Noise, But Not Uncoupled Stability, Reduces Realism and Likeability of Bilateral Teleoperation

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***Abstract*—In bilateral teleoperation, user performance, user acceptance, and transparency are functions of the control laws that govern slave tracking and master force feedback. This study investigates the effects of teleoperator stability margin and quantization error noise on performance, likeability, and realism for a palpation task. With low noise, increased controller stiffness resulted in higher realism ratings—even when operating above the uncoupled stability limit, where the system would be unstable if the user removed his or her hand. Our results did not show any significant negative effects of stability margin on likeability or performance. In contrast, as noise increased, we observed that perceived realism and likeability of haptic feedback decreased significantly. However, noise did not impact task performance. This work aims to aid teleoperator system designers to select control parameters based on their impact on likeability, realism, and performance.**

***Index Terms*—Haptics and Haptic Interfaces, Telerobotics and Teleoperation.**

I. Introduction

TELEOPERATION, in which an operator interacts with a remote environment by controlling a robotic tool, is used in minimally invasive robotic surgery, the nuclear industry, mining, bomb disposal, and many other scenarios. In bilateral teleoperation, kinesthetic (force) feedback is provided to the operator from the environment. Fig. 1a shows a schematic of a bilateral teleoperator. This kind of haptic feedback could enable users to perform teleoperated tasks with more speed, precision, and accuracy. However, results from research in bilateral teleoperation user acceptance are confusing. For example, in some cases, highly realistic feedback has no significant impact on task performance but receives positive reviews from users [1]. Alternatively, haptic teleoperators that produced significant improvement in task performance have received negative reviews from users [2]. An understanding of what factors make haptic feedback realistic or likeable to humans completing teleoperation tasks could facilitate better teleoperation control design choices.

Accurate haptic feedback renders impedance to the human that is similar to the impedance of the environment. Transparency is the similarity of position and force signals between the master and slave devices. Transparent haptic feedback minimizes the difference between the rendered impedance and environment impedance while also minimizing noisy force signals and maintaining system stability [3], [4]. A perfectly transparent teleoperator should feel as if the master device is interacting directly with the environment.

Unfortunately, bilateral teleoperator transparency is limited by stability and quantization error noise effects [4], [5]. Previous research has analyzed how stiffness, damping, time delay, and low-pass filtering impact the accuracy of kinesthetic feedback systems [6]. Understanding how control parameters such as these affect the balance of stability, transparency, and quantization error noise is helpful for designing haptic systems, but little research has been done on how these three fundamental parameters affect users' performance completing teleoperated tasks and how users *like* the feeling of the feedback.

Stability is dependent on many factors, including device physical properties, controller gains, and, particularly for teleoperators, time delay [7]. Stability can be ensured by the passivity of the teleoperator when coupled to a passive human and environment. Past researchers have explored methods for maximizing transparency while guaranteeing passivity [8], [9], [10]. However, passivity criteria can be overly conservative compared to uncoupled or coupled stability [3], [11]. Designing controllers for uncoupled stability—stability of the system when not in contact with a human operator or the environment—is less conservative, but serves as a practical stability condition for many scenarios. Targeting coupled stability—stability dependent on that contact—is even less conservative. Hulin et al. showed that including a human arm modeled as a mass-spring-damper in stability analysis broadens the range of virtual stiffness and damping that can be stably rendered in a haptic device [12], [13]. Similarly, Buerger and Hogan introduced *complementary stability*, a target for stability which considers a range of possible human dynamics [14]. A teleoperation device that is unstable when uncoupled (and therefore not passive) may be stabilized by contact with the user or the environment because of energy dissipating effects. Fig. 1b shows the dissipation of forces on a master teleoperator that is uncoupled unstable when contacted by the operator. However, it is unknown whether the behavior of a device that is uncoupled unstable has any effect on human operator performance or the likeability of the feedback. Operators may consciously or unconsciously modulate their arm dynamics to maintain system stability, affecting their perception of the haptic feedback.

