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Improvement of Model-Mediated Teleoperation using a New Hybrid Environment Estimation Technique

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***Abstract*— In a haptic teleoperation system, the incorporation of knowledge about the remote environment in the controller design can improve stability and performance. Model-mediated teleoperation adopts this idea by rendering an estimated model of the remote environment on local site instead of transmitting force/velocity flows. Thus, the user perceives locally generated forces corresponding to the estimated and transmitted model parameters and the control loop between master and slave is opened. Less conservative stability boundaries and the applicability to teleoperation systems with arbitrary time delay are the main advantages of this approach. In order to guarantee a high fidelity, the estimation has to fit well with the measurements. In this paper, we extend the approach of model-mediated teleoperation to a full 6 degrees-of-freedom (DOF) teleoperation system with negligible time delay. We furthermore propose a hybrid approach for the estimation of the remote environment by combining the classical Kelvin-Voigt model and the nonlinear Hunt-Crossley model. Persistent excitation and device-dependent limitations of the estimation algorithm are discussed. Experimental results show stability and accuracy of the estimation technique as well as a superior fidelity of the proposed approach compared to a position-based admittance controller with fixed parameters even with negligible time delay.**

I. Introduction

Haptic teleoperation systems allow a human operator to perform complex tasks through a teleoperator or slave while receiving feedback about the interaction between robot and remote environment. Main objectives for the controller design are *robustness* and *transparency*. The controller is required to be robustly stable with respect to a prespecified set of uncertainties introduced by operator, remote environment, communication channel, and sensors. Transparency means that the technical medium between operator and remote environment is not felt. The two objectives are, however, conflicting, see [1], such that a compromise has often to be found. A measure for transparency is *fidelity*. It captures the capability of a teleoperation system to accurately display the remote environment to the operator.

In an extensive survey by Hokayem & Spong [2], a large amount of control architectures are reviewed. Yet, most of these approaches do not exhibit a high degree of fidelity.

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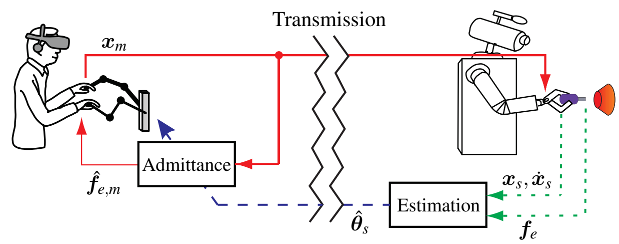

Fig. 1. Model-mediated teleoperation scheme

One of the reasons is, that the control loop is always closed over the communication channel. Thus, back in 1989, Hannaford [3] proposed the so-called *bilateral impedance control*. Instead of transmitting efforts and flows, he proposed to exchange estimated operator and environment impedances. This leads to two decoupled control loops on operator and teleoperator site. With the focus on estimating the environment impedance, similar approaches, also called impedance reflecting, virtual-reality based or *model-mediated* teleoperation have been recently proposed by various research groups [4]–[10]. As shown in Fig. 1, the environment impedance is estimated on teleoperator site and transmitted and recreated as a virtual environment (VE) on operator site. The benefits of this approach were shown in [8] in terms of fidelity improvement and in [10] in terms of a significantly improved feeling of perceived realism. The main differences between the approaches are the estimation algorithm as well as the updating procedure of the virtual model.

The requirement for model-mediated teleoperation to work properly is an accurate estimation of the interaction between teleoperator and remote environment. Consequently, one of the main challenges is to automatically gain accurate object dynamics, when contact occurs on the remote site. The two main models used in robotics research are the linear *Kelvin-Voigt* model and the nonlinear *Hunt-Crossley* model. In the above mentioned approaches, the underlying model is in all cases the Kelvin-Voigt model, except in [4], where a mass-spring-damper system is used. However, due to physical inconsistencies, the Kelvin-Voigt model is not suitable to accurately model soft objects. We will therefore adopt a hybrid modeling approach, including both, the linear Kelvin-Voigt and the nonlinear Hunt-Crossley model.

For stiff objects, the Kelvin-Voigt model is the simplest model due to its linearity and does not show inaccuracies for these kind of objects. Estimation of parameters of the Kelvin-Voigt model for use in a model-mediated teleoperation approach is typically performed by adapting recursive least-squares (RLS) approaches with constant forgetting factor as in Weber et al. [10] or using self perturbation as in Mobasser & Hashtrudi-Zaad [5]. Also, an adaptive control method has been proposed by Tzafestas et al. [8].

