Extended Predictive Model-Mediated Teleoperation of Mobile Robots through Multilateral Control

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***Abstract*— Despite the substantial progression of autonomous driving systems, their application is often limited e.g. due to safety margins which can be caused by uncertainties in the environment reconstruction. Then, via teleoperation as a fallback solution, a human-in-the-loop can be introduced as the main decision maker. However, high delay in the communication channel distorts the performance of direct force feedback teleoperation for example in space or disaster scenarios. On the other hand, model-mediated teleoperation can provide instantaneous and even predictive force feedback to the user, but the performance is limited due to state mismatches, incomplete models, model errors and the modeling challenges of complex wheel-ground contacts. Therefore, in this paper we introduce the concept of extended model-mediated teleoperation with a car like interface for mobile robots by fusing local fictitious and remote force feedback, which can be measured, computed or fictitious. We provide a method to guarantee stability of the extended model-mediated teleoperation (involving time delay, multilateral coupling, fictitious force feedback and permanent updates of the local model) based on the passivity theorem. The benefits of the approach are highlighted by human-in-the-loop experiments with a wheeled mobile robot. *Index Terms*— model-mediated teleoperation, time delay, force feedback fusion, TDPA**

I. Introduction

The deployment site of mobile robots is often unstructured or narrow due to obstacles. Typical tasks under these circumstances are the cleaning of nuclear plants, clearing of mines or the inspection of underwater structures. In such scenarios, a complete autonomous task execution is often not feasible. This is due to the fact that e.g. the scene analysis of rough terrain might be incomplete as a result of occlusions, or the safety margins may hinder the autonomous system in passing through narrow canyon-like structures. Thus, a human operator with an input device (master) has to be considered in the control loop in order to teleoperate the remote robot (slave) in demanding situations that require expert knowledge. Literature even proposes teleoperation of road vehicles in urban areas [1]–[4].

In teleoperation, generally the computed controller force, an interaction force measured by force sensors or a fictitious force calculated from modeled environments at the slave side is fed back to the operator to raise his/her feeling of immersion. However, there is a trade-off between performance and stability for large time delays, whereby the controller guarantees stability of the overall system at the cost of reduced quality of haptic feedback [5], [6]. In order to compensate for delay effects to some extent, model-mediated teleoperation (MMT) has been proposed [7], where a local virtual model of the slave robot and/or its environment can provide instantaneous force feedback to the operator's commands. The remote slave is controlled by the delayed user inputs and the virtual model on the master side is updated by the states and the sensor information of the remote slave robot. The fictitious local force feedback is mostly calculated from repulsive potential fields or stiffness models [8]–[11]. Also, a model-based prediction can be integrated to prevent unsafe maneuvers [4], [12]. There are pros and cons to both, delayed force feedback teleoperation and MMT. The prior has the force feedback from the remote environment delayed, thus introducing low transparency due to control techniques, however, the remote haptic feedback is more accurate and refers to the exact state. Similarly, MMT might have errors in the local model and depend on the delayed state of the remote slave resulting in incorrect haptic cues, especially when they are predictive, but the benefit is that the local fictitious force is displayed instantaneously.

Also, the delayed haptic feedback can contain information that is often not considered in models, such as the ground friction causing wheel slip or little obstacles that were not recognized by the sensors but hinder the wheel motion. The predictive fictitious force feedback applied here is based on the concept of [4] that does not consider slopes in the robot environment. In such setups, haptic feedback calculated from the IMU of the remote slave can support the operator's perception of the robot dynamics. Regarding such possible additional haptic cues, a fusion of local and remote force feedback seems highly reasonable. The remote force feedback can be measured, computed or fictitious. Still, permanent remote force feedback may disturb the operator's perception, such that e.g. computed force feedback from a velocity controller that is gravely affected by the robot inertia is not recommended.

This paper introduces the concept of extended MMT which is based on the recent developments in multilateral control as the methodology for passivity-based multilateral teleoperation (MPMT, [13]). That allows the coupling of multiple agents that can be the operator with the master device, the slave robot in its environment or artificial agents such as modeled robots in a virtual reality. So far, multilateral control has been applied for the coupling of stationary robots and in swarm robotics [14]–[17]. Here, the field of multilateral control applications is extended to the fusion of

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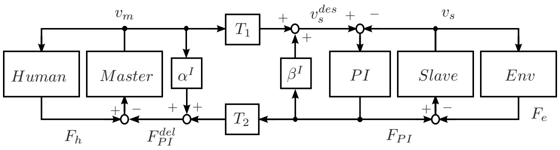

Fig. 1. Signal