A survey of environment-, operator-, and task-adapted controllers for teleoperation systems

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Abstract

Bilateral haptic teleoperation systems allow humans to perform complex tasks in a remote or inaccessible environment, while providing haptic feedback to the human operator. The incorporation of online gained environment-, operator-, or task-specific (EOT) information in the controller structure can lead to significant improvements in robustness, task performance, feeling of presence, or fidelity without compromising stability. This article provides a classification as well as a survey of approaches, called EOT-adapted controllers, which have been developed in this area. A discussion of improvements and requirements is provided for each method. The performed analysis indicates that several methods require the usage of additional sensors or are based on accurate model assumptions. The benefit of EOT-adapted controllers is mostly application-dependent, as each method focuses on the improvement of a specific aspect like coping with time delay or avoiding forbidden regions.

Keywords: teleoperation, assistance, haptics, performance

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1. Introduction

A bilateral haptic teleoperation system allows a human operator to perform complex manipulations in a remote environment while receiving haptic feedback. As illustrated in Fig. 1, a human operator controls a remotely located teleoperator or slave device via a haptic interface or master device. As signals are exchanged between the two subsystems human-master and slave-environment the control loop is closed over a communication channel.

Main objectives for designing teleoperation systems are *robustness, feeling of presence, task performance,* and *transparency.* Ideally, these objectives are simultaneously optimized without risking stability of the closed-loop system. For this purpose, system-specific parameters such as the type of master and slave device, sensor and actuator deficiencies, quantization effects, as well as time delay or packet loss in the communication channel have to be considered in the controller design. For realizing a high-quality teleoperation system, further improvements can be achieved when additionally taking into account information about the human *operator*, the remote *environment*, as well as the actual *task* to be performed.

Many bilateral controllers do not adapt online to the operator behavior, the encountered remote environment, or the current task. These control approaches are referred to as *classic control approaches* in the following. The tuning of their control parameters can, however, be based on assumptions like passively behaving operator and environment [69], simplified model assumptions for human and environment (like LTI mass-spring-damper systems with exogenous force or position inputs [37]), or static upper and lower bounds on model parameters or mag-

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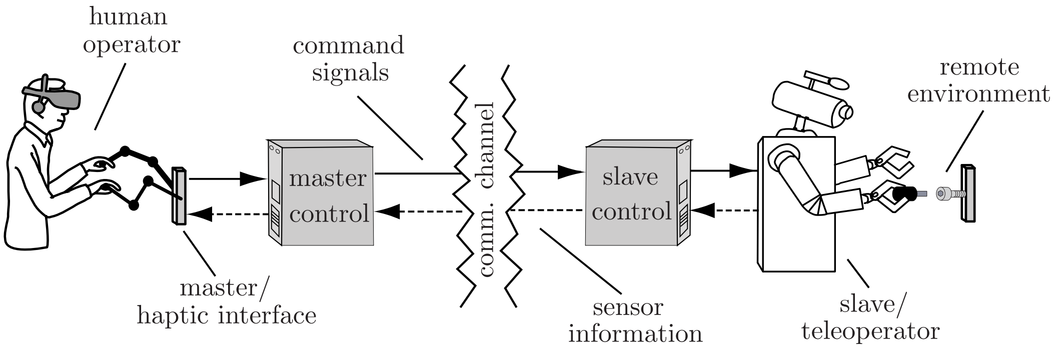


Figure 1: Haptic teleoperation system

nitude of transfer functions. Such classic control approaches are summarized in an extensive and comprehensive survey by Hokayem & Spong [40].

Beside these classic control approaches, a variety of controllers were developed, which depend explicitly on online gained environment, operator, or task knowledge. Through the incorporation of this additional knowledge in the controller, quality improvements can be achieved. To the authors' knowledge, a comprehensive survey of these controllers does not exist. In this article, we present an overview of state-of-the-art literature in this area and propose an appropriate classification. As the field is very broad, and borders are subject to discussion, we do not claim the survey to be complete, but to cover and highlight most important aspects.

The article is structured as follows: after having discussed objectives on a teleoperation system in Sec. 2, a classification for advanced teleoperation controllers incorporating environment, operator and task knowledge is proposed, see Sec. 3. Sec. 4 presents the main part of the article: it provides an overview of existing state-of-the-art controllers in this field. The methods are compared with each other on the basis of requirements and improvements in one or more of the listed objectives. The report concludes with a summary and an outlook to future research directions.

2. Objectives

Four basic objectives can be distinguished for teleoperation systems: *robustness, task performance, feeling of presence,* and *transparency.* As all these objectives are supposed to be optimized using the control algorithms discussed in this article, they are shortly reviewed in the following paragraphs.

Robustness: In a teleoperation system, the operator, the remote environment, the communication channel, as well as the sensors introduce uncertainties in the system due to their varying, unstructured, and potentially unknown behavior. Consequently, the controller is required to be robustly stable with respect to a prespecified set of uncertainties introduced by the different components. If a teleoperation system is designed to be passive [69] or absolutely stable [5], the set of uncertainties for which stability can be guaranteed consists of all operators and environments that can be represented as arbitrary passive one-ports and a single force source. H_∞ [90] and $\mu-$synthesis optimization procedures [53] are another possibility to derive controllers based on a priori known sets of uncertainties in the system components. In order to gain information about the acceptable uncertainty, also a robustness analysis can be conducted after having designed the controller by testing a set of uncertainties for stability [72].

Task performance: The main purpose of a teleoperation system is to provide technical means to successfully perform a desired task in a remote environment. Consequently, these systems should be designed in such a way that a high task performance can be achieved. Under the assumption of a fixed field of operation, the minimum required task performance is the realizability of a task. This implies to overcome barriers like distance, scale, time delay, or hazardousness. Taking the human role into account, task performance can be further improved if the system allows an intuitive and easy to understand interaction with the remote environment. Besides that, teleoperation systems are not only capable of overcoming limitations in the environment but also those inherent to the operator. For example, by reducing the surgeon's hand tremor in a microsurgical application, the resulting task can be performed even better than if the operator had performed it directly. Similarly, a micro-assembly task is considerably facilitated for the operator, if the movements can be performed on human scale in the local site and be scaled down in the remote place.

For evaluation, physically accessible quantities which are suitable for the considered task have to be found. The most common quantities are task completion time, error measures, applied forces, or induced or dissipated energies. An overview of performance measures for virtual environments is given in [67].

Feeling of presence: Feeling of presence is a subjective objective. It refers to the operator's *feeling of being there*, the feeling of being present in the remote environment [67, 81, 97]. Ideally, the operator cannot distinguish between the feeling of being present in a remote place and the real world. Technical limitations, however, make it difficult to reach this state. But even under the assumption of reaching this state the question arises, why it is important to make the operator feel present at the remote site? The preliminary reason arises from the belief, that presence is correlated with task performance in a positive, causal way [58, 95]. This means, that by improving the feeling of presence task performance is improved as well. Some studies support this statement, see [45] for single-user and [79] for multi-user systems. Yet, contradictory statements are also found in literature, see [20, 74]. In the study by Clarke [20], it is found, for example, that the prediction of positions on teleoperator site clearly improve task performance, while participants do not report an improved feeling of presence. Pongrac et al. [74] cannot show a correlation between presence and performance measured over task execution time or covered distance. However, they found a positive effect between feeling of presence and applied forces and torques. Due to these contradictory statements the question of a positive influence of feeling of presence on task performance remains open.

One feasible conclusion is drawn by Welch [95] and Ma et al. [58]. They state that it may depend on the scenario and task, if a correlation between task performance and increased feeling of presence can be expected or not. For everyday tasks, a human may not need a strong feeling of being present in the remote environment, as those tasks are done almost automatically. For unknown tasks or in unstructured, unknown and changing environments, however, a strong feeling of presence will help the operator to better perform the task, such that feeling of presence could have a positive effect on task performance in these kind of scenarios. Furthermore, if such a correlation exists, it may depend on the choice of the task performance measure. For teleoperation tasks, it is therefore necessary to take multiple task performance measures into consideration, as shown by [36, 74].

Beside the reasoning about a possible correlation between feeling of presence and performance, providing a strong feeling of presence also gives the operator the possibility to perform the task in a more natural way, i.e. such that actions in teleoperation mode are similar to actions in the real world [83]. Otherwise, the system cannot be used intuitively and the operator would have to train intensively to control the system in a desired and successful way. For evaluation, mostly subjective presence measures, e.g. questionnaires or ratings, are used.