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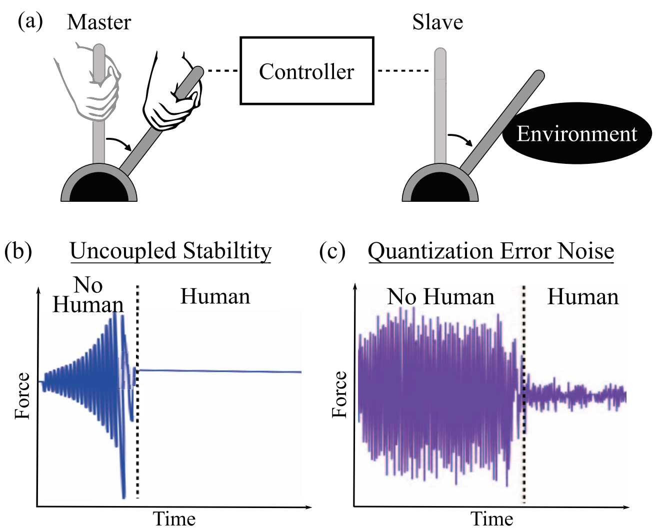

Fig. 1. (a) Schematic of a bilateral teleoperator. (b) Force on the master device with uncoupled-unstable dynamics, with and without human hand contact. (c) Force on the master device with noisy dynamics, with and without human hand contact.

Quantization error noise in kinesthetic feedback (high frequency force vibrations) also results in energy being dissipated through the operator's hand. It can cause unrealistic forces to be applied to the master device [15], and it may affect task performance and subjective experience. The controller stiffness as well as the quantization interval, damping gains, and filtering properties affect the level of quantization error noise. Fig. 1c shows the forces rendered to the master in a noisy teleoperator.

The behavior of an unstable teleoperator is different from the behavior of a noise sensitive teleoperator that has limit cycles. Specifically, an unstable teleoperator will feature asymptotically unbounded oscillations to any non-zero initial condition, while a "noisy" teleoperator will feature bounded limit cycles. Quantization introduces finite error, so it cannot cause a stable system to go unstable in the bounded-input, bounded-output (BIBO) sense [16].

Other researchers have investigated subjective responses to haptic refresh rate [17] or to different kinds of feedback in touch screens [18]. We aim to understand the effect that parameters such as stability and quantization error noise have on users' affective responses to haptic feedback in bilateral teleoperation systems.

In this letter, we consider a simple linear impedance bilateral teleoperation controller, i.e. a proportional-derivative controller on the position error between the master and slave. The proportional term acts as stiffness, and the derivative term acts as a damper. Higher controller stiffness creates a tighter coupling between the devices, improving the haptic transparency, which can improve user performance [19], [20], [21]. However, higher stiffness also reduces the teleoperator stability and increases noise.

In a palpation task, we investigated the effects of these parameters, focusing on how much operators like the haptic rendering, how realistic the haptic feedback feels, and how accurately users are able to identify stiffer regions of the environment.

Instability and noise can be studied separately by designing the teleoperator control law to be very stable, but sensitive to noise, or conversely, insensitive to noise, but close to instability. We predicted theoretical limit cycle and uncoupled instability boundaries and then confirmed them experimentally to select controller parameters that can separately analyze stability and noise. In half the feedback conditions tested, collectively called the *stability study*, quantization error noise in the system was removed with an aggressive low-pass filter, and stiffness gains ranged above and below the uncoupled-stability limit. In the other half of the feedback conditions tested, collectively called the *noise study*, noise was not filtered aggressively, allowing it to increase with increasing stiffness gains, and uncoupled stability was maintained.

Participants completed the palpation task and answered survey questions about the realism of the feedback and how much they liked it. In the *stability study*, we found that increasing stiffness above the uncoupled unstable limit did not degrade participants' ratings for likeability or realism, and performance was not significantly affected. Results from the *noise study* indicate that increasing quantization noise significantly hurt user ratings for likeability and realism, but did not result in worse task performance.

II. Modeling Uncoupled Stability and Limit Cycle Boundaries

In order to isolate uncoupled unstable and noisy behaviors, we used the models developed in [7] and [22] for a bilateral teleoperator consisting of two GeoMagic Phantom Premium 1.5 haptic devices and a simple proportional-derivative controller. Here, we describe the controller used in the study and the models used to predict whether a teleoperator with given stiffness, damping, and filter characteristics will exhibit uncoupled instability or limit cycles due to quantization error.