The nonlinear Hunt-Crossley model allows for a consistent dynamic description especially of soft materials. Online RLS estimation techniques for the use in robotic systems have been developed by Diolaiti et al. [11] and Haddadi & Hashtrudi-Zaad [12]. To our knowledge, an application to teleoperation has not been presented.

In this paper, we extend the model-mediated teleoperation approach to arbitrary point contacts between slave end-effector and remote object. The approach is applicable to peg-in-hole tasks, e.g. replacing a screw, repairing tasks like screwing or palpation tasks like in minimally invasive surgery. The proposed approach allows motions and provides haptic feedback in 6 DOF. Furthermore, we propose a new hybrid model for describing the interaction between teleoperator and static objects. Due to its simplicity and due to the dynamic behavior of the parameter estimation, we prefer the Kelvin-Voigt model for describing stiff objects, while we use the Hunt-Crossley model for soft objects. We then propose to switch between these models, depending on the encountered object type. A self-perturbing recursive least-squares algorithm (SPRLS) is chosen as estimation method. For the proposed estimation method, we discuss persistent excitation and device-dependent limitations. The model-mediated control approach is verified on a 6 DOF robotic teleoperation system with negligible time delay in the communication channel. We can show an improved fidelity in terms of smaller virtual mass and damping for the model-mediated control approach compared to a position-based admittance controller with fixed parameters.

The paper is organized as follows: in Sec. II, a hybrid environment model is presented. In Sec. III, the SPRLS is introduced and persistent excitation and device-dependent estimation limitations are analyzed. In Sec. IV, the control design for model-mediated teleoperation is presented. Experimental setup and results for model-mediated and admittance controller are described in Sec. V. The results are compared in terms of stability and fidelity. Sec. VI concludes the paper with a summary and outlook.

II. Environment Modeling

The choice of a suitable environment model is based on the following assumptions about teleoperator and environment:

- The end-effector tool is rigid with a small contact area. Grasping does not occur.
- The objects are static and their surface is smooth. Motions tangential to the surface are not considered, i.e. the geometry of the object is not estimated.
- The dynamics of the remote object are not coupled with each other in different directions of penetration.
- Damping can only occur when pushing into the object. Otherwise, we would assume, that the robot's tool sticks together with the object.

With these assumptions, the simplest and most popular model is the linear Kelvin-Voigt model (KVM). In order to account for the unilateral damping, enforced by the last assumption, the damping term of the original KVM is slightly modified. The mechanical equivalent of this model is the parallel of a spring and a unilateral damper. For translations, the object dynamics are described in Cartesian space as

$$\boldsymbol{f}_e = \begin{cases} \boldsymbol{K}_{kv}\delta\boldsymbol{x}_s + \boldsymbol{B}_{kv}\delta\dot{\boldsymbol{x}}_s, & \text{if } \delta\boldsymbol{x}_s \geq 0 \wedge \delta\dot{\boldsymbol{x}}_s \geq 0 \\ \boldsymbol{K}_{kv}\delta\boldsymbol{x}_s, & \text{if } \delta\boldsymbol{x}_s \geq 0 \wedge \delta\dot{\boldsymbol{x}}_s < 0 \\ 0, & \text{else} \end{cases} \tag{1}$$

where $\boldsymbol{f}_e$ are the measured contact forces and $\delta\boldsymbol{x}_s, \delta\dot{\boldsymbol{x}}_s$ are penetration depths and velocities into the remote object. The matrices $\boldsymbol{K}_{kv}$ and $\boldsymbol{B}_{kv}$ represent the object's stiffness and damping of the KVM in the different directions. Due to the assumption of decoupled dynamics, they are diagonal.

In the original version of the KVM without unilateral damping, the stiffness term vanishes at the beginning and end of contact, as the penetration depth is zero, and the environment is only represented by the damping term. Since the velocity is not necessarily zero at these moments, a non-zero force jump can occur, when contact is established and lost. This furthermore implies, that some power $P = \boldsymbol{f}_e\delta\dot{\boldsymbol{x}}_s$ is already stored at the beginning and end of contact, as shown in Fig. 2. This, however, is contradictory to physical observations. In a modified KVM with a unilateral damping as presented above, the power jump occurs only, when contact is established, while it is removed at the end of contact, see Fig. 2. Furthermore, the modified KVM does not lead to negative forces at the end of the restitution phase caused by a negative velocity. This property avoids a sticky feeling when releasing contact with the object.

As damping is not negligible compared to stiffness for soft objects, the discontinuity of the power flow is not negligible either and limits the applicability of this model for soft objects. Regarding stiff objects, the Kelvin-Voigt model may be even superior to the Hunt-Crossley model, as it captures by construction the linearity between $\boldsymbol{f}_e$ and $\delta\boldsymbol{x}_s$, which is characteristic of stiff objects. This again facilitates the estimation process, as will be shown in experiments. Furthermore, the damping term becomes negligible compared to the stiffness term for these materials, reducing considerably the magnitude of the power flow discontinuity at the beginning of contact. Therefore, we will further work with this model, when interaction with stiff objects occurs.

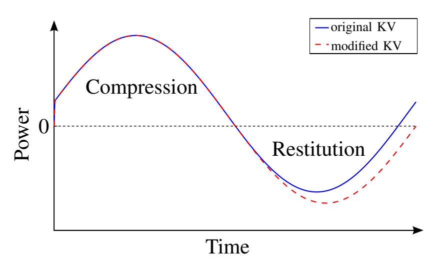

Fig. 2. Power flow for the Kelvin-Voigt model

For soft objects, the Hunt-Crossley model (HCM) is chosen. Physical inconsistencies are avoided and the nonlinear behavior of soft objects is captured more precisely. Similar to the modification for the Kelvin-Voigt model, a unilateral damping is introduced. The dynamics is described as

$$\boldsymbol{f}_e = \begin{cases} \boldsymbol{K}_{hc}\delta\boldsymbol{x}_s^{\boldsymbol{n}_{hc}} + \boldsymbol{B}_{hc}\delta\boldsymbol{x}_s^{\boldsymbol{n}_{hc}}\delta\dot{\boldsymbol{x}}_s, & \text{if } \delta\boldsymbol{x}_s \geq 0 \wedge \delta\dot{\boldsymbol{x}}_s \geq 0 \\ \boldsymbol{K}_{hc}\delta\boldsymbol{x}_s^{\boldsymbol{n}_{hc}} & \text{if } \delta\boldsymbol{x}_s \geq 0 \wedge \delta\dot{\boldsymbol{x}}_s < 0 \\ 0 & \text{else} \end{cases} \tag{2}$$

with $\delta\boldsymbol{x}_s^{\boldsymbol{n}_{hc}} = [\delta x_{s,1}^{n_{hc,1}} \; \delta x_{s,2}^{n_{hc,2}} \; \delta x_{s,3}^{n_{hc,3}}]$. The matrices $\boldsymbol{K}_{hc}$ and $\boldsymbol{B}_{hc}$ capture the parameters of the HCM. The exponent $\boldsymbol{n}_{hc}$ reflects contact geometry and material by altering the stiffness depending on the size of the contact area. Another aspect of the HCM is the dependency of the damping term on the penetration depth. As a result the damping term vanishes when the displacement becomes small, hence avoiding physical inconsistencies when establishing and loosing contact.

As outlined above, the choice of the model depends on the encountered object type. We therefore propose a *hybrid object modeling approach*, in which the Kelvin-Voigt model is selected for stiff objects and the HCM for soft objects. The estimation is running for both models during contact with an object. Initially the Kelvin-Voigt model is assumed. After a time of 50 ms to check the convergence of both models, a switching between both models occurs if the estimated stiffness of the Kelvin-Voigt model $\boldsymbol{K}_{kv}$ falls below a prespecified threshold k_{th} in one direction. This hybrid switching between the models *Kelvin-Voigt model* (*kv*), and *Hunt-Crossley model* (*hc*) can be described by the switching operator $\mathbf{S}(\cdot)$ in direction i:

$$\mathbf{S}(\boldsymbol{k}_{kv}) = \begin{cases} kv, & \text{if } k_{i,kv} \geq k_{th} \\ hc, & \text{else.} \end{cases} \tag{3}$$

As the estimation error is small enough for both models when switching, force discontinuities are not perceivable.