Transparency: Compared to feeling of presence, making a teleoperation system transparent is a quantitative objective. Transparency means that the technical medium between operator and environment is not felt, i.e. that the dynamics of master and slave are canceled out. Transparency has been independently defined by Yokokohji & Yoshikawa [100] and Lawrence [52]. In the most general way, transparency is defined in [100] as the equality of velocities and forces, i.e.

$$f_h = f_e \quad \wedge \quad \dot{x}_m = \dot{x}_s. \tag{1}$$

If the impedance mapping from velocities to forces, defined in the frequency domain as

$$\begin{array}{rcl} F_h(\omega) & = & Z_t(\dot{X}_m(\omega), \omega) \\ F_e(\omega) & = & Z_e(\dot{X}_s(\omega), \omega), \end{array} \tag{2}$$

is known, the above transparency definition can be transformed into the equality of the impedance transmitted to the operator Z_t and the impedance of the real environment Z_e and equality of velocities,

$$Z_t = Z_e \quad \wedge \quad \dot{X}_m = \dot{X}_s. \tag{3}$$

Lawrence [52] defined transparency in this way. Thus, a teleoperation system is transparent, if no external dynamics are felt in free space and the remote objects are exactly represented at the master site during contact. Transparency and robustness are, however, conflicting objectives, as a transparent four- or two-channel teleoperation system is marginally stable [37]. A trade-off between robustness and transparency has therefore to be found.

A measure for transparency is *fidelity*. It describes the capability of a teleoperation system to accurately display the remote environment to the operator. Assuming a fixed experimental setup, the question arises which controller leads to the highest degree of fidelity. In order to answer this question, different measures for assessing the degree of fidelity have been proposed, see [19]. The most popular ones are position/velocity and force errors between master and slave (tracking errors) [100] and the Z-width, a measure based on the dynamic range.

Colgate & Brown [21] proposed to consider the dynamic range, defined as the range of achievable impedances, i.e. impedances, that can be displayed to the operator while guaranteeing passivity of the system. A larger range implies a higher degree of fidelity. However, in order to compare different dynamic ranges, the Z-width has been defined as the area between lower and upper limit curves of the dynamic range, see [19]. The upper limit is the transmitted impedance for infinitely stiff contacts, while the lower limit is the transmitted impedance for free space:

$$\begin{array}{ll} \text{Lower limit :} & Z_{t,min} = Z_t|_{Z_e=0} \\ \text{Upper limit :} & Z_{t,max} = Z_t|_{Z_e\to\infty}. \end{array} \tag{4}$$

The Z-width is then determined as the area between the absolute values of these two curves over a frequency range $[\omega_{min}; \omega_{max}]$, suitable for the specific application:

$$Z_{t,width} = \frac{1}{\omega_{max} - \omega_{min}} \int_{\omega_{min}}^{\omega_{max}} |Z_{diff,t}(j\omega)| d\omega \tag{5}$$

with

$$Z_{diff,t}(j\omega) = |\log Z_{t,max}(j\omega)| - |\log Z_{t,min}(j\omega)|.$$

Furthermore, Lawrence [52] proposed the transparency error as a fidelity measure. It is defined as the error area between the absolute values of a specific environment impedance curve $Z_e^\star$ and the transmitted impedance curve corresponding to $Z_e^\star$ over a certain frequency range:

$$Z_{error} = \frac{1}{\omega_{max} - \omega_{min}} \int_{\omega_{min}}^{\omega_{max}} |Z_{diff,e}(j\omega)| d\omega \tag{6}$$

with

$$Z_{diff,e}(j\omega) = |\log Z_e^\star(j\omega)| - |\log Z_t(j\omega)|_{Z_e^\star}|.$$

The lower the transparency error, the higher is the degree of fidelity. Finally, another fidelity measure is proposed by Çavuşoğlu et al. [14]. Hereby, the sensitivity of the transmitted impedance is compared with the change in environment impedance

$$\left\| W_s \frac{dZ_t}{dZ_e}\Big|_{Z_e=Z_n} \right\|_2, \tag{7}$$

where W_s stands for a frequency dependent weighting function and Z_n for the nominal environment impedance.

3. Classification

As stated above, improvements in the quality of teleoperation systems can be achieved when the controller uses environment-, operator-, or task-specific information. To the authors' knowledge, most of the state-of-the-art methods in advanced teleoperation control focus on one of these system components. This is not surprising, as the dynamics and methods for modeling human, environment, or task differ significantly from each other. Considering a transportation task, for example, the important knowledge is the sequence of subtasks, an operator plans to perform. Subtasks in this case could be path-following, obstacle avoidance or positioning. For contact with objects in the remote environment, on the contrary, a physically motivated model of the object yields important information. Therefore, we propose a classification according to the system component on which a specific controller is based, see also Fig. 2.

Definition. *A controller is called EOT-adapted controller, if online gained information about the environment, operator, or task are explicitly taken into account in the control law.*

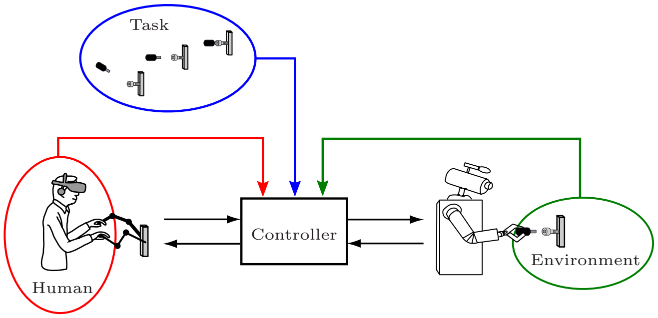


Figure 2: Illustration of EOT-adapted controller

This classification comprises a broad area of concepts. One important concept is *shared control*, where the operator is supported in performing the task by an additional control action from an autonomously acting agent. Generally, EOT-adapted controllers imply additional features and functions to be used in a teleoperation system that adapt to the specific operator or environment based on estimations or predictions of their current and future behavior. This implies, for example, the adaptation of control parameters according to an estimated model of operator or environment.

The state-of-the-art literature discussed in this article is classified according to the above definition. Moreover, methods from the field of physical human-robot interaction or human-robot collaborative manipulation (HRCM), where robots have to collaborate with people and actively support them, are considered. They typically apply operator-focused control methods. As some of these methods are directly transferable to teleoperation systems, they are also presented in this article.

Methods, which have to be used in order to obtain additional knowledge about operator, environment, or task, are also discussed along with different EOT-adapted controllers.

4. State-of-the-art EOT-adapted controllers

This section gives an overview of EOT-adapted controllers found in literature. Methods are classified according to their focus on environment-, operator-, or task-related aspects. Approaches are compared at the end of each subsection with respect to their *improvements* in at least one objective and their *requirements*. For this purpose requirements are divided into two categories: i) additional hardware (HW), e.g. a sensor, and ii) model-based estimators which use available measurements or data (SW). Model assumptions and required system information are determined for each method. At the beginning of each subsection, an overview of models and identification techniques used in the presented approaches is given. This, however, serves only as a short introduction into further research areas, such as behavior modeling, when considering human-related factors, estimation methods for physical models of the environment or task segmentation techniques. For a summary of models and methods in the different areas, the reader should refer to corresponding surveys.

The following nomenclature will be used in this article. Subscripts m, s, h, e and d, i, f stand for master, slave, human, environment and desired, initial, and final; and superscripts f, i, c stand for free space, impact, and contact. Variables de-

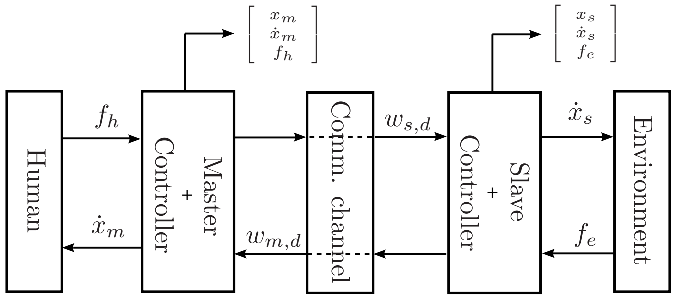


Figure 3: Signal flow in a classic teleoperation system

noted by $x, \dot{x}, \ddot{x}$, and f represent position, velocity, acceleration and force, respectively. A hat denotes an estimated quantity. The physical quantities mass, damping, and stiffness are denoted by m, d, and k. A general signal flow diagram is shown in Fig. 3. The variables $w_{m,d}, w_{s,d}$ denote the desired input command to the slave and master controller, respectively.

4.1. Environment-related controllers

In this section, EOT-adapted controllers with focus on *additional knowledge about the remote environment* are presented. These methods aim at providing a realistic feeling of the remote environment and at assisting the operator to establish stable contact. Objects are assumed to be static. In many cases, they are modeled as a spring-damper system

$$f_e = -(k_e(x_s - x_o) + d_e(\dot{x}_s)) \tag{8}$$

where k_e, d_e are stiffness and damping, and x_o is the initial point of contact with the object. Depending on the method, information about some of the parameters of the model have to be known before or estimated during contact. How these variables are measured or estimated is discussed shortly in the following paragraphs, as this is one important aspect for the formulation of requirements.

Object position x_o: To gain information about the position of an object, additional sensors are needed. This includes cameras, laser range finders, as used e.g. in [28], or an eye tracking system, measuring the gaze direction of the operator. This is not only a cost factor. It also implies that, depending on the reliability of the estimation, sensor uncertainties must be taken into account in the control design.

Impedance characteristics k_e, d_e: During contact, an estimate of the environment model can be obtained in real-time using appropriate identification techniques. Among others, approaches based on adaptive control [27, 80, 82], recursive least-squares (RLS) [23, 56], or neural networks [92, 98] have been proposed in robotics research. Some of these ideas have also been applied to teleoperation systems and will be presented in detail in the following sections. Important aspects in the context of environment estimation are the convergence time of the algorithm, persistent excitation necessary to guarantee convergence of the parameters to true values, and the accurateness of the assumed model.

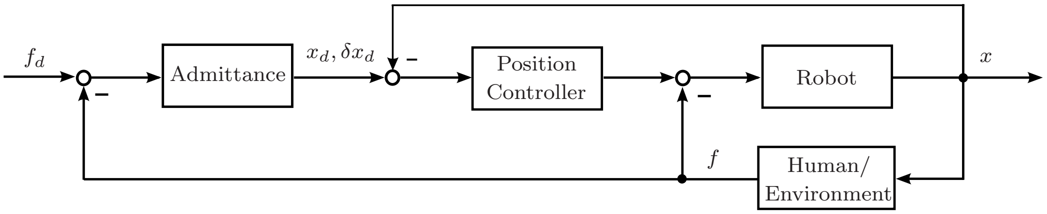
4.1.1. Variable impedance controller

In robotics, admittance or impedance control, first introduced by [38], uses a mass, spring and damper system to form a virtual dynamics, see Fig. 4. Based on this dynamics, a desired position x_d or position modification δx_d is generated from an input force in admittance control. In impedance control, a reference force f_d is generated from an input position. The corresponding physical model is described by

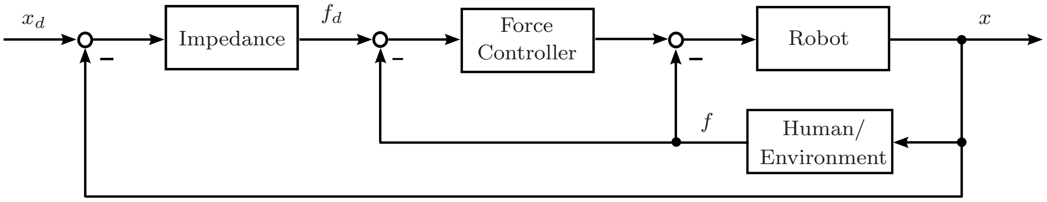
$$f = m\ddot{x} + d\dot{x} + k(x - x_o), \tag{9}$$

where x_o is the position of the relaxed spring. Underlying force or position controllers are then used to drive the robot to the desired reference signal. Furthermore, model-based compensations of device dynamics, such as frictional and gravitational forces, as well as a force feedforward can be incorporated in the control architecture. As a consequence, neglecting disturbances and controller deficiencies, the closed-loop robotic system behaves according to the dynamics described in the impedance/admittance blocks.

Then, the idea of incorporating knowledge of the environment in the control design arose. With this method, typically fixed control parameters are made adaptive. In telerobotics, Love & Book [57] propose an *adaptive admittance control* approach to overcome some of the limitations of robust control approaches, see Fig. 5. A



(a) Admittance control



(b) Impedance control

Figure 4: Admittance and impedance controller

position-force architecture with local admittance controllers is used, i.e. positions are sent from master to slave and forces from slave to master. On master site, the admittance controller represents a target dynamics, while the admittance controller on slave site implements a compliant behavior of the teleoperator. During contact with a stiff object, represented as a linear spring with stiffness k_e, the overall system is assumed to behave as a second-order mass-spring-damper system,

$$f = m_d\ddot{x} + d_d\dot{x} + (k_{e,d} + k_e)(x - x_o). \qquad (10)$$

The environmental spring k_e modifies the natural frequency ω^c and damping ratio ξ^c

$$\omega^c = \sqrt{\frac{k_{e,d} + k_e}{m_d}}, \qquad \xi^c = \frac{d_d}{2m_d\omega^c}, \qquad (11)$$

which does not necessarily correspond to the desired system behavior. This leads to the idea to select a desired damping ratio ξ^c_d of the coupled robot-environment system and to adapt the target damping d_d on master site correspondingly. This results in the following adaptive expression for $\hat{d}_d$:

$$\hat{d}_d = 2\xi^c_d\sqrt{m_d(k_{e,d} + \hat{k}_e)}. \qquad (12)$$

To realize this approach, an estimate of the environmental stiffness $\hat{k}_e$ is required. In [57], an RLS algorithm is used to estimate the stiffness of a static, remote object in two translational degrees of freedom (DOF). The object position x_o does not need to be known, as the estimation works locally. The damping factor of the master admittance is updated according to the sensed stiffness of the remote environment. During unconstrained motions, $\hat{k}_e$ is zero and $k_{e,d}$ determines the minimum required damping for stable free space operation and transition from free space to contact. The stiffer the object, the more damping is introduced. The advantage of this approach lies in the reduced damping characteristics in free space, which cannot be obtained using fixed, robustly stable target parameters. However, it remains open, if the proposed MIMO-RLS estimation method can be extended to rotational movements or movable objects. Furthermore, stability of the adaptive controller is not shown. Especially an analysis of the transition between free space and contact is missing.

Taking time delay into account, Cho & Park [16] propose the adaptation of the slave damping according to the distance between slave and remote objects. Their aim is to obtain both, good tracking performance and robust stability, when moving from unconstrained to constrained space. The same architecture as in the approach by Love & Book is used. First, a performance index for free space is formulated to minimize the tracking error. Second, a performance index for contact is formulated to minimize contact forces and position errors and to guarantee stability. Optimal

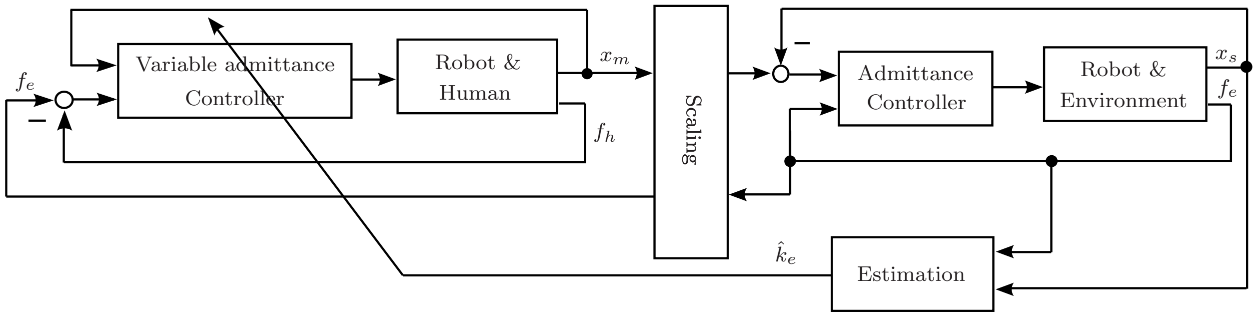


Figure 5: Adaptive admittance control approach by Love & Book [57]

damping ratios for free space $\xi_d = 1$ and contact $\xi_d = \frac{1}{\sqrt{2}}$ are chosen as desired values. By using these values and by applying Llewellyn's absolute stability criterion, bounds for slave damping in free space d_s^f and contact d_s^c are found

$$d_s^f = 2\sqrt{m_s k_{e,d}} \qquad d_s^c = \sqrt{2 m_s k_{e,d}}, \tag{13}$$

where m_s is the mass of the slave admittance and $k_{e,d}$ is selected as the maximum stiffness lying in the stability region obtained with Llewellyn's criterion. A third order spline is defined for fading between free space and contact damping, starting at a prespecified distance from the object. The distance is hereby measured using an ultrasonic sensor. With this approach, the magnitude of impact forces and the tracking errors are reduced. However, damping values are derived to guarantee absolute stability for a specific, stiff object. For soft objects, $k_{e,d}$ would be different such that the chosen damping values are not optimal anymore. For such an interaction, a considerable improvement in tracking performance and impact stability cannot be expected.

4.1.2. Assistance functions for the moment of impact

As outlined by various researchers in the 1980's [34, 39, 96], an autonomous robot using a stiff controller with force feedback often lacks asymptotic stability when *going from free space to contact with a stiff object.* Either the system runs unstable or a never-ending oscillation between free space and contact occurs. The goal, however, is to establish a constant interaction force between robot and object. This implies that the system has to be asymptotically stable with respect to a global equilibrium state despite switching between free space and contact.

From a control theoretic point of view, the transition between free space and contact can be formulated as switched system dynamics. This implies, that even if the system is shown to be asymptotically stable or the subsystems are passive in free space and rigid contact using classic control theory, the transition is not necessarily stable, and/or passive [55, 103]. A transition is called stable, if the system can be shown to settle down in the subsystem to which the global equilibrium state belongs *after a finite number of switchings*. One possibility to show stability/ passivity of the switched system is to find a global Lyapunov/storage function satisfying the conditions for Lyapunov stability/passivity. As it is often difficult to find such a function, other methods for analyzing stability of switched systems like the multiple Lyapunov/storage function (MLF/MSF) approach have been developed [11, 103].

The MLF concept has been applied to teleoperation systems by Ni & Wang [68]. They show that asymptotic stability of a teleoperation system switching between unconstrained and constrained motions depends on the switching strategy between controllers. The MSF concept has been used for the investigation of passivity for haptic interaction with virtual environments [60].

The finding of instability during transition can also be explained from a physical point of view. At the moment of impact, the robot is suddenly decelerated to almost zero velocity. This means, that the momentum of the robot $p = m_s \dot{x}_s$ decreases. This sudden change in momentum, however, leads to a large change in the interaction force. If the controller is not adequately damped, the large interaction forces are passed to the controller resulting in a large position change out of the object. If the position change is too large, contact is lost. A switching behavior between free space and contact occurs. If the transition is stable, the interaction forces at the beginning of contact are small enough after a finite number of switchings, such that the system stays in contact with the object. Small interaction forces again imply a small momentum and, thus, a small impact velocity.

In a teleoperation system, not only the controller, but also the operator as well as the time delay in the communication channel are determining factors for the critical stiffness, i.e. the maximum stiffness, with which stable contact can be established. If large force peaks are sent to the operator due to large impact velocities or if the force feedback is unsynchronized with the operator's actions due to time delay, the operator will jerk back out of the object due to the unexpected high feedback. If the operator is not able to control these sudden jerks back and forth due to limited reaction times or insufficient arm damping, stable contact with the object cannot be accomplished.

One of the earliest solutions to this problem is a highly compliant controller. It damps high-frequency force components and, thus, avoids large position changes, as shown in Fig. 6. This controller, however, significantly distorts the haptic impression of the object [34]. It feels softer than it is. In general, for achieving stable contact with stiff objects like wood or steel, a low human arm impedance in combination with an admittance controller or a high human arm impedance in combination with an impedance controller are, for example, suitable. E-adapted controllers [28, 64, 94] are based on the physical considerations about impact behavior. They aim at guaranteeing an upper bounded slave velocity at the moment of impact in order to avoid large interaction forces or at canceling high-frequency motion components. In the most conservative case, a zero impact velocity is chosen.

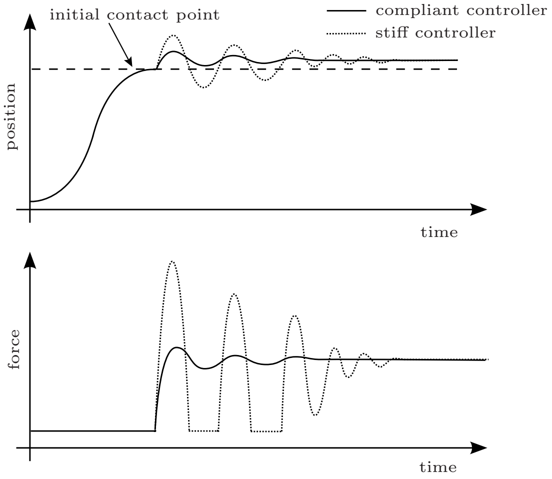


Figure 6: Qualitative illustration of impact behavior for stiff vs. compliant controller

In autonomous robotic manipulation, compliant motion controllers or a passive mechanical compliance are often used to reduce high interaction forces between robot and environment. Measured forces at the end-effector are transformed into position correction terms, $\delta x = HcF$, where H is a transfer function of a spring-damper or mass-spring-damper system, and c is referred to as compliance gain. The desired trajectory is modified by δx, such that the impact is smoothed. Al-Jarrah & Zheng [7] propose a human-inspired approach for choosing the compliance gain c in order to minimize the interaction forces, i.e. the performance criterion $E = \frac{1}{2}f^2$. A spring-damper behavior is assumed for H. By combining this objective with the finding that the stiffness of a human muscle grows exponentially with the force, an optimal compliance gain can be chosen for the compliant motion controller

$$c = v(1 - e^{-\alpha|f|}) \tag{14}$$

where $\alpha[k+1] = \alpha[k] + l(f[k] - f[k-1])f[k]$ and v, l are positive constants. This method was combined with the variable impedance controller by Love & Book [57], see Sec. 4.1.1, in a teleoperation setup by Cheung & Chung [15]. In addition, a Lyapunov-based approach is used to adapt the dynamics of the slave controller. Depending on the measured force from the environment, the adapted slave dynamics are smoothly faded to the biology-inspired compliant controller. The resulting system exhibits desired dynamics using the variable impedance controller on master site and avoids high interaction forces using the compliant controller on slave site.

Everett & Dubey [28] propose a variable spatial velocity mapping, based on the estimated distance to the contact point using a laser-range finder. Hereby, velocities sent from master to slave and from slave to master are transformed using a varying, nonlinear Jacobian. For deriving the velocity mapping, a third-order spline is used to formulate a smooth fading from the commanded to the maximum allowable impact velocity within the deceleration distance δ

$$\begin{aligned} \dot{x}_s(x_s) &= -2\frac{\dot{x}_{s,nom}-\dot{x}_{s,min}}{\delta^3}(x_s-x_{s,1})^3 \\ &+ 3\frac{\dot{x}_{s,nom}-\dot{x}_{s,min}}{\delta^2}(x_s-x_{s,1})^2 \\ &+ \dot{x}_{s,min}. \end{aligned}$$

A safety distance $x_{s,1}$ is hereby chosen such that the desired impact velocity is reached with a specified probability, see Fig. 7. By further incorporating a model of the sensor inaccuracy with a standard deviation σ, the reliability of the distance measure is used to adapt the effect of the sensor measurement on the velocity mapping from master to slave $s(x)$ using a weighting function $w(\sigma)$,

$$s(x_s) = w(\sigma)s_{nom} + (1-w(\sigma))s_s(x_s) \qquad (15)$$

with $s_s(x_s) = \frac{\dot{x}_s(x_s)}{\dot{x}_{m,max}}$. If no measurements are available, i.e. $w(\sigma)=1$, a constant mapping s_{nom} is chosen. If an accurate distance estimation, i.e. $w(\sigma)\rightarrow 0$ is available, the velocity is reduced on slave site only in the near distance to the object, while fast motions are possible in the remaining environment. Furthermore, not only the sensor is inaccurate in providing distance measurements, but also the human's accuracy of the distance is impaired by the video system used to provide visual feedback. Therefore, depending on the choice of the camera system, both uncertainties are weighted against each other and taken into account in the mapping design. Experiments show reduced force peaks during impact. This becomes especially evident, if the sensor is assumed to be reliable. Furthermore, this method shows improvements, if time delay is present in the communication channel. Due to the delayed impact response, the operator is not able to react fast enough to minimize contact forces, even if he or she slowed down the slave before. This sensor-based assistance is also advantageous, if the human's assessment of the distance to the object is impaired. Consequently, the method leads to a superior performance over purely human-controlled teleoperation. On the other hand, an additional sensor is required. So far, a quality evaluation of the approach, especially of the impact behavior, is not provided such that statements about qualitative objectives cannot be made.

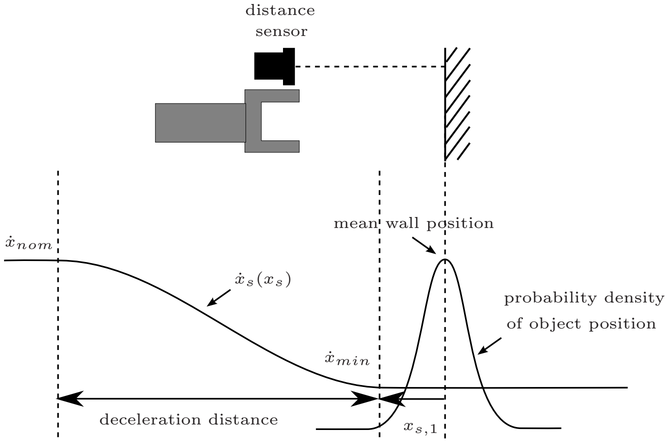


Figure 7: Variable velocity mapping by Everett & Dubey [28]

McAree & Daniel [64] propose a switching from the operator commanded to an autonomous slave trajectory to force a desired impact velocity. Measurements from a vision system are used to estimate the contact point. The approach is based on the following idea. A cost function is derived based on the error between a desired $x_{s,d}(t)$ and a transient-free slave trajectory $x_n(t)$, i.e. without oscillations at the moment of contact:

$$\begin{aligned} J &= \int_0^{t:x_{s,d}=x^i} \left[x_{s,d}(t)-x_n(t)\right]^2 \, dt \qquad (16) \\ &+ \mu \int_{t:x_{s,d}=x^i}^{\infty} \left[x_{s,d}(t)-x_n(t)\right]^2 \, dt. \qquad (17) \end{aligned}$$

By incorporating a model of the sensor accuracy, the expected costs of impact $E[J]$ are obtained. Through minimization of this criterion using models of the slave and environment dynamics, the optimal slave trajectory $x_{s,d}$ is found by solving a first-order differential equation. The point, at which the desired slave trajectory is switched from the operator-commanded to the optimized trajectory $x_{s,d}$, is selected depending on the sensor uncertainty. Experimental results show reduced interaction for- ces as well as an increased bandwidth of stable force feedback. As large distance measurement errors are observed for the used vision system, control has to be withdrawn earlier from the operator than for accurate measurements. The loss of control degrades, in most cases, the perceived feeling of presence, or leads to irritations of the operator. This effect is also reported by McAree & Daniel. In order to reduce the autonomous operation time, an improved sensor system or processing algorithm could be used. Furthermore, in the calculation of the minimum expected cost trajectory the environment is assumed to be infinitely stiff. This makes the approach rather conservative, as for soft objects, the approach velocity is chosen considerably slower than necessary.

Assuming perfect knowledge about the object position, another approach to minimize the slave velocity at the moment of impact is presented in [94]. The focus of this method is to leave as much control as possible with the operator and to avoid irritation of the operator caused by applying large modifications to the commanded trajectory. A position-force architecture is used, where the master position enters the slave controller as reference command, while forces from the environment enter the controller on operator site. In this approach, the operator movement is estimated assuming a minimum-jerk motion with non-zero impact velocity. As this model is discussed in more detail in Sec. 4.2, it should only be pointed out here that the duration of the movement is the only unknown model parameter, which is estimated using a nonlinear RLS algorithm. The estimated master trajectory is then used to reshape the approach trajectory on teleoperator site to enforce zero impact velocity. Through a linear combination, the human commanded trajectory is smoothly faded to the desired trajectory. A psychophysical study has shown that the objective of avoiding operator irritations and loss of feeling of presence can be achieved with this approach. However, sensor deficiencies are encountered in real applications and would need to be incorporated in the control design. Similar to the previous approach by McAree & Daniel, also zero impact velocity is enforced, which is too conservative for soft objects.

Instead of reducing the slave velocity before impact the approach by Kuchenbecker & Niemeyer [50, 51] is based on the idea of canceling induced high-frequency motions of the operator. Unexpectedly high force feedback leads to oscillatory operator motions. By canceling the type of motions induced by haptic feedback, the operator's trajectory is considerably smoothened, i.e. less oscillatory. Thus, instead of sending the measured master position, motions based on the model-based estimation of induced dynamics are subtracted from the master position before sending. Results show improved robustness and a more realistic touch of the remote objects.

4.1.3. Model-mediated teleoperation

If the delay in the communication channel becomes too large, transmitted signals are out of phase compared to local signals. Thereby, the causality between action and reaction gets lost and operators usually change their behavior to a move-and-wait strategy. In a *model-mediated* or *VR-based teleoperation system*, as described in [20, 41, 65, 66, 87, 94, 101] this limitation is overcome by basically estimating the geometric shape and the material properties of the objects in the remote environment and rendering a corresponding virtual model on operator site, see Fig. 8. Thus, the operator is haptically interacting only with a locally rendered virtual object and receives non-delayed feedback. This makes the approach robust to time delays. The stability of the model-mediated teleoperation system can be determined by the closed-loop stability of the operator-virtual-object subsystem, on the one hand, and the stability of the slave-object subsystem, on the other hand. The stability of the operator-virtual-object subsystem de-

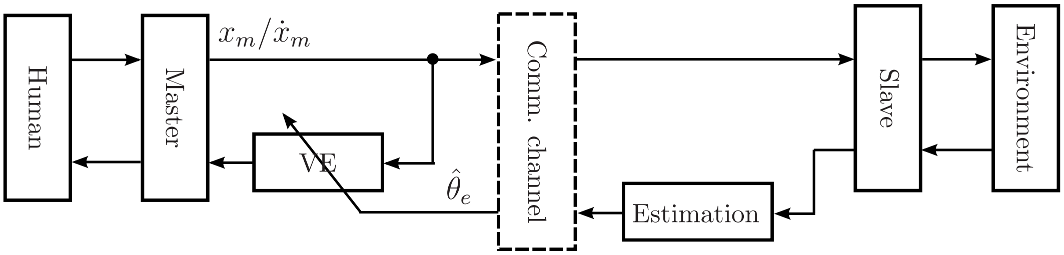


Figure 8: Model-mediated control architecture

pends among others on the stability of the estimation algorithm. For a high fidelity, the errors between virtual model and real environment have to be small, i.e. the estimation has to work properly.

The application of model-mediated teleoperation leads to a considerable improvement in fidelity, as shown in [87] using a fidelity measure based on the error between ideal and estimated model. A significantly stronger feeling of perceived realism is reported in [94] when applying model-mediated teleoperation.

The main differences between the approaches lie in the algorithm for estimating the parameters of the environment model as well as in the updating procedure of the virtual model. Assuming some time delay in the communication channel, one way consists in generating virtual forces after the first impact between slave and object [20, 65, 87]. First estimation steps to adapt the parameters of the environment model can be performed and the position of the object does not need to be known. However, when the slave touches the object, which enters the virtual model at contact point x^i, the master already passed this point without noticing it due to missing feedback. This can lead to safety problems, i.e. possible damage to remote environment or slave device, during the first time of contact. If the object's position is measured during first contact, the virtual model is shifted to account for the difference in slave and master position [65]. At the second time of contact, the learned contact point is used to present undelayed feedback to the operator. In [66], a distance sensor is used to make this approach applicable in unknown remote environments. Another approach [94] assumes perfect knowledge of the position of the remote object. In both cases, the virtual forces can be provided to the operator at the same moment when contact between slave and object occurs.

For model-mediated teleoperation, the most significant improvements of fidelity and robustness can be expected, if considerable time delays are present in the communication channel, as for example shown in [87]. The main problem of this approach arises from the estimation of the remote objects. One important issue is persistent excitation, which is addressed for model-mediated teleoperation in [4]. The estimated parameters only converge to the true parameters, if the input signal of the estimated system excites all parameters of the model. First of all, the necessity of persistent excitation has to be investigated. If there is negligible time delay in the communication channel, the master and slave positions are the same. Thus, it is not important, if the parameters are the true ones or not, as long as the predicted forces are the same than the measured ones. If time delay is present, a thumb rule can be adopted, which asks for an input signal to contain $\lceil n/2 \rceil$ distinct non-zero frequencies for a model of order n to guarantee persistent excitation [43]. For a spring model which is of order zero with respect to position as input, the input signal does not have to exhibit a non-zero frequency. For a spring-damper model, however, one non-zero frequency has to be contained in the input signal. Due to the natural tremor of human arm movements, see [33], the operator unconsciously provides input signals with at least one non-zero frequency component and, thus, persistent excitation is guaranteed for a spring-damper model. However, this property

Method	Improvement	Requirements
Variable impedance on master site [57]	fidelity feeling of presence (felt dynamics in free space ↓)	SW (model correctness, persistent excitation)
Variable impedance on master and slave site [16]	robustness (contact force ↓) fidelity (tracking error ↓)	HW (distance sensor)
Impact stabilization by reducing impact velocity [28, 64, 94]	robustness (contact force ↓)	HW (distance sensor)
Impact stabilization by canceling high-frequency motions [50, 51]	robustness	SW (model correctness)
Model-mediated teleoperation [20, 41, 65, 66, 87]	fidelity feeling of presence (felt dynamics in free space ↓)	SW (model correctness, persistent excitation)

Table 1: Summary of E-adapted controllers

has to be investigated when considering different environment models. If the operator does not sufficiently excite the system, additional artificial excitation should be provided. Furthermore, the questions raised in the introduction of this section, namely model uncertainties or fast varying environments have not been addressed from a theoretical point of view.

4.1.4. Summary

To summarize, the presented methods mainly aim at ensuring stability during the transition from free space to contact and at synchronizing operator-applied forces and feedback from the remote environment when time delay is present. Additional sensors and model assumptions about remote objects are used to obtain improved robustness, fidelity, and feeling of presence. This comparison between improvements and requirements is summarized in Table 1.

4.2. Operator-related controllers

In the following section, EOT-adapted controllers which take specifically the *human role* in the teleoperation setup into account are presented. The aim of these methods is mostly the facilitation of the task execution or an improvement in the fidelity of the system by predicting human behavior. Especially, free space motions and transportation tasks are under consideration. One of the big challenges for operator-oriented controllers lies in modeling and recognizing the user's behavior. Many approaches exist to model the human behavior as some kind of Hybrid Dynamical System (HDS), deterministically as in [70] or stochastically as in [99]. The resulting behavior is a concatenation of motion primitives or switched dynamics. Models have to be trained with a sufficient amount of data sets. As this cannot be done for every possible task, the model will probably not fit in every scenario. For application in an EOT-adapted control method, the current state of the human behavior has to be recognized using these methods.

A widely used model for point-to-point unconstrained arm motions is the minimum hand jerk model, proposed by Flash & Hogan [32]. By minimizing the hand jerk, which is defined as the third time-derivative of the Cartesian hand position, and assuming zero initial and final velocities and accelerations, a fifth-order polynomial is obtained

$$x(t) = x_i + (x_f - x_i)\left(6\tau^5 - 15\tau^4 + 10\tau^3\right) \quad (18)$$

with $\tau = \frac{t-t_i}{T}$ and x_i, t_i, T, x_f initial position and time, motion duration and final position. These parameters have to be known or estimated. The resulting trajectories are straight and the velocity profile is bell-shaped.

Finally, the human arm impedance can be taken into account in the control design. It is typically modeled as a passive mass-spring-damper system

$$f_h = m_h \ddot{x}_h + d_h \dot{x}_h + k_h x_h. \quad (19)$$

4.2.1. Variable impedance controller

In the area of human-robot collaborative manipulation (HRCM), one of the first *variable impe-*

dance controller was proposed by Ikeura & Inooka [42] and further developed in [75]. A similar approach for the lower extremities was presented by Tanaka et al. [85]. The methods are the same as described in Sec. 4.1, only the motivation is different. While in teleoperation the control is shared over the master device between an autonomously acting agent and the operator, the control is shared between human and autonomous robot in a HRCM task. When human and robot perform a task together, for example moving an object, the main goal is that human and robot adapt to each other, as humans would do when performing the task together.

In [42], an offline identification of operator mass m_h and damping d_h was conducted for segmented position and force trajectories of two persons performing a point-to-point movement. In [75], mass, spring and damping coefficients of the human arm impedance were identified offline. As the variance in the mass parameter was low, m_h was set to a constant value in both cases. The damping parameter [42] or the damping and the stiffness parameters [75] of the impedance controller of the robot can then be varied according to the found heuristics to improve human-robot collaboration. Equivalently, the variable impedance controller can be used as the master controller in a teleoperation system. It can be expected, that the variable impedance controller facilitates teleoperated motions. This method was further developed by various authors, as presented in the following. The control parameters are made online adjustable and the method exhibits superior performance and becomes suitable for a larger application area. Again, instead of implementing the controller on an autonomous robot, it can be implemented as an autonomously acting agent on the master site of a teleoperation system. The control over the master device and, thus, over the slave device, is hereby shared between operator and agent.

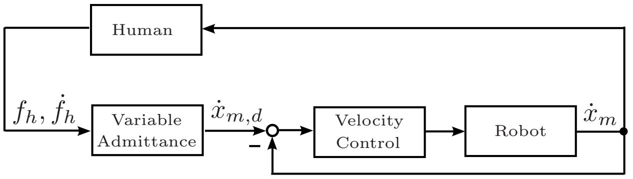


Figure 9: Variable admittance approach by Duchaine & Gosselin [26]

Tsumugiwa et al. [86], for example, adjust the damping parameter in the robot's admittance controller according to the estimated stiffness of the human arm using an RLS algorithm,

$$\hat{d}_m = \alpha \hat{k}_h, \tag{20}$$

where $\hat{d}_m$ is the damping in the admittance controller, α is a scaling factor, and $\hat{k}_h$ represents the estimated human arm stiffness. Using this approach, the precision of a drawing task, collaboratively performed between human and robot, could be improved. Furthermore, a higher fidelity can be achieved, as the damping parameter in the controller is chosen as low as possible for a particular arm stiffness. This concept can also be implemented in a teleoperation system, although attention has to be paid, if contact with remote objects is encountered. If the damping parameter is too small due to a low arm stiffness the system can become unstable. Consequently, in a teleoperation system, this method would only work in free space, and the transition from unconstrained to constrained motion has to be recognized fast enough in order to switch off this function during contact. Although the estimation algorithm shows good convergence results for linear mechanical springs, a similar analysis can be hardly done for the human arm stiffness. Furthermore, a user study would be necessary to show the improvements of this approach compared to non-adaptive approaches.

The variable admittance control approach of Duchaine & Gosselin [26] is based on an intuitive relationship between haptic data and human intention. By looking at the time derivative of the applied force and the sign of the velocity, desired accelerating actions of the human can be distinguished from decelerating ones. With this knowledge, the damping parameter in the robot's admittance controller is decreased/increased during accelerating/decelerating motions according to

$$f = m\ddot{x} + d(\dot{f}_h, \dot{x}_h)\dot{x}, \tag{21}$$

with

$$d(\dot{f}_h, \dot{x}_h) = d_0 - \alpha \dot{f}_h \operatorname{sgn}(\dot{x}_h).$$

The parameter d_0 is used to ensure stability when no adaptation takes place, and α is used to weight the amount of adaptation. The approach is illustrated in Fig. 9. With this approach, less effort is required for accelerating motions due to reduced damping, and positioning or stopping motions are facilitated due to increased damping. As shown in a small study [26], the proposed adaptation leads to an improved task performance for a cooperative drawing task and a pick-and-place task. The concept has been extended to three dimensional motions [25]. Furthermore, a stability observer, based on the estimated human arm stiffness, has been introduced to guarantee stability during adaptation of the damping parameter. The main advantage of this method, as proposed in [26], is two-folded. It is not model-based, and no prior information about the operator or the task has to be given. It is well applicable in a teleoperation setup, where the damping is chosen to be dependent on the sum of human and environmental force such that contact situations do not destabilize the system. As force measurements are noisy, the derivative of the force is even more noisy. To overcome these limits, either a filter can be applied to the signal or the factor α has to be adjusted to lower the influence of the noise. In order to rely on this method, a larger experimental study is necessary to prove its effectiveness.

4.2.2. Motion estimation

By applying variable impedance control, the reactive behavior of the system, especially during free space motions, can be improved. However, an active support of the operator's intended movements is not provided. Recent papers in this area [22, 44, 59] propose *motion estimation* to improve the fidelity of the system. Generally, these methods are model-based and exhibit certain restrictions.

Maeda et al. [59] and Corteville et al. [22] propose an active robot assistant. Based on an estimated human motion profile according to Flash & Hogan's mimimum-jerk criterion [32], the reference position of an admittance controller is adjusted according to

$$\text{Corteville et al. [22]:}\quad x_d = \int \alpha \dot{\hat{x}}_h \, dt \tag{22}$$

$$\text{Maeda et al. [59]:}\quad x_d = \hat{x}_h \tag{23}$$

where $\hat{x}_h, \dot{\hat{x}}_h$ represent the estimated motion and velocity, and α determines the degree of assistance. In [59], a nonlinear least-squares method is used to estimate the duration and final position of the movement. With these parameters, the minimum-jerk model is completely determined. In [22], an extended Kalman filter is used to estimate the duration and, thus, the speed of the movement. Comparing an unassisted with an assisted ($\alpha = 0.75$) point-to-point movement, not only the speed profile converges to a bell-shaped profile, but also the applied forces are reduced considerably. In [22], although not representative, the 10 participating operators confirm an improvement when applying this assistance method. Through the active participation of the robot, the task is performed more easily, and the feeling of cooperating with the machine is improved. In [59], a decrease in unnecessary energy transfer, which is a measure for disharmony between human and robot, is shown. Only slight adaptations are necessary to make the method applicable in a teleoperation setting. However, if for some reason the model of the movement does not fit, the assistance can degrade overall performance. This is observed in [22], if, instead of the minimum-jerk model, a triangular speed profile is used. Moreover, a closed solution to the minimum-jerk criterion has not been found for 3D motions. The model may also not fit, if the operator changes his/her intention.

Compared to Corteville's approach, where the assistance is applied online, Jarrasse et al. [44] show an improved fidelity by predicting human's motion. Hereby, the replay of recorded trajectories either on the position or the actuator torque level is combined with an online force feedback controller such that the operator can alter the replayed trajectory. It is shown that the interaction forces are considerably reduced, if an equally weighted combination of force feedback and trajectory tracking is used. This implies an improvement in fidelity. As the trajectory tracking seems to be most efficient during the accelerating and decelerating phase, the authors propose to vary the degree of assistance in future. The results were obtained for free space motions and can be different for constrained motions. Moreover, a simple replay of trajectories cannot be used in a teleoperation system, as the trajectory is not known at the beginning of the movement. In tasks, where objects in the remote environment are approached, which can be measured using an additional distance sensor, the end-point of the movement can be inferred. A prerecorded trajectory of the operator can then be scaled to the expected movement and the assistance is applicable.

4.2.3. Role-based shared control approaches

In the above presented approaches, the autonomous agent behaves either passively or actively during the whole task. Another recently emerging field of operator-related control approaches in HRCM deals with dynamic role sharing between operator and agent. Although these approaches are applied to HRCM tasks, they are directly applicable to teleoperation systems. Role-based shared control over the master device takes hereby place between autonomously acting agent and operator. Reed & Peshkin [76] found a dynamically changing leader-follower behavior distribution between two haptically interacting persons. This behavior has been transferred to human-robot collaborative manipulation [30, 31, 88, 93]. The idea is to adapt the behavior of the agent to the human behavior. If, on the one hand, the human is leading, the agent behaves passively using an impedance controller, for example. If, on the other hand, the human is following, a leader-like behavior as presented in Sec. 4.2.2 is chosen for the agent's behavior. A partial leader- or follower-behavior is considered in the framework by Evrard & Kheddar [30], i.e. the human can behave with a proportion $\alpha \in [0; 1]$ as follower and $1 - \alpha$ as leader. The robot will apply a mirrored version of the human behavior. While a user study for the approaches by Evrard & Kheddar [30, 31] is still missing, Ueha et al. [88] reported the simplification of control actions for human and robot and an improved task performance. Open issues are mainly the online estimation of the human behavior gains α and an automatic selection of the robot's behavior gains.

4.2.4. Motion prediction in time delayed systems

A third group of operator-oriented control concepts deals with *motion prediction* in the context of time delay in a teleoperation system. One possibility would be to use predictive displays [8, 12, 13, 18, 48], which realize an immediate visualization of the commanded operator position in virtual or augmented reality. However, even in the case of an augmented environment, the distinction between contact and non-contact is difficult for the operator due to impaired or unsufficient 3D visual feedback. Therefore, it is desired, not only to predict visual, but also haptic actions and reactions.

In [94] and [84], prediction algorithms of the operator trajectory are proposed based on an online estimated minimum-jerk trajectory. The operator positions are predicted over the horizon of the one-way time delay. In [84], the prediction of operator trajectories are applied in a teleoperated ball-catching experiment. Experimental results show significant improvements compared to a Smith-predictor approach for time delays of up to 70 ms. In [94], the objective is a minimization of impact forces. Thus, the predicted trajectory is used to compute another predicted optimal trajectory, which minimizes impact forces. These trajectories are merged on the remote site by gradually fading from the directly commanded to the predicted optimal trajectory. Especially in the final phase of the movement, large position overshoots, which can lead to instability when contact is encountered, are reduced and facilitate the positioning of the slave end-effector. Although only shown for small round-trip time delays up to 20 ms, this idea is extensible to larger delays. The

Method	Improvement	Requirements
Variable impedance [86]	fidelity (felt dynamics in free space ↓)	SW (model correctness)
Variable impedance [26]	fidelity (felt dynamics in free space ↓)	HW (high-quality force sensor)
Motion estimation [22, 59]	task performance	SW (model correctness)
Motion estimation [44]	task performance	HW (distance sensor) SW (trajectory estimation)
Dynamic role division [30, 31, 88]	task performance	SW (role detection algorithm)
Force scaling [10]	fidelity/feeling of presence	SW (model correctness)
Motion prediction [20, 84]	task performance	-
Tremor cancelation [10, 33, 77]	task performance (tremor cancelation)	-

Table 2: Summary of O-adapted controllers

drawbacks lie again in the model-based character of the approach.

In [20], a position prediction algorithm based on double exponential smoothing (DESP) is presented. Compared to Kalman filter-based approaches, DESP is faster without degrading performance. The idea is to predict the operator's motion based on a linear regression model with slowly varying parameters, whereby the observation is smoothed twice. Two parameters have to be selected to rate the influence of past data to actual data. Interestingly, while prediction improved performance, it did not improve the feeling of presence. Furthermore, the smallest root-mean-square error for different time delays (30,60,...,120 ms) was always achieved for a prediction horizon of 30 ms. The method is applicable in 6 DOF and has been successfully applied for time delays of up to 120 ms. Furthermore, it is model-independent. To derive a more general statement, different evaluation methods, such as tracking error or applied forces, and a larger user study needs to be performed to statistically confirm the findings.

4.2.5. Perception-oriented force scaling & tremor cancellation

The following approaches are inspired from findings in psychophysics [10] and physiological facts [33, 77]. The work of Botturi et al. [10] is based on human capabilities of discriminating forces in different directions. In a psychophysical experiment, they found a relationship between the just-noticeable difference (JND) and force intensity from the environment:

$$\alpha(f_e) = 1 + e^{-k(f_e+c)} \tag{24}$$

where α is the JND, k is specified for each direction and c is a constant correction term. This finding is used to derive a scaling function, applied to signals sent from slave to master, in order to increase the performance. In the resulting system, small force differences should be distinguishable at low force intensities. The approach is therefore most valuable in tasks requiring the distinction of small forces. Although a user study is still missing, preliminary results show the desired effect. Stability is shown using a Port-Hamiltonian based approach.

Many tasks require a high precision, such as in minimally-invasive surgery. They become especially difficult and require a high concentration of the operating person due to the physiological tremor, inherent to all human motions. Due to the spatial decoupling of the human from the environment, teleoperation systems offer the possibility to cancel these involuntary movements on the way from master to slave. A weighted-frequency Fourier linear combiner [77] and an optimal signal processing technique [33] are proposed to cancel tremor. A reduction of tremor motions up to 67% is reported in [77] for physiological tremor without phase lag and up to 97% in [33] for a person with Parkinson's disease.

4.2.6. Summary

Taking the human role in the teleoperation setup into account leads to improved fidelity, feeling of presence, or a facilitation of the task. For some approaches, additional sensors or model assumptions about the human behavior are required. This comparison between improvements and requirements is summarized in Table 2.

4.3. Task-related controllers

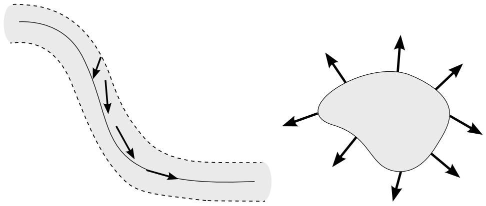
The following control concepts relate to the *task* itself. If the type of task is known, e.g. peg-in-hole, obstacle avoidance, or tracking, the necessary operator skills can be supported through the teleoperation system such that the task performance is increased. The main challenge lies in a reliable recognition of simple and general task segments, called primitives, and features relevant for the task-based control method. Hidden Markov Models (HMM), trainable statistical models with unobservable states, have been used for this purpose. Originally known for application in speech recognition, first approaches also exist to apply HMM in the telerobotics field [1, 35, 49, 54, 102]. The recognition of task primitives is especially important to make the presented methods adaptable and generalizable to a broad area of different, possibly unknown tasks. Another aspect in the design of task-related controllers is the effect on the operator subjective rating of the applied method. Care has to be taken in choosing the amount of assistance such that the operator does not feel to be too strongly restricted in his or her actions or get dependent on the assistance.

4.3.1. Virtual fixtures & potential fields

In a number of teleoperation tasks, *virtual fixtures* (VF) are used to enhance task performance in terms of execution time and error rates and to avoid motions into specific regions. Main objectives are avoidance of forbidden regions, guidance in minimally invasive surgery, or load compensation. Rosenberg, who was the first researcher in this area, describes virtual fixtures in [78] as perceptual overlays to improve performance. The way of operation is similar to using a ruler when drawing a straight line, as outlined in his paper. Hereby, speed, accuracy, safety, and easiness are greatly enhanced. Virtual fixtures are applied to either guide the operator's motion along a certain trajectory or path [9] or to prevent penetration into undesired parts of the workspace [3, 71, 78], as shown in Fig. 10. Furthermore, VFs can be either of admittance-type, if forces are the input, and velocities or position are the output of the virtual fixtures, or of impedance-type, where input and output are reversed. The advantage of admittance-type VFs lies in their inherent passivity and high precision. They are therefore made applicable to be used with impedance-type devices, see [73]. A stability analysis for forbidden-region virtual fixtures is conducted in [2].

For guiding virtual fixtures, task-relevant motions are supported, while deviations from the desired path are constrained [3], see Fig. 10. In a first step, the user's motion is decomposed into a tangential and a perpendicular direction to the desired path. These components are then weighted with different compliance gains, which determine the tradeoff between guidance and free motion. In [73], virtual fixtures are proposed, which correct deviations from the desired path and guide the user towards the desired speed profile.

For avoiding penetration into critical regions, virtual walls can be implemented. They either attenuate the slave's motion in the undesired direction, or completely suppress it by restricting the slave's position to the uncritical workspace.



(a) Guiding virtual fixture

(b) Forbidden region virtual fixture

Figure 10: Concept of virtual fixtures

In [9, 62, 63], the effect of the compliance gain on task performance for different types of tasks is investigated. It is found that a higher degree of guidance is favorable for a predefined path following task, as the task performance increases considerably. For off-path targeting or obstacle avoidance, however, the operator should have a high influence on the slave actions such that a low level of compliance should be applied. Otherwise, the operator would have to work against the fixture, leading to reduced accuracy and increased execution time. Furthermore, a large gain subsumes most of the control from the operator such that this parameter has to be chosen carefully to find a good tradeoff between task performance and user control. In [62, 63], a selection process for determining the compliance values is presented. In a first step, separate admittance gains are found which optimize error and time. Then, a weighting factor between the two gains is derived to find an optimal tradeoff between the task performance criteria.

For applying the appropriate fixture, the current subtask has to be known. In [1] and [102], a hidden Markov model is used to classify the human intended type of task. After training the model, the classifiable tasks can be arbitrarily combined, and a suitable virtual fixture is applied. For guiding VFs, the trajectory that should be followed has to be given. This requires knowledge about the task and the remote environment.

In summary, the main challenges for applying virtual fixtures are the choice of the right fixture, the optimal tradeoff between completely human-commanded and purely computer-controlled operation, and the recognition of task primitives.

Another class of task-oriented controllers are potential fields [6, 17, 46, 91], which provide the operator with haptic cues to avoid certain regions in the workspace of the slave. Either repulsive force fields, potential hills, are created around objects, which should be avoided, or attractive force fields, potential wells, around target regions, where the operator should be directed to. In most cases, these fields are of simple geometric shape, conical, quadratic, or elliptic, but can be superimposed, as shown in [6]. Chong et al. [17] apply this method for collision avoidance in a teleoperation system with multiple operators and robots and time delay in the communication channel. A predictive simulator is introduced, which shows the predicted positions of the other robots, virtually enlarges their thickness and applies a repulsive force field around the other robots, if the distance between two robots becomes too small. For this method to be applicable, the position of the object, around which a potential field is to be created, has to be known, at least roughly. This requires the use of an additional sensor.

4.3.2. Master/Slave mappings

Compared to a guidance along a desired trajectory, a more general approach, as described by [24, 29, 61], consists in *variable position or velocity mappings* between master and slave devices. The axis and amount of scaling is derived based on an optimization criterion. Dubey et al. [24] present a velocity mapping for an improved task execution time in a pointing task as well as in a teleoperated docking task. Manocha et al. [61] apply velocity scaling to pipe cutting such that large unwanted velocities along the pipe axis are avoided. In [29], a variable position mapping is presented with which a desired orientation can be maintained more easily and the probability of hard impact is reduced due to slower velocities near walls.

In [89], a computer assistance concept for reaching movements is proposed which increases task performance without deteriorating the feeling of presence. The presented method corrects the displacement between the teleoperator and a remotely located screw by applying a suitable velocity or force mapping between master and slave device. A position dependent velocity mapping, where only motions perpendicular to the desired path are damped, combined with a final position correction significantly increased positioning accuracy and feeling of presence. Furthermore, a high strength of assistance was desired. It is assumed in this approach that the target is known exactly, and the trajectory from start to goal position is assumed to be a straight line. For application in an unknown environment, sensory information has to be used to estimate the target position. Furthermore, position or force deviations between master and slave devices can occur. With these approaches, the operator stays in full control of the teleoperator and is not explicitly pushed to-

Method	Improvement	Requirements
Virtual fixture/potential field [3, 6, 9, 17, 46, 71, 78, 91]	task performance	SW (forbidden region/trajectory knowledge)
Virtual fixture [1, 102]	task performance	SW (HMM state estimation)
Master/Slave mapping [24, 89]	task performance	HW (distance sensor) SW (task knowledge)
Master/Slave mapping [29, 61]	robustness (contact force ↓)	HW (distance sensor)
Hidden robot concept [47]	feeling of presence (most natural task execution) task performance	SW+HW (complete model of environment needed)

Table 3: Summary of T-adapted controllers

wards a certain trajectory. However, as in many task-oriented approaches, the environmental situation with target objects and the desired final slave position have to be known to apply a suitable mapping.

4.3.3. Hidden Robot Concept

One of the assistance concepts with the highest abstraction level for a teleoperated task is the *hidden robot concept* by [47]. The idea can be summarized in two main steps: first, the desired task is performed in a natural way in a virtual environment; second, it is reproduced by the teleoperator in the remote environment. Thereby, the master subsystem is decoupled from the slave subsystem, resulting in two closed-loop systems with high bandwidth. Due to the intuitiveness of the task execution, the main challenge consists in the transformation of human actions into robot controller commands. Furthermore, deviations of the real environment from the virtual one have to be accounted for in order to successfully realize the desired task. The hidden robot concept allows for a natural task execution and, thus, leads to a high task performance. Also the feeling of presence probably increases. The method is applicable to arbitrary time delays in the communication channel. However, the requirements are equivalently high. The environment has to be known exactly. This makes the approach inflexible and implies that unforeseen events cannot be captured with this method, as the virtual model of the environment would have to be updated in real-time, which is not possible for many situations. While the robot may be able to deal with these changes by, e.g., appropriate obstacle avoidance algorithms, this behavior cannot be caused by the operator, as he or she will not perceive the changed situation in the real environment. A further problem consists in the mapping of operator into robot commands, especially for grasping.

4.3.4. Summary

The objective of applying task-related controllers is mainly an improvement of task performance. This comparison between improvement and requirement is summarized in Table 3.

5. Conclusion and future work

In this article, EOT-adapted controllers are defined as methods which take online gained information about the environment-, operator-, and task-related aspects in a teleoperation setup into account in order to improve the overall performance compared to classic control approaches. State-of-the-art methods in this area are classified and presented according to this definition. For each method, it is analyzed in detail, which kind of improvements can be expected and which information is required for its application. Hereby, it is found that a lot of methods require the use of an additional sensor and accurate model assumptions as well as the convergence of parameters to their true values. This requirement is, however, often not considered in the analysis or only heuristically assessed. Furthermore, stability analysis and user studies to evaluate the subjective rating of the approach are often missing. This makes it difficult to compare different methods.

In summary it can be stated, that classic control approaches have the benefit of being application-independent, while EOT-adapted controllers are mostly application-dependent. One exception are variable impedance controllers, either E- or O-adapted, as they are an easily implemented and efficient extension to any impedance controller with fixed parameters. Generally, however, there is no overall "best EOT-adapted approach", as optimality depends on the application.

More specifically, if the time delay in the communication channel is negligible, there exist classic control approaches, which provide a high degree of fidelity. In these cases, it has to be determined, whether the costs of integrating an EOT-adapted controller which requires an additional sensor or an accurate model are too high compared to the benefit. If, on the contrary, the time delay in the communication channel is large as for intercontinental distances or in space applications, especially E-adapted control approaches such as impact stabilizing or predictive methods are recommendable, as they lead to a significant increase in robustness and fidelity. In applications, where the environment and the task can be assumed to be known, such as in medical applications, especially T-adapted controllers like virtual fixtures are proved to considerably increase the overall performance.

Limitations in the applicability of EOT-adapted controllers are a robust task recognition and environment perception. Without the knowledge of task primitives together with task-specific parameters such as end-points of a movement for example or environmental parameters such as the position of an object, several approaches cannot be adopted. Current setups often do not provide required sensors and recognition methods are still limited with respect to the number and the scalability of tasks.

Regarding future work, one idea is to combine the robustness of classic controllers and the performance improvement of EOT-adapted controllers by switching between the controllers. The switching logic can be made dependent on the level of confidence about the required information for the EOT-adapted controller. Thus, a classic controller guaranteeing high robustness against uncertainties and safety would be selected in a primarily unknown environment or for a novice operator. If enough reliable information for the use of a EOT-adapted controller is gathered, the controller would be switched from classic to EOT-adapted controller, leading to improved fidelity.

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