A. Bilateral Teleoperator Controller

In our teleoperator, the slave tracked the master based on the difference in position and velocity between the two devices. K is the position gain, B is the velocity gain, x_m is the position vector of the master, and x_s is the position vector of the slave.

$$f_m(t) = K[x_m(t) - x_s(t)] + B[\dot{x}_m(t) - \dot{x}_s(t)] \qquad (1)$$

The haptic feedback to the operator was the negative of the forces commanded to the slave:

$$f_s(t) = -f_m(t) \qquad (2)$$

The velocity of the devices was calculated by numerical differentiation and a second-order low pass filter:

$$\dot{x} = -f_p^2 \dot{x}_{-2} + 2 f_p \dot{x}_{-1} + (1 - f_p)^2 \dot{x}_0, \qquad (3)$$

where f_p is the filter parameter $f_p = e^{-2\pi f_0 T}$, in which f_0 is the filtering cutoff frequency, and $T = 0.625$ ms is the sample period. $\dot{x}_0$ is the current velocity estimate, calculated as $\dot{x}_0 = (x_0 - x_{-1})/T$. $\dot{x}_{-1}$ is the previous filtered velocity estimate, and $\dot{x}_{-2}$ is the filtered velocity estimate from two samples ago.

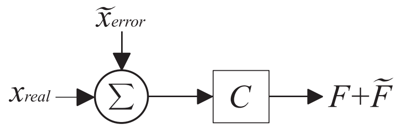

Fig. 2. Block diagram representation of the addition of quantization error modeled as pseudo-quantization noise, manifesting as an output error force $\tilde{F}$. C is the transfer function from position to force given by Equation (6).

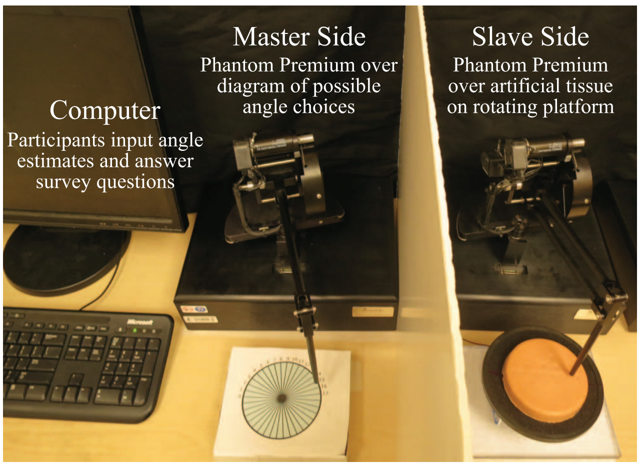

Fig. 3. The experimental setup. Participants sat at a computer next to the master Phantom Premium. A diagram on the table below the master portrays possible angles of the stiff tube. A divider obscures a slave Phantom Premium, the artificial tissue, and the rotating platform from the participant's view.

B. Uncoupled Stability

We used a continuous model for the teleoperator and approximated time delay with a fifth order Pade approximate, P. The theoretical closed-loop impedance Z_{to} transmitted to the operator is given by

$$Z_{to} = \frac{F_h}{V_h} = \frac{(Z_m + C_m P)(Z_s + C_m P + Z_e) + C_{ms} C_{sm} P^2}{Z_s + C_s P + Z_e}. \tag{4}$$

The impedance of the master, slave, and environment are:

$$\begin{aligned} Z_m &= m_m s + b_m \\ Z_s &= m_s s + b_s \\ Z_e &= 0 \end{aligned} \tag{5}$$

where m_m and b_m are the mass and damping of the master, respectively. The slave impedance (m_s and b_s) is the same as the master for our setup. We model the environment with zero impedance, corresponding to no contact between the teleoperator and a human or environment.

In our simple controller, the control terms are all equivalent:

$$C_m = C_s = C_{sm} = C_{ms} = \frac{K}{s} + \frac{f_0}{s + f_0} B \tag{6}$$

For no artificial time delay, the average delay in the system due to sample and hold effects is $T/2$, where T is the sample period. By evaluating the poles of Equation (4) it is possible to predict theoretical uncoupled stability limits for a teleoperator for different values of K, B, and f_0 in the controller. A transfer function with poles in the right-half-plane will be unstable. In this way, we are able to study how likeability, realism, and user performance may vary for teleoperators above and below the uncoupled stability limit.