III. Estimation Technique

A. Algorithm

Recursive least square schemes with different modifications allow for a fast converging and stable estimation. In this paper, the SPRLS as proposed in [13] is employed. This algorithm showed superior convergence speed and tracking properties compared to RLS with variable forgetting factor or adaptive identification techniques. In general, the least squares estimation can be described as an optimization problem where the estimation error $\hat{\boldsymbol{e}} = \boldsymbol{y} - \hat{\boldsymbol{y}}$ between measured and estimated system output has to be minimized. The model has to be transformed into the *linear-in-parameter* form $\boldsymbol{y} = \boldsymbol{\theta}^T\boldsymbol{\phi}$ with $\boldsymbol{y}$ the system output and $\boldsymbol{\phi}$ consisting of input variables. Using the SPRLS algorithm, the optimal estimate of the parameter vector $\hat{\boldsymbol{\theta}}$ can be found by solving the following set of equations at each discrete time step k:

$$\hat{\boldsymbol{\theta}}_k = \hat{\boldsymbol{\theta}}_{k-1} + \boldsymbol{K}_k\left(y_k - \boldsymbol{\phi}_k^T\hat{\boldsymbol{\theta}}_{k-1}\right) \tag{4}$$

$$\boldsymbol{K}_k = \boldsymbol{P}_{k-1}\boldsymbol{\phi}_k\left(1 + \boldsymbol{\phi}_k^T\boldsymbol{P}_{k-1}\boldsymbol{\phi}_k\right)^{-1} \tag{5}$$

$$\boldsymbol{P}_k = \left(\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{\phi}_k^T\right)\boldsymbol{P}_{k-1} + \beta\mathbf{NINT}(\gamma\hat{e}_{k-1}^2)\boldsymbol{I}. \tag{6}$$

where β is a design constant and γ the sensitivity gain. These parameters have to be adjusted with respect to the measurement noise of $\boldsymbol{y}_k$ and $\boldsymbol{\phi}_k$. The function $\mathbf{NINT}(\cdot)$ is defined as a component-wise round off operator:

$$\mathbf{NINT}(\gamma\hat{e}_{k-1}^2) = \begin{cases} \gamma\hat{e}_{k-1}^2, & \text{if } \gamma\hat{e}_{k-1}^2 \geq 0.5 \\ 0, & \text{else.} \end{cases} \tag{7}$$

In the original RLS, the covariance matrix $\boldsymbol{P}_k$ would become small, if the estimation error $\hat{e}_k$ gets small. This in turn would lead to a decline of the adaptation matrix $\boldsymbol{K}_k$ and the algorithm would become unable to react on parameter changes. The self perturbation term in (6), as proposed by [12], is introduced to avoid this behavior. The algorithm acts like the general RLS algorithm whenever $\hat{e}_{k-1}$ is within the maximum error bound defined by γ. Otherwise the self perturbation is activated and $\boldsymbol{K}_k$ increases automatically whenever a parameter change occurs and $\hat{\boldsymbol{e}}_{k-1}$ increases.

B. Adaptation to Kelvin-Voigt and Hunt-Crossley model

The Kelvin-Voigt model can be transformed into the linear-in-parameter form without further modifications: $\boldsymbol{y}_s = \boldsymbol{f}_e$, $\boldsymbol{\phi}_s = [\delta\boldsymbol{x}_s \; \delta\dot{\boldsymbol{x}}_s]^T$ and $\hat{\boldsymbol{\theta}}_s = [\boldsymbol{K}_{kv} \; \boldsymbol{B}_{kv}]^T$.

Due to its nonlinearity, the Hunt-Crossley model is not suitable for the SPRLS estimation in its original formulation. According to [14], a solution is to linearize the model's equation by taking the natural logarithm of (2):

$$\ln(\boldsymbol{f}_e) = \ln(\boldsymbol{K}_{hc}) + \boldsymbol{n}_{hc}\ln(\delta\boldsymbol{x}_s) + \ln(1 + \boldsymbol{K}_{hc}^{-1}\boldsymbol{B}_{hc}\delta\dot{\boldsymbol{x}}_s). \tag{8}$$

By assuming that $\ln(1+\alpha) \cong \alpha$ for $|\alpha| \ll 1$ equation (8) can be rewritten as:

$$\ln(\boldsymbol{f}_e) = \ln(\boldsymbol{K}_{hc}) + \boldsymbol{n}_{hc}\ln(\delta\boldsymbol{x}_s) + \boldsymbol{B}_{hc}\boldsymbol{K}_{hc}^{-1}\delta\dot{\boldsymbol{x}}_s. \tag{9}$$

Equation (9) only holds if the term $\boldsymbol{K}_{hc}^{-1}\boldsymbol{B}_{hc}\delta\dot{\boldsymbol{x}}_s$ is very small compared to one. Since, for most robotic applications, the velocity is small during contact with the environment, and the stiffness $\boldsymbol{K}_{hc}$ is commonly larger than the damping $\boldsymbol{B}_{hc}$ this condition can assumed to be met. The formerly nonlinear system is now expressed by a linear equation and is therefore compatible with the SPRLS algorithm. The system output $\boldsymbol{y}_s$, the regression vector $\boldsymbol{\phi}_s$ and the estimated parameter vector $\hat{\boldsymbol{\theta}}_s$ can be rewritten as: $\boldsymbol{y}_s = \ln(\boldsymbol{f}_e)$, $\boldsymbol{\phi}_s = [\boldsymbol{I} \; \delta\dot{\boldsymbol{x}}_s \; \ln(\delta\boldsymbol{x}_s)]^T$ and $\hat{\boldsymbol{\theta}}_s = [\ln(\boldsymbol{K}_{hc}) \; \boldsymbol{K}_{hc}^{-1}\boldsymbol{B}_{hc} \; \boldsymbol{n}_{hc}]^T$.

C. Persistent excitation & estimation limits

According to Yokokohji [15], a teleoperation system is transparent, if the forces on master and slave site as well as the positions on master and slave site are equal. Assuming contact, if master and slave position coincide, the generated forces on master and measured forces on slave site will be equal for our approach. If, however, different controllers are used on master and slave site or if time delay is present in the communication channel, a difference in master and slave positions may occur. In this case, a high fidelity can only be achieved, if the estimated parameter vector is equal to the true parameter vector. This can be guaranteed, if the input signal is persistently exciting (PE), i.e. if the input signal contains enough different frequency components to excite all parameters of the model. A thumb rule says, that $\lceil n/2 \rceil$ distinct non-zero frequencies are necessary for a model of order n to guarantee persistent excitation [16]. As all environment models in our approach are of order one, also one non-zero frequency should be contained in the input signal. In teleoperation, due to the natural tremor of human arm movements, see [17], the operator unconsciously provides input signals with at least one non-zero frequency component and, thus, persistent excitation is guaranteed.

Another important aspect is the identifiable range of parameters, which limits the estimation to some extent. This range essentially depends on the robotic device, used for identification, as it is connected in serial with the object. Assuming an admittance-type robot, for example, its mechanical structure can be simplified to a spring-damper system denoted by k_r, b_r, interacting with another spring-damper-like object, denoted by k_o, b_o. The maximum identifiable stiffness is therefore the serial connection of k_r and k_o, i.e.

$$k_{max} = \frac{k_r k_o}{k_r + k_o}.$$

In the case of a completely stiff wall, the identifiable stiffness is consequently limited by the robot's mechanical stiffness. Given PE, the obtained parameters are therefore not the true values of the object's model alone, but the true values of the interacting robot-object system. These limits have to be considered in the interpretation of the obtained parameter values. For control, this estimation limitation becomes critical only, if the stiffness of the device, where the parameters are applied to, is higher than the stiffness of the device, with which the parameters have been obtained.

IV. Model-mediated Control Approach

By applying the hybrid environment estimation technique in a teleoperation setup, a model-mediated control approach can be realized. The teleoperator is position controlled in joint space using a high-gain PD controller. The desired position and orientation in task space are commanded from the operator. On operator site, a position-based admittance control approach, as presented in [18], is chosen for the given setup. Using a virtual mass-damper system, the difference of forces and torques applied by the operator, $\boldsymbol{f}_h$ and $\boldsymbol{\tau}_h$, and external forces and torques, $\boldsymbol{f}_e$ and $\boldsymbol{\tau}_e$, are transformed into desired position and orientation, respectively, i.e.

$$\boldsymbol{f}_h - \boldsymbol{f}_e = \boldsymbol{M}_c \ddot{\boldsymbol{x}}_m + \boldsymbol{B}_c \dot{\boldsymbol{x}}_m \quad (10)$$

$$\boldsymbol{\tau}_h - \boldsymbol{\tau}_e = \boldsymbol{M}_o \dot{\boldsymbol{\omega}}_m + \boldsymbol{B}_o \boldsymbol{\omega}_m. \quad (11)$$

The virtual inertia and damping matrices are chosen as $\boldsymbol{M}_c = 5 \cdot \boldsymbol{I}$ kg and $\boldsymbol{B}_c = 1 \cdot \boldsymbol{I}$ Ns/m for translations and $\boldsymbol{M}_o = 0.1 \cdot \boldsymbol{I}$ kgm^2 and $\boldsymbol{B}_o = 0.05 \cdot \boldsymbol{I}$ Nms/rad for rotations. The desired position and orientation are controlled using a high-gain PD-controller in joint space. In order to avoid the dynamics of the underlying position controller, the desired position and orientation are sent to the teleoperator site.

To realize model-mediated teleoperation during contact, the environment parameters have to be estimated on slave site, sent back to the master site and local external forces and torques have to be generated. It is assumed, that only point contacts occur between teleoperator and remote objects. Therefore, during contact, only forces and no torques are measured at the tip of the tool, i.e. in the tool-tip frame (TT), see Fig. 3. Using these forces and corresponding positions and velocities as input to the above described hybrid estimation technique, an estimate of the environment parameter vector can be obtained for the three translational directions.

On master site, local forces are generated during contact with a remote object using the received parameter vector $\hat{\boldsymbol{\theta}}_s$ and a regression vector $\boldsymbol{\phi}_m$, depending on the environment model

$$\hat{\boldsymbol{f}}_{e,m} = \begin{cases} \hat{\boldsymbol{\theta}}_{s,kv} \boldsymbol{\phi}_{m,kv}, & \text{if } \mathbf{S}(\boldsymbol{k}_{kv}) = kv \\ \hat{\boldsymbol{\theta}}_{s,hc} \boldsymbol{\phi}_{m,hc}, & \text{if } \mathbf{S}(\boldsymbol{k}_{kv}) = hc, \end{cases} \quad (12)$$

where $\boldsymbol{\phi}_{m,kv}$ and $\boldsymbol{\phi}_{m,hc}$ are calculated on master site by integration over the desired master velocity $\dot{\boldsymbol{x}}_m$ when estimates of the parameter vector $\hat{\boldsymbol{\theta}}_s$ are available. When the first estimate is received, the penetration depths are set to zero. For the haptic feedback on master site, it is furthermore assumed, that the operator should feel as holding a tool, like a screwdriver, for example. Consequently, also torques have to be computed at the grasping point of the tool, i.e. in the wrist frame (W), see Fig. 3. The geometry of the tool mounted on the teleoperator's end-effector and with it the distance vector $\boldsymbol{r}$ from wrist frame to tool-tip frame, is assumed to be known. Thus, the cross product between $\boldsymbol{r}$ and the force vector $\hat{\boldsymbol{f}}_{e,m}$ is calculated in order to determine the torque $\hat{\boldsymbol{\tau}}_{e,m}$:

$$\hat{\boldsymbol{\tau}}_{e,m} = \boldsymbol{r} \times \hat{\boldsymbol{f}}_{e,m}. \quad (13)$$

On master site, it is assumed, that, for a natural feeling of the haptic feedback, the human intuitively grasps the handle at the tool center point, where all axis of rotation intersect. The estimated forces and torques $\hat{\boldsymbol{f}}_{e,m}, \hat{\boldsymbol{\tau}}_{e,m}$ provide the operator with haptic feedback about the interaction between teleoperator and remote objects. As mentioned above, with this approach the feedback loop from remote to local site is closed locally, such that the dynamics on the remote site do not alter the haptic feedback.

V. Experimental Validation

A. Experimental setup

For evaluating the proposed method, we used a robotic system, consisting of a redundant 7 DOF haptic interface ViSHaRD7 [19] and an anthropomorphic 7 DOF robotic arm [20]. Both devices have a relatively large, human-like workspace and a high force output capability. The redundancy on operator site is used to decouple translational from rotational movements, while on teleoperator site it is used to

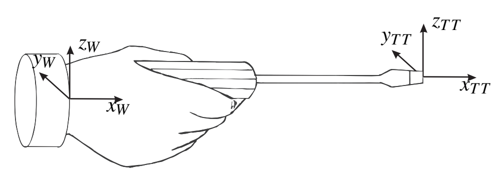

Fig. 3. Wrist frame and tool-tip frame

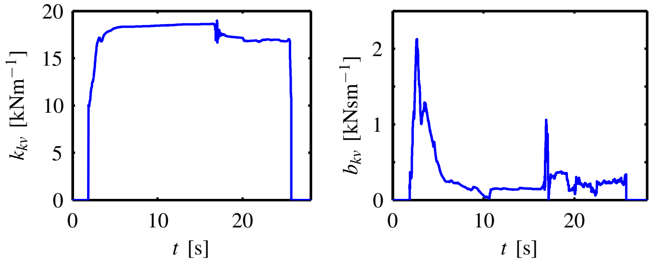

Fig. 4. Estimated stiffness k_{kv} and damping b_{kv} for contact with the steel plate in the direction of penetration

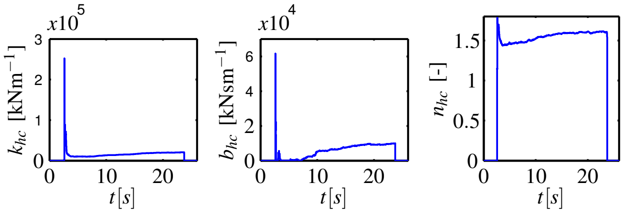

Fig. 5. Estimated parameters k_{hc}, b_{hc} and n_{hc} for contact with the silicone cube in the direction of penetration

avoid singular configurations. A 6 DOF force/torque sensor is mounted at the end-effector of the devices and end-effector positions are obtained by applying the forward kinematics to the measured joint angles. Gravity forces are compensated in the force measurements and inertial forces due to the end-effector mass are neglected assuming slow velocities during contact. An aluminium bar is used as handle for the operator, while a steel pin is mounted on the teleoperator's end-effector simulating a rigid tool. Thus, the operator should feel as holding some kind of tool like a screwdriver, for example. The operator had a direct view on the teleoperator site.
For estimation, the parameters were initialized with $\hat{\boldsymbol{\theta}}_{kv} = [10000, 200]$ and $\hat{\boldsymbol{\theta}}_{hc} = [\log(3000), 1/30, 1.3]$ and for the self-perturbation, the parameters were chosen as $\gamma_{kv} = 1, \beta_{kv} = 50$ and $\gamma_{hc} = 19000, \beta_{hc} = 1$. The stiffness threshold for the hybrid estimation approach was chosen as $k_{th} = 2500$ N/m.

B. Results

Using this setup, experiments were conducted, where the operator remotely established and kept contact with two objects of different material using the model-mediated control approach. In order to show the applicability of the approach to a wide range of materials, a steel plate and a soft silicone cube were used as objects and mounted on a solid surface. The true model parameters of these two materials are not known. In the following, estimation results, fidelity, and stability during teleoperation are discussed. Furthermore, a comparison between the proposed method and a control approach with fixed parameters is performed.

1) Estimation: Regarding the estimation results, the important aspects are speed, accuracy and a correct switching between Kelvin-Voigt and Hunt-Crossley model. In Fig. 4 and Fig. 5 the estimated model parameters for the steel plate and the soft silicone cube are shown in the direction of penetration. The parameters converge in less than 1s, which enables a good rendering of contact forces and torques on master site. For a realistic impression of the object, the time of contact has to be longer than the convergence time. Otherwise, the haptic impression of the object is determined by the initial values of the estimation. Furthermore, the normalized root-mean-square error (NRMSE) between measured and estimated forces on slave site is calculated in the direction of penetration

$$NRMSE = \frac{1}{f_{e,max} - f_{e,min}} \sqrt{\frac{\sum_{n=1}^{N} (f_{e,n} - \hat{f}_{e,s,n})^2}{N}}.$$

It is 1.16% for the steel plate and 1.67% for the silicone cube, which is very good. As described in Sec. III-C, the stiffness of the Kelvin-Voigt model is the maximum identifiable stiffness of the robot-object interaction. It is consequently limited to the robot's stiffness when touching a rigid wall. Therefore, the estimated value of $k_{kv} \approx 17$ kN/m seems plausible. The initial peak in the damping value occurs, because the penetration depth is very small, while the measured forces are not. As the parameters of the Hunt-Crossley model are not physically interpretable, a statement about the accuracy can hardly be done. Finally, the hybrid switching technique chose the correct models for the right material, i.e. Kelvin-Voigt for the steel plate and Hunt-Crossley for the silicone cube.

2) Model-mediated control approach: For teleoperation, the most important aspects are robustness and fidelity. The observed behavior was always stable, i.e. moving in freespace and establishing and keeping contact did not lead to oscillations or instabilities. For fidelity evaluation, the force measured at the wrist of the teleoperator's end-effector and the virtual force generated in the wrist frame on master site were recorded and are shown in Fig. 6 for the steel plate and in Fig. 7 for the silicone cube in the direction of penetration. The virtual forces generated by both models fit well with the measurements. In steady-state, the force error for the steel plate and the silicone cube is always smaller than the the just noticeable difference (JND) for force (10% for the arm/forearm, see [21]). Thus, in steady-state, the estimated forces can not be distinguished from the measured ones by the operator. This is a satisfactory fidelity. Furthermore, the high-frequency oscillations of 1-2 N are not perceivable for the operator as they lie below the JND. Besides force tracking, a high degree of fidelity requires a good position tracking, i.e. a position error between master and slave as small as possible. As the desired master position

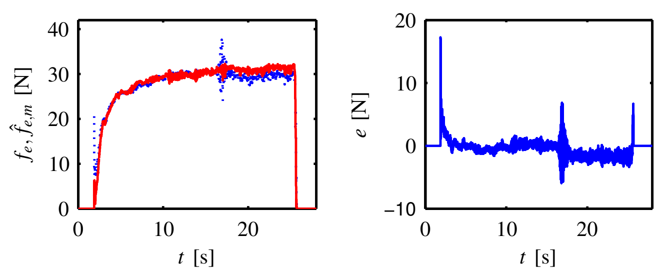

Fig. 6. Left plot: Measured force on slave site (solid) and virtual force on master site (dashed) for the steel plate, right plot: force error

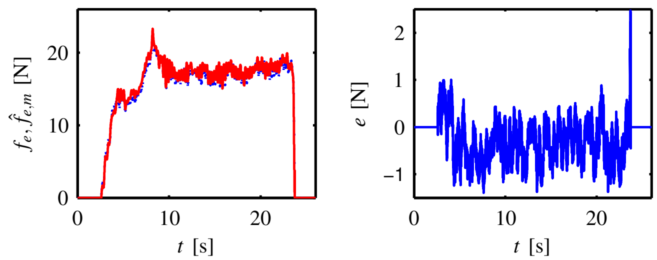

Fig. 7. Left plot: Measured force on slave site (solid) and virtual force on master site (dashed) for the silicone cube, right plot: force error

and orientation are sent to the slave site and tracked using a high-gain PD-controller, only the dynamics of the underlying master and slave position control loops can be observed when comparing master and slave position or orientation. Thus, the tracking error is small.

3) Controller comparison: We compared this approach with a position-based admittance controller with force-force exchange between master and slave, see [19] for details. The virtual mass and damping of the admittance, which have to be equal on master and slave site, were chosen as $\boldsymbol{M}_c = 10 \cdot \boldsymbol{I}$ kg, $\boldsymbol{B}_c = 10 \cdot \boldsymbol{I}$ Ns/m for translations and $\boldsymbol{M}_o = 0.2 \cdot \boldsymbol{I}$ kgm^2, $\boldsymbol{B}_o = 0.5 \cdot \boldsymbol{I}$ Nms/rad for rotations. While the contact with the silicone cube was stable, stable contact with the steel plate was only partly achieved. Thus, even with a doubled virtual mass and 10 times higher damping than for the model-mediated approach, stable contact was only partly possible. Moreover, higher forces had to be applied in freespace due to these parameters. This shows a superior fidelity for the model-mediated teleoperation approach even for a system with negligible time delay.

VI. Conclusions and Future Work

Summarizing this paper, we extended the model-mediated teleoperation approach to 6 DOF tasks with point contact between teleoperator and remote objects. We estimate the translational impedance at the end of the teleoperator's endeffector tool. The obtained parameters are transmitted to the master site, where they are transformed from the tip to the wrist of the tool. Thereby, virtual forces and torques are generated according to the touched object. For modeling the interaction between teleoperator and remote objects, we proposed a switching strategy between Kelvin-Voigt and Hunt-Crossley model depending on the encountered object type. For estimation, we used a self-perturbing recursive least-squares algorithm, which in combination with a sufficiently exciting human input force, showed very good estimation results for different materials. However, the stiffness of the robotic system reduces the set of identifiable parameters. Yet, we can show, that less conservative control parameters could be used for the model-mediated control approach compared to an position-based admittance controller with fixed parameters without risking stability.

Future work consists in the extension to systems with time delay in the communication channel and to movable objects. Furthermore, a sound stability analysis for the model-mediated teleoperation approach is missing. For a qualitative evaluation, a psychophysical study needs to be conducted.

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