance trade-off is the main determinant of the control design for teleoperation systems. Both performance and stability are inherently dependent on the task for which the system is designed. This paper addresses the issues in bilateral control design for telemanipulation of soft objects. The motivation behind this study is robotic telesurgery, where a surgical operation is performed by robotic instruments controlled by surgeons through teleoperation [2]. The goal of robotic telesurgery is to improve dexterity and sensation in minimally invasive surgery through the use of teleoperation technology.

As noted by Lawrence in [15], teleoperation controller architectures given in the literature can be classified in terms of the stability-performance trade-off. Control algorithms for ideal kinesthetic coupling [19] form one end of the spectrum, whereas passive communication based algorithms [1] form the other end. Conventional algorithms such as position error based force feedback and kinesthetic force feedback lie in the middle. There are also more recent controller designs using robust control theory. Kazerooni established an H_∞ based framework to design a teleoperation controller which transmits only force information and no position or velocity data [12]. Yan and Salcudean used H_∞ optimization to design controllers for motion scaling [18], and Hu et al. formulated the teleoperator control design as a convex H_∞ optimization problem [10]. Leung et al. used μ-synthesis to design controllers for teleoperation under time delay [16].

Operator performance is one of the important components of teleoperator design. Therefore experimental evaluation of control algorithms is crucial. Experimental studies at the NASA Jet Propulsion Laboratory [5, 13, 9] and by Lawn and Hannaford [14] compare various teleoperation algorithms within the context of operator performance. Human perceptual capabilities should also be considered. Jones and Hunter [11] performed experiments on determining human perceptual capabilities within the context of teleoperation. In a recent work, Daniel [4] takes into account considerations for improved stimulation of the tactile and kinesthetic receptors during teleoperator controller design by modifying the filter in the force feedback path. Colgate [3] introduced impedance shaping bilateral control as a means of "constructively altering the impedance of a task".

In the design of a teleoperation system controller, there are three considerations we believe to be important. First, it is important to have task-based performance goals rather than trying to achieve a marginally stable, physically unachievable ideal teleoperator response. Second, teleoperator controller design should be expressed explicitly as an optimization problem to accommodate task-based performance goals. Third, design of the teleoperation system must be oriented towards improving performance with respect to human perceptual capabilities. It is necessary to experimentally quantify human perceptual capabilities and to develop control design methodologies which will provide the means to include this in the control design.

In this paper a new measure for fidelity in teleoperation is introduced which quantifies the teleoperation system's ability to transmit changes in the compliance of the environment. 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 bilateral teleoperation controller design problem is then formulated as the optimization of this new metric with constraints on free space tracking requirements and robust stability of the system under environment and human operator uncertainties. The analysis is also extended to compare different sensor schemes within this context.

2 Formulation

The teleoperator can be modeled as a two-port network element relating force and position of the master manipulator, F_m and X_m, to the slave manipulator, F_s and X_s[1] (Fig. 1). We follow Hannaford [7] in using the hybrid parameters to characterize system behavior (Fig. 3)

$$\begin{bmatrix} F_m(s) \\ X_s(s) \end{bmatrix} = \begin{bmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{bmatrix} \begin{bmatrix} X_m(s) \\ F_s(s) \end{bmatrix} \quad (1)$$

Environment impedance transmitted through the teleoperator can be calculated as

$$Z_t = \frac{F_m}{X_m} = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21})Z_e}{1 + h_{22}Z_e} \quad (2)$$

[1]In the literature, generally a force/velocity representation is used instead of a force/position representation. Although force/velocity representation has an advantage since the power is immediately given by the terminal variables of the two port, it introduces a pole/zero pair at the origin causing complications in stability analysis conditions, which is purely an artifact of the representation. Here, the force/position representation is used to avoid these complications.

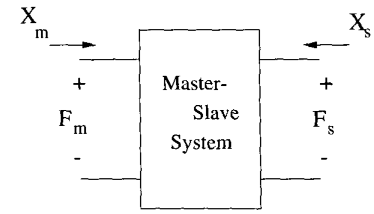

Figure 1: Two port input-output model of a teleoperation system.

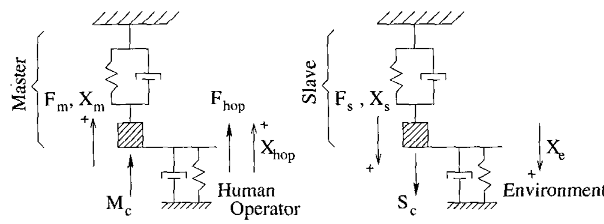

Figure 2: Physical model of the teleoperation system.

using the hybrid parameters. We will consider the model given in Fig. 2 as the underlying physical model throughout the analysis. This model is a linear model, and is only accurate locally. In Fig. 2, M_c and S_c are respectively the master and slave control inputs and F_{hop} is the human operator force.

3 Fidelity

Yokokohji defined an ideal response for teleoperation systems in [19]. With this, the goal of the control design was to match the position and forces at the master and slave manipulators exactly or through a virtual impedance. Lawrence defined transparency in [15] as the ratio between the transmitted and the environment impedances. Lawrence's design goal was to keep this ratio close to one over a maximal bandwidth. But, neither explicitly expressed their definitions of performance as measures that could be optimized.

We would like to explicitly distinguish the term *fidelity* in teleoperation. We define fidelity as a task dependent measure of performance which will be optimized during teleoperator controller design.

Transparency can be expressed as an optimization criterion, which will then be a specific choice of fidelity measure which quantifies how close the transmitted impedance is to the environmental impedance. However, if this particular choice of fidelity is best for a given task or not is another question.

In robotic telesurgery one would like to improve the ability to detect compliance changes in the environment

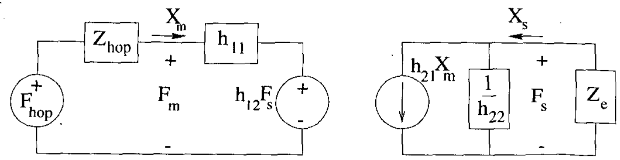

Figure 3: Hybrid parameters of a teleoperation system.

in addition to the basic requirement of "good" tracking in free space and while in contact with tissue. This compliance detection is critical in a surgical application in two ways. First, the interaction of the needle with tissue during suturing, such as to feel when the needle punctures or leaves tissue, can be detected through the change in the compliance. Second, the structures hidden inside the tissue, such as blood vessels, major nerves, or tumors, can be located by noninvasively probing the tissue. In these cases, it is more desirable to have the ability to detect the changes in the environment impedance than simple position or force tracking between the master and slave manipulators. Therefore, it is necessary to introduce a fidelity measure which quantifies this ability.

The measure of fidelity proposed in this paper is the sensitivity of the transmitted impedance to changes in the environmental impedance. This can be defined as

$$\left\| W_s \left. \frac{dZ_t}{dZ_e} \right|_{Z_e = \hat{Z}_e} \right\|_2 \tag{3}$$

where W_s is a frequency dependent weighting function, and $\hat{Z}_e$ is the nominal environment impedance.

In this study, a low pass filter with cutoff frequency of 40 Hz is used as the weighting function. This frequency was determined from our pilot experiments for determining human compliance discrimination thresholds. It is possible to improve this fidelity measure by including the frequency-dependent sensitivity of the human operator to compliance stimuli by incorporating it in the weighting function. A parallel research study is being conducted by our research group to determine this operator sensitivity function through psychophysics experiments [6].

4 Task-Based Optimization of the Teleoperation Controller

The controller to be used for the teleoperation system needs to satisfy some basic requirements such as stability under specified environment and operator variations. Once these are satisfied, the remaining freedom in the controller can be used to optimize a task dependent performance measure, in this case fidelity.

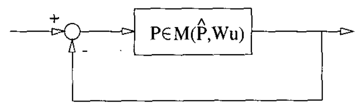

Figure 4: Closed loop system with multiplicative uncertainty.

4.1 Stability

Any teleoperation system must maintain stability under operator and environment variations. Robust stability of the closed loop system under unstructured uncertainty can be used to check this by properly modeling the operator and environment variations as uncertainty in the system.

For stability analysis, we use a robust stability criterion for unstructured uncertainties as given in Zhou, Doyle, and Glover [20]. For SISO systems, the criterion is as follows.

Theorem 1 (Robust Stability Criterion) *Consider the closed loop system shown in Figure 4 with multiplicative unstructured uncertainty. The uncertainty is defined as*

$$P \in M(\hat{P}, W_u) = \{\hat{P}(1 + W_u\Delta) : \Delta \in \mathcal{R}, \sup|\Delta(jw)| < 1, \\ \#\ \text{of rhp poles}(\hat{P}) = \#\ \text{of rhp poles}\ (\hat{P}(1 + W_u\Delta))\}, \tag{4}$$

where P is the loop gain, $\hat{P}$ is the nominal plant loop gain, W_u is the uncertainty weighting function, and $\mathcal{R}$ is the set of proper real rational functions. Then, the closed loop system shown is stable for all $P \in M(\hat{P}, W_u)$, if and only if it is stable for the nominal plant $\hat{P}$, and

$$\|W_u T\|_\infty \leq 1, \tag{5}$$

where $T = \frac{\hat{P}}{1+\hat{P}}$.

The uncertainty weighting function $|W_u(jw)|$ can be interpreted as the percentage uncertainty in $\hat{P}$ at the frequency w.

For the teleoperation system, the loop gain P is calculated in Hannaford [8] as

$$P = \frac{-h_{12}h_{21}Z_e}{(h_{11} + Z_{hop})(1 + h_{22}Z_e)} \tag{6}$$

where Z_e and Z_{hop} are respectively the environment and human operator impedances.

In this study we will consider the uncertainties in the human operator and the environment impedances.

First, consider the variation in the environment. Since Z_e appears as $\frac{Z_e}{1+h_{22}Z_e}$ in the loop gain expression, we proceed to put an upper bound to the variation in this term for the possible set of environments, $Z_e \in \mathcal{Z}_e$.

Start with some manipulation

$$P = \frac{-h_{12}h_{21}Z_e}{(h_{11}+Z_{hop})(h_{22}Z_e+1)} \tag{7}$$

$$= \underbrace{\frac{-h_{12}h_{21}}{(h_{11}+Z_{hop})}\frac{\hat{Z}_e}{h_{22}\hat{Z}_e+1}}_{\hat{P}}\underbrace{\frac{h_{22}\hat{Z}_e+1}{\hat{Z}_e}\frac{Z_e}{h_{22}Z_e+1}}_{1+W_{ue}\Delta} \tag{8}$$

Since we want to have the nominal environment $\hat{Z}_e$ for $\Delta = 0$, we pick

$$W_{ue}\Delta = \frac{1+h_{22}\hat{Z}_e}{\hat{Z}_e}\frac{Z_e}{1+h_{22}Z_e} - 1 \tag{9}$$

$$= \frac{1}{h_{22}\hat{Z}_e}\frac{Z_e-\hat{Z}_e}{\frac{1}{h_{22}}+Z_e} \tag{10}$$

then we pick an upper bound to

$$\left|\frac{Z_e-\hat{Z}_e}{\frac{1}{h_{22}}+Z_e}\right| < |\Phi(jw)| \tag{11}$$

for the possible environment values, which gives

$$W_{ue} = \frac{1}{h_{22}\hat{Z}_e}\Phi. \tag{12}$$

Φ can be a function of the controller values and other known variables present in h_{22}.

Similarly, for the operator impedance variation, we proceed to put an upper bound to the term $\frac{1}{h_{11}+Z_{hop}}$ for the possible set of operator impedances, $Z_{hop} \in \mathcal{Z}_{hop}$. We pick

$$W_{uh}\Delta = \frac{h_{11}+\hat{Z}_{hop}}{h_{11}+Z_{hop}} - 1 = \frac{\hat{Z}_{hop}-Z_{hop}}{h_{11}+Z_{hop}} \tag{13}$$

to have $\hat{Z}_{hop}$ for $\Delta = 0$. Then, we can pick an upper bound

$$\left|\frac{\hat{Z}_{hop}-Z_{hop}}{h_{11}+Z_{hop}}\right| < |W_{uh}(jw)| \tag{14}$$

which can be a function of the known variables present in h_{11}.

The two uncertainty terms can be combined to give a single multiplicative uncertainty weighting function as

$$W_u = W_{ue} + W_{uh} + W_{ue}W_{uh}. \tag{15}$$

4.2 Tracking Requirement

The tracking requirement is necessary to prevent the final controller parameter optimization from yielding trivial solutions. To illustrate this complication, consider the case of optimizing a controller for transparency at a given environment stiffness as operating point. The trivial solution to this optimization is to have a master controller which gives the master manipulator an apparent stiffness equal to the nominal environment stiffness, and have no feedback from slave to master or even not actuate the slave at all. The most natural constraint to prevent this kind of behavior is to require the teleoperation system to have sufficient tracking performance in free space. We will pose this tracking requirement as a condition on the disturbance sensitivity function of the forward position loop during motion in free space. In the hybrid parameter formulation of the teleoperator, this sensitivity function is given by

$$S = 1 - h_{21}. \tag{16}$$

Then the tracking requirement can be posed as

$$|S(jw)| < |b(jw)| \iff \|SW_p\|_\infty \le 1,\ W_p = 1/b(jw) \tag{17}$$

which dictates a tracking error less than $|b(jw)|$ for a sinusoidal input with angular frequency w and magnitude 1. This effectively puts a condition on the slave position gain when the slave is controlled by the master position (position only loop in the forward direction).

4.3 Optimizing for Fidelity

The controller gains are chosen to optimize the fidelity among the set of controller values which satisfy stability and tracking requirements.

$$\arg \sup_{\substack{\|W_uT\|_\infty \le 1 \\ \text{stable for } \hat{P} \\ \|W_pS\|_\infty \le 1}} \inf_{\tilde{Z}_e \in \tilde{\mathcal{Z}}_e} \left\| W_s \left.\frac{dZ_t}{dZ_e}\right|_{\tilde{Z}_e} \right\|_2 \tag{18}$$

The fidelity term is slightly modified from (3) to be more general, optimizing the worst case fidelity for a given set of environment values, $\tilde{\mathcal{Z}}_e$. $\tilde{\mathcal{Z}}_e$ is the range of environments in which sensitivity of the transmitted impedance to environment impedance variations is desired. It is important to note that this is not a convex optimization since $\left\|W_s\frac{dZ_t}{dZ_e}\right\|_2$ is not convex in the controller parameters. Therefore, proper numerical techniques should be used during the computation.

5 Comparing Controller Architectures and Sensors

We would like to determine if the use of a force sensor is necessary on the slave manipulator of the telesurgical workstation for sufficient fidelity. For better performance, it is almost always desirable to put additional sensors on the manipulators, however, as this sensor will be located on the part of the instrument which will be inside the body, it is a source of complications in the manipulator design, sterilization requirements, and adds to the cost of the final product.

Within this context, we will compare three different control architectures: position error (PERR), kinesthetic force feedback (KFF), and position error plus kinesthetic force feedback (P+FF) (Fig. 5). In the PERR architecture, the force sent to the master is 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.

Essentially, the PERR and KFF architectures are the limit cases of the more general control architecture P+FF. Therefore it is possible to quantify the improvement due to using a force sensor for a given task by looking at how the fidelity of the P+FF architecture changes as the force gain is changed.

We define the *alpha*-curve is as the highest fidelity achievable with the P+FF controller as a function of the force gain α, subject to the stability and tracking constraints.

$$f(\alpha) = \sup_{\substack{\|W_u T\|_\infty \leq 1 \\ \text{stable for } \hat{P} \\ \|W_p S\|_\infty \leq 1 \\ G_m, G_s}} \inf_{\tilde{Z}_e \in \tilde{Z}_e} \left\| W_s \left. \frac{dZ_t}{dZ_e} \right|_{\tilde{Z}_e} \right\|_2 \tag{19}$$

The shape of this curve depends on the stability constraint as well as the fidelity measure being used. There are three different cases based on location of the maximum point of the curve (Fig. 6). If the PERR end is the maximum, use of a force sensor does not improve performance. If the KFF end is the maximum, then it is better to use purely the force sensor output as the source of force feedback. Finally, if the maximum is located at an intermediate point, it is possible to have better performance by using a combination of position error and the force measurements to generate force feedback. The relative value of the peak value of the curve to the PERR value can be used to judge if the amount of performance improvement justifies the use of the force sensor.

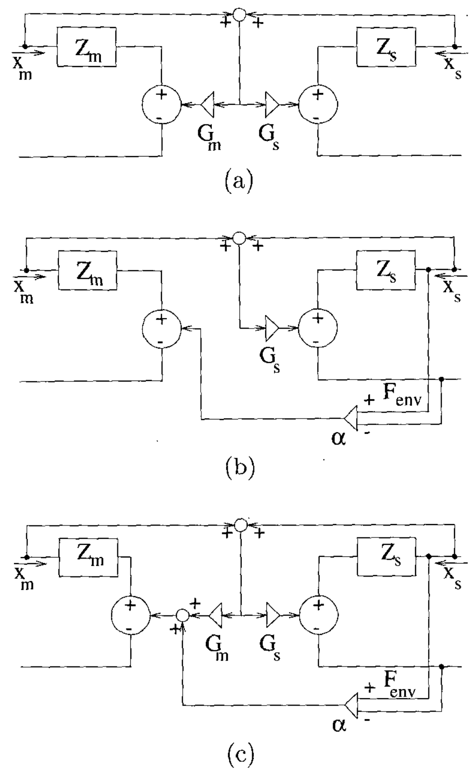

Figure 5: PERR, KFF and P+FF architectures

6 Case Study

The testbed used to evaluate the analysis described above is a teleoperation system with two identical three degree of freedom (DOF) robotic manipulators, Phantom v1.5 haptic interfaces (Sensable Technologies, Cambridge, MA) with custom motor drive electronics. The analysis here is carried out with a one DOF model, along the vertical direction, which is the axis orthogonal to the surface of the deformable body being manipulated. The local linear model of the manipulator in the vertical direction around the operating region is estimated as[2]

$$Z = \frac{1}{9.641e^{-5}s^2 + (0.002665 + D_x)s + 0.0322} \tag{20}$$

[2] All the units are in Newtons for force and mm for distance.

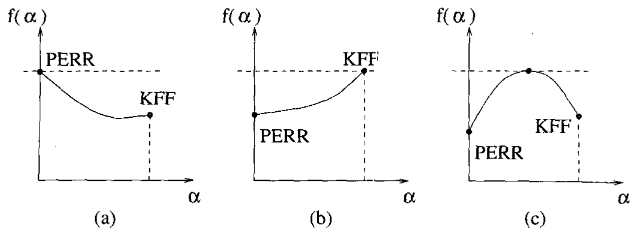

Figure 6: Possible cases for the shape of *alpha*-curve

where D_x is the active damping used. This model is constructed from black box system identification. In this study, active damping of $D_x = 5 \times 10^{-4}$ has been used on the slave side to improve the stability of the manipulator.

The following environment and operator impedance variations are considered

$$Z_e \in \{(B_e s + 1)K_e : B_e \geq 0.05, 0 \leq K_e < \infty\}, \quad (21)$$
$$Z_{hop} \in \{(0.0219s + 1)K_{hop} : 0.2 \leq K_{hop} \leq 2\} \quad (22)$$

with nominal impedances

$$\hat{Z}_e = 0.35(0.05s + 1) \quad (23)$$
$$\hat{Z}_{hop} = 1.51(0.0219s + 1). \quad (24)$$

The range of Z_e represents environments from 0 to infinite stiffness with a lower bound on damping. The nominal value of Z_e is the stiffness of the silicon gel used in experimental evaluation of teleoperation systems in [17]. The range and nominal value of Z_{hop} are experimentally determined from subjects using the haptic interface.

The following empirically determined upper bounds for the uncertainty terms of (11) and (14) are used in the stability analysis

$$\Phi(s) = 10^{3.8/20}\left(\frac{\frac{s}{19}+1}{\frac{s}{80}+1}\right)^2\left(\frac{\frac{s}{125}+1}{\frac{s}{75}+1}\right)^3 \quad (25)$$

$$W_{uh}(s) = 10^{15.3/20}\left(\frac{\frac{s}{60}+1}{(s^2+20.760s+60^2)/60^2}\right). \quad (26)$$

These upper bounds are determined by systematically varying the parameters G_s, B_e, K_e for (25) and G_m, K_{hop} for (26) within their specified limits (Fig.7). The upper bound used for tracking sensitivity function is

$$b(s) = \left(\frac{9.64\times10^{-5}+3.66\times10^{-3}s+0.032}{9.64\times10^{-5}+3.66\times10^{-3}s+0.232}\right) \times\left(\frac{\frac{s}{70}+1}{\frac{s}{100}+1}\right)^8\left(\frac{\frac{s}{138}+1}{\frac{s}{100}+1}\right)^8. \quad (27)$$

This upper bound requires good position tracking at low frequencies where the voluntary hand movements occur. The first term is chosen using the sensitivity function S at $G_s = 0.2$ and the remaining terms are chosen to accommodate underdamped behavior occurring for $G_s > 0.2$. The resulting $b(s)$ practically puts a lower bound on the slave position gain as $G_s \geq 0.2$.

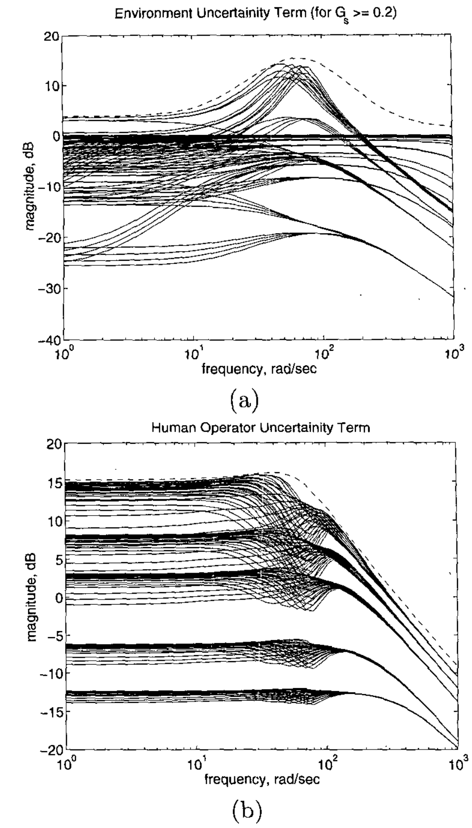

Figure 7: Uncertainty weighting functions: (a) Environment uncertainty term (b) Human operator uncertainty term. Dashed line is the upper bound for the uncertainty.

It is important to note that the stability analysis performed with these upper bounds is conservative in the sense that it doesn't completely capture the dependence of the uncertainty weighting function on the known variables, such as controller gains. For example, the bound in (25) is chosen to be a constant transfer function, whereas it is actually possible to pick an upper bound which is a function of the controller gains. This dependence is a nontrivial function of controller gains, so a constant upper bound is used here.

It is also possible to find a single upper bound for the combined environment and operator uncertainties. However, the combined bound would have been completely independent of controller gains, whereas the

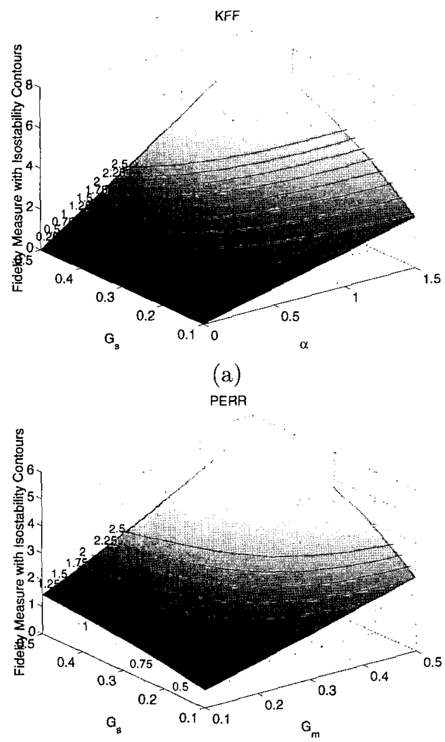

Figure 8: Fidelity of the PERR and KFF architectures as a function of controller parameters. Contours of constant stability are shown overlaid on the fidelity surface for comparison. Note that stability decreases as fidelity increases.

bound constructed from pieces have some (even though not complete) dependence from (12), since h_{22} is a function of controllers. This gives a less conservative upper bound than we would get with a single term.

The fidelity plots for the KFF and PERR controllers superimposed with isostability curves are shown in Fig. 8. The fidelity-stability trade-off can easily be observed on these plots, as the stability degrades as fidelity improves. The resulting *alpha*-curve is shown in Fig. 9. This curve predicts that using a force sensor will improve the performance and the KFF algorithm will perform best for the choice of the fidelity measure, tracking requirements, and the uncertainty bounds considered.

7 Discussion and Conclusion

As mentioned before, experimental evaluation of teleoperation systems is an important aspect of teleoperator controller design. Experiments comparing controllers designed following the methodology proposed in this paper are presented by the authors in [17], and it is one of the major thrusts of our future research.

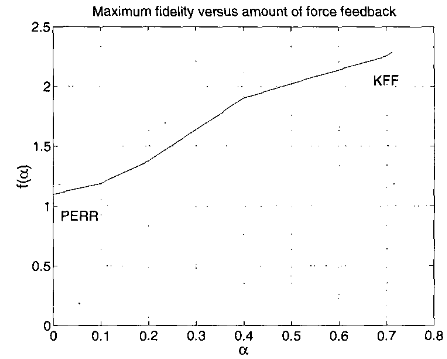

Figure 9: *Alpha*-curve for the teleoperation system studied

It is important to note that the stability measure developed here is on the conservative side, mainly due to modeling errors in the weighting functions. It was possible to manually increase the gains of the physical setup and still maintain stability. It would be more appropriate to use a structured uncertainty model to best capture this kind of uncertainty. We are currently working on using linear fractional transformations to develop a better uncertainty model.

We are also working on a more detailed model of the system which includes the noise and the dynamic characteristics of the force sensor which were not modeled in the analysis. Including the non-idealities of the sensors is important to make a better comparison between the sensory schemes. For example, absence of noise in the force sensor model gives an unfair advantage to the KFF algorithm in the *alpha*-curve analysis. These modeling efforts will emphasize developing other quantitative means to compare sensory schemes.

As the final words, we would like to reemphasize three important points: 1) In design of teleoperation systems, it is important to have task-based performance goals rather than trying to achieve a marginally stable, physically unachievable ideal teleoperator response. 2) Teleoperator control design should be explicitly formulated as an optimization to accommodate task-based performance metrics. 3) Design of the teleoperation system must be based on human perceptual capabilities. For this, it is necessary to quantify human perceptual capabilities, and to have means to incorporate them into the control design (design methodology, tools, and proper formulation). This paper addresses these points by proposing a new fidelity measure for the compliance discrimination task, and developing a design methodology using robust control theory for task-based optimization of the teleoperation controller, focusing on telemanipulation of deformable objects. The analysis has also been used to evaluate the improvement from the use of a force sensor in the teleoperation system.

Acknowledgments

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