C. Limit Cycles From Quantization Error Noise

We model the noise in our system as white noise, or pseudo quantization noise (PQN), as proposed by Bennett [23]. In [22], encoder error is characterized for robotic systems, and, in particular, kinesthetic feedback haptic devices. A diagram of the PQN model is provided in Figure 2. The average actuator error force is

$$\tilde{F} = ||C||_{H_2} \Delta \tag{7}$$

where Δ is the quantization interval and $||C||_{H_2}$ is the H_2 norm of transfer function from the error source to the actuator. If the average noise force from quantization is greater than the Coulomb friction in the teleoperator, limit cycles are probable [22], [24], [25].

III. Methods

Ten healthy individuals (5 male and 5 female, ages 22 to 30) participated in the experiment with informed consent. All participants were right-handed and had experience with haptic devices and teleoperation. The Stanford University Institutional Review Board approved the experimental protocol.

A. Task

In the experiment, modeled after similar experiments in [26], [27], participants operated a bilateral teleoperator consisting of two Phantom 1.5 Premiums (GeoMagic) to palpate a disk made of soft artificial tissue with a thin, stiff tube embedded across its diameter one centimeter beneath the surface Fig. 3. The goal of the task was to discern the angle of the tube. This task was chosen because it requires haptic feedback and the performance metric is straightforward [2]. Three parameters of the teleoperator controller were varied across the trials: stiffness, damping, and low-pass cutoff frequency filtering of the velocity estimate. After each trial, participants answered questions about the realism and likeability of the haptic feedback condition provided.

B. Experimental Setup

Fig. 3 shows the experimental setup. Participants manipulated the stylus of the master haptic device, linked by a bilateral proportional-derivative controller to a slave haptic device, to interact with artificial tissue. Fig. 4 shows the nonlinear stiffness characteristics of the soft tissue and the region where the tube was embedded. The artificial tissue was placed on a motorized platform that rotated the tissue between trials. The slave and the tissue model were occluded with a wooden divider. On the master side, a paper circle corresponded to the position of the circular tissue model so that participants would know where

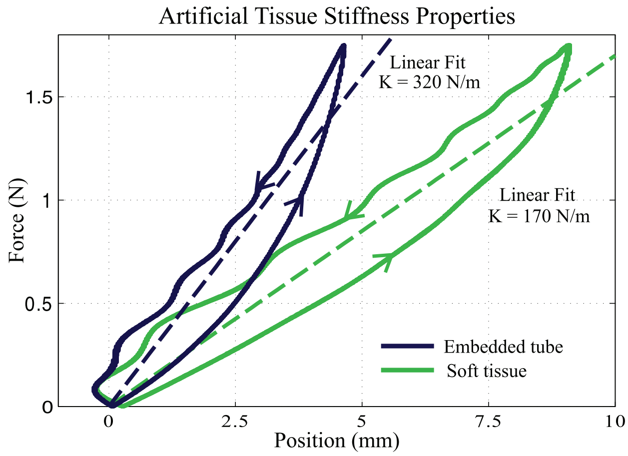

Fig. 4. The nonlinear force-displacement characteristics of the artificial tissue and embedded tube for 12 palpation cycles. The tube region has a higher stiffness.

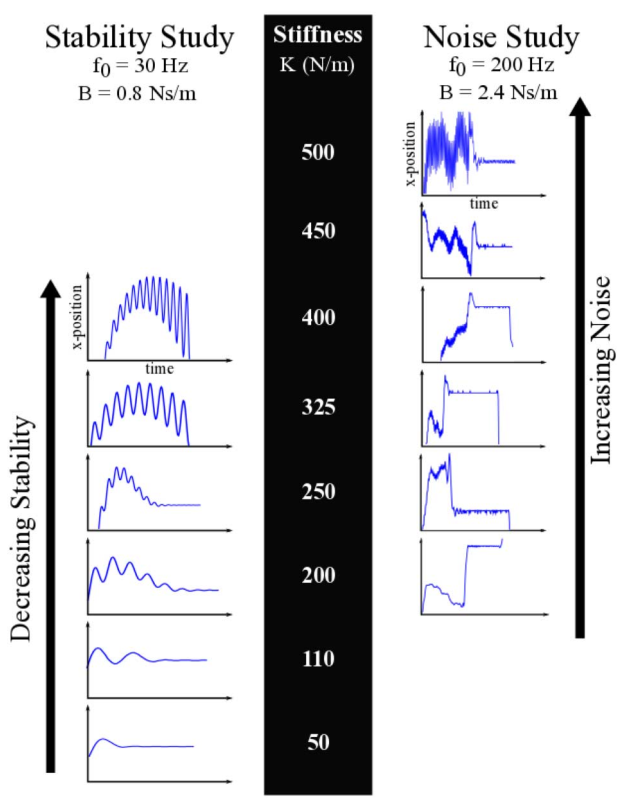

Fig. 5. The two studies each had six conditions: in the *stability study*, the filtering cutoff frequency and damping are low, and stability degrades as stiffness increases, eventually becoming uncoupled-unstable. In the *noise study*, the filter cutoff frequency and damping are higher, and forces felt by the master are noisier as stiffness increases.

the stylus was positioned in relation to the tissue. Eighteen lines were drawn at equally spaced angles across the center of the paper circle, corresponding to angles at which the tube could be oriented.

C. Procedure

Before beginning the experiment, participants interacted with the artificial tissue on the slave side of the setup both with their fingers and while holding the slave stylus. Participants then completed six practice trials using the teleoperator for various feedback conditions. They were instructed to keep their right hand on the stylus to maintain coupling between the participant and the master device, preventing potential unstable activity. Participants wore headphones playing white noise to mask sounds from the devices or rotating platform. Each participant completed 24 experimental trials.

In each trial, the participants manipulated the master stylus to palpate the tissue with the slave Phantom stylus. The participants' objective was to determine which line on the paper circle in front of the master corresponded to the angle of the embedded tube in front of the slave. The tissue model was rotated to a different orientation between each trial.

After each trial, the computer screen prompted participants to respond to three survey questions with ratings from 1-5, similar to a 5-point Likert Scale, with corresponding descriptions to clarify the decision:

1) How accurately do you think you were able to determine the orientation of the stiffer region? (1: I just guessed. 5: It is probably within 10° of my estimate.)
2) How realistic did the haptic feedback feel? (1: There are many dissimilar sensations between the two. 5: It felt exactly the way the actual tissue felt.)
3) How much did you like the way the feedback felt? (1: It was extremely unpleasant and annoying. 5: I would be comfortable experiencing feedback like that for long periods of time.)

We view realism and likeability as separate parameters: realism is related to the accuracy of the feeling of the tissue, and

TABLE I
THE CONTROLLER PARAMETERS SELECTED FOR IN THIS STUDY ARE PREDICTED TO HAVE THE FOLLOWING STABILITY AND NOISE PROPERTIES BY THE THEORETICAL MODELS

	Stability Study	
Stiffness [Nm]	Poles in RHP	Average Noise Force [N]
50	No	0.010
110	No	0.013
200	No	0.018
250	No	0.021
325	Yes	0.025
400	Yes	0.029
	Noise Study	
200	No	0.138
250	No	0.140
325	No	0.143
400	No	0.147
450	No	0.149
500	No	0.152

TABLE II
RESULTS OF MIXED EFFECTS MODELS FOR BOTH STUDIES

Stability Study			
	Likeability	Realism	Angle Error
Fixed Effect	1.20×10^{-3}	4.28×10^{-3}	-0.02379
p-value	0.459	0.006	0.1975
Noise Study			
	Likeability	Realism	Angle Error
Fixed Effect	-1.28×10^{-2}	-8.13×10^{-3}	0.0223
p-value	3.63×10^{-8}	1.38×10^{-5}	0.2189

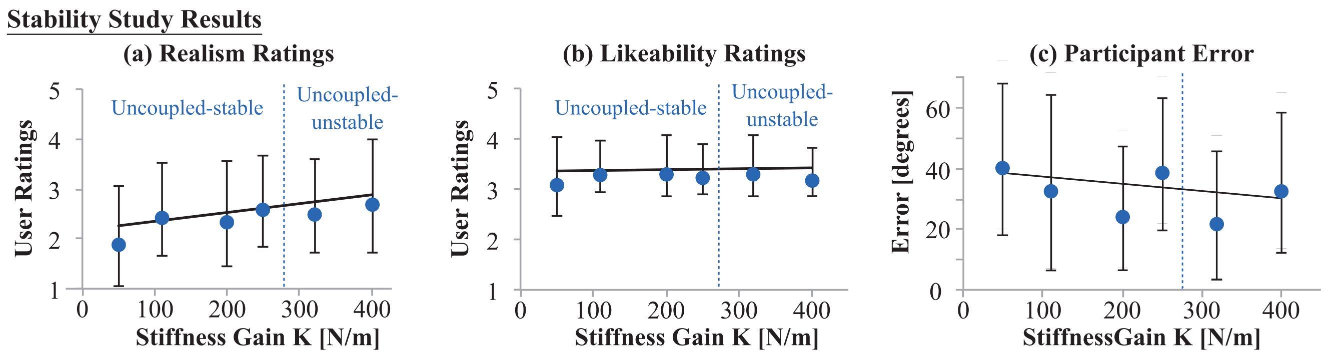

Fig. 6. (a) Realism Ratings Increased With Increasing Stiffness Gains, Even Above the Uncoupled-Unstable Limit. (b) Likeability Ratings and (c) Participant Error Identifying the Stiff Tube Did Not Change Significantly With Stiffness Gains.

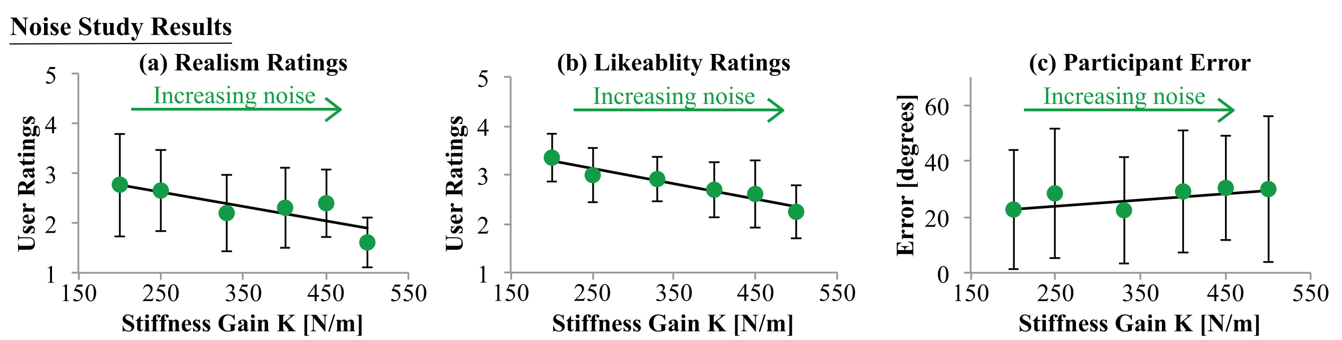

Fig. 7. (a) Realism ratings and (b) likeability ratings dropped as noise increased with controller stiffness. (c) Participant performance did not change significantly with changing stiffness gains.

likeability is how the participant felt about the feeling of operating the haptic device in general, not just in contact with the artificial tissue.

In each trial, the parameters of the teleoperator controller were varied to explore stability margin and quantization error noise. Twelve different feedback conditions were used, and they are listed in Fig. 5. Six conditions were selected for the *stability study* to have low noise and span above and below the uncoupled stability limit. Another six conditions were selected for the *noise study* to be stable even when uncoupled, but experience increasingly noticeable limit cycles. Predicted behavior for each feedback condition, in terms of instability and limit cycles, is provided in Table I. Uncoupled instability occurs in controllers with poles in the right-half plane, exhibited as exponentially growing oscillations in response to an impulse. The friction force in our teleoperator is 0.145 N, so controllers with an average noise force above that show limit cycle behavior, exhibited as bounded oscillations. The predictions were confirmed experimentally.

For the *stability study*, the damping gain was constant at $B = 0.8$ Ns/m and the velocity estimate was filtered with a second-order filter with a cutoff frequency of 30 Hz. This resulted in haptic feedback with very low noise and uncoupled unstable behavior for stiffness conditions above 250 N/m, as predicted by theoretical calculations and confirmed experimentally. In the *noise study* the damping gain was set at $B = 2.4$ Ns/m, and a second-order filter with a cutoff frequency of 200 Hz was used for the velocity estimate. With these parameters, the limit on the stiffness gain to maintain uncoupled stability was well above 500 N/m, which was the maximum used in these trials. The noise felt by the participant increased with increasing stiffness gains. Fig. 5 shows the stability margin and/or noise properties of each of the six conditions used in the two studies. The range of stiffnesses for the two trials is different because of the effect that filtering quantization noise has on stability. Aggressive filtering in the *stability study* reduces the stability limits. Allowing higher frequency force signals through, as in the *noise study*, allows for higher stiffness gains while maintaining uncoupled-stability.

D. Analysis

The parameter used to evaluate task performance was the error in degrees between the actual orientation of the stiff tube and the participant's selected orientation. For assessing subjective views of the haptic feedback, we used participant ratings to determine the realism and likeability of the teleoperator conditions. Repeated measures were taken on the same participants over a range of stiffness values, and there was variation between participants. We assumed that the random effect due to differences between participants was normally distributed. Checking for normality of residuals and random effects, we analyzed the results for task performance using the following linear mixed effects regression model:

$$y = \beta_K K + bS + \beta_0 + \epsilon, \tag{8}$$

where y is the parameter of interest (error), β_k is a fixed effect parameter to model the effect of stiffness gain K, b is a random effect parameter to model the differences across participants S, B_0 is an intercept value, and ϵ is residual error. Statistical significance was determined using a maximum-likelihood test.

For likeability and realism ratings, we used ordinal logistic regression models, as described in [28]. Statistical significance was assessed using the Wald Statistic. All statistical analyses were completed using R's *lme4* and *ordinal* packages [29].

IV. Results

A. Stability Study

Table II lists the fixed effects from the models as well as the p-values from the maximum likelihood tests, and Fig. 6 shows the mean ratings with standard deviations and linear fits for increasing stiffness gain. In the *stability study*, the mean realism rating was 2.57 (out of 5) with a standard deviation of 1.01. Increasing the stiffness gain slightly improved the ratings for realism Fig. 6a). The results of the ordinal logistic regression and Wald test confirmed that this was a significant effect (p = 0.006) . The mean likeability rating was 3.39 (out of 5) with a standard deviation of 0.58, and there was no significant change in likeability with increasing stiffness, as is seen in Fig. 6b. The mean error in identifying the stiff tube's orientation was 34.5° with a standard deviation of 24.2°. Average participant performance for this task was poor but better than chance, which would have resulted in a mean error of 45°. There was very high variance in performance results, which may be due to the difficulty of the task. There was a slight but not significant improvement in performance as stiffness increased (as seen in Fig. 6c).

B. Noise Study

Table II also lists the fixed effect values, intercepts, and p-values for the *noise study*. The mean realism rating was 2.31 (out of 5) with a standard deviation of 0.85. The mean likeability rating was 2.80 (out of 5) with a standard deviation of 0.64. There was a clear decline in both realism and likeability ratings as the stiffness gain K increased, as shown in Fig. 7a and 7b. Wald statistics confirmed a significant effect of controller stiffness on likeability and realism ($p = 3.63 \times 10^{-8}$ and 1.38×10^{-5}, respectively). We observed a very slight increase in participants' error as stiffness and noise increased, and it was not significant Fig. 7c). The mean error was 27.2°, with a standard deviation of 21.7°. In both the *stability study* and the *noise study*, variance was high.

V. Discussion

Increasing teleoperator controller stiffness creates a tighter coupling between the master and slave devices, resulting in more accurate force rendering and improved transparency. Higher stiffness gains have been shown to improve user performance in discrimination tasks such as palpation [19], [21]. Unfortunately, increasing stiffness also amplifies noise due to quantization error and reduces system stability. Filtering high frequency signals in velocity estimates can reduce this noise, but it also limits stiffnesses that can be rendered while maintaining passivity or uncoupled stability. Our goal was to understand how (1) decreasing stability or (2) increasing noise affects how realistic haptic feedback feels and how likeable it is. Here, we discuss the insights gained from the two studies.

A. Uncoupled-Instability Did Not Negatively Affect User Performance or Subjective Response

Most haptic systems are designed to maintain passivity, which is a conservative way to guarantee stability, but in our study controller gains were selected that spanned stable and uncoupled-unstable. Contact with the operator's hand can stabilize a system that, on its own, would be uncoupled-unstable [12]. The human dissipates energy, maintaining overall system stability. Coupled stability is a realistic stability requirement for many tasks. For some tasks, the user may be touching the device at all times, or, less strictly, at all times that the teleoperator must render high forces from contact with the environment. Tasks could be designed so that a teleoperator is coupled to a material providing some impedance when it is released from the user's grasp, or so that controller stiffness is adjusted during a task based on sensed user coupling. In situations such as these, designers can take advantage of coupled stability to allow higher stiffness gains than for a passive system.

To date, whether active behavior of a haptic device (behavior of a system that is outside the passivity bounds) feels unpleasant to human operators has not been characterized quantitatively. Although a coupled system of this type is stable, the device is doing work on the human, which, we hypothesized, could result in discomfort. We were also interested in discovering any effects on performance due to possible modulation of the user's impedance to stabilize an uncoupled-unstable system.

The results from this experiment indicate that there is not a negative effect of operating in the uncoupled-unstable stiffness region. There was no significant change in the likeability ratings throughout all the trials in the *stability study*. Additionally, there was a significant increase in users' ratings for realism of the feedback as stiffness increased. This is consistent with what we would expect as transparency increases, even though the system was uncoupled-unstable at the two highest stiffnesses tested. These results imply that bilateral teleoperators that are active but stable through coupling with the user provide improved haptic realism and do not result in negative user reactions despite the user playing a role in stabilization Fig. 6. In lightweight teleoperators where operator safety can be assured, limiting controllers by passivity is more conservative than necessary, and coupled stable systems should be considered. We believe this idea extends to additional tasks and devices, and experiments with other teleoperators would clarify the user impedance required to make uncoupled stability a realistic control goal.

We anticipated that task performance would improve with increasing stiffness gains, as the slave-side forces are rendered more accurately to the operator. However, for this task there was no significant improvement as *K* increased. There was also no clear change in performance above the uncoupled unstable limit. This was a difficult palpation task with high mean errors and variance, which may explain the lack of significant improvement as transparency increased, yet results indicate that active or uncoupled unstable systems do not degrade task performance. Performance and likeability are not impaired, and users rate higher stiffness controllers as more realistic regardless of passivity. This underscores the importance of approaches that take advantage of human effects on system dynamics, e.g. [12], [13], [14]. For many teleoperators, a broader range of control parameter values can be used than just those that maintain complete system passivity.

B. Increasing Noise Reduced Realism and Likeability

Without heavy filtering, increasing controller stiffness amplifies noisy force signals rendered to the user. By filtering the velocity estimate, the noise can be reduced, but the stability of the system is compromised. Teleoperator controllers must trade off transparency and noise while maintaining stability. In the *noise study*, we selected parameters that maintained complete stability for all trials and applied a filter with a high cutoff frequency of 200 Hz, allowing noise to increase noticeably with increasing stiffnesses, with limit cycles probable for the three highest stiffnesses used. In this way we explored the effect of increasing noise independently of stability effects. User ratings from the *noise study* indicate that the realism of the haptic rendering as well as how much operators like the feedback declines with increasing noise Fig. 7a and b). However, performance completing the task was not significantly affected. Although it is not surprising that noise in the force signal makes haptic feedback less compelling for the user, we believe that understanding this is valuable for designing controllers. It is important that teleoperators do not sacrifice comfortable, low-noise feedback for higher stiffness gains.

Performance was slightly better in the *noise study* than in the *stability study*. This may be due to the use of higher stiffness parameters. These were selected to provide the best range of noisy force signals. It is also possible that the removal of high-frequency forces in the *stability study* eliminated some valuable feedback, making it more difficult to identify the stiffer region. While this was not a focus of our experiment, examination of the value of high-frequency force signals could further improve teleoperator controller design.

C. Designing Controllers With User Acceptance in Mind

Previous work has developed relationships between controller parameters and their effects on stability, noise, and haptic accuracy [6], and here we extended this to understand the impact on the operator. Both uncoupled-instability and quantization error noise result in the system doing additional work on the operator's hand to dissipate energy. However, in this preliminary investigation we found that this energy was experienced in different ways by the users. While noise can have a dramatic negative effect on users' feelings about haptic feedback, decreasing stability beyond the uncoupled-stability limit does not. Considering operator coupling with the device creates an opportunity to use higher stiffness gains without negatively impacting performance, haptic realism, or likeability. However, noise in the force feedback needs to be limited to make operating a teleoperator a comfortable experience. Further research can be performed to understand in more detail how changing control parameters can impact user subjective acceptance of teleoperators and task performance. Managing the trade-offs of transparency, noise, and stability is a challenge in bilateral teleoperation, and exploring the effects of these trade-offs on users can help guide the selection of controller gains.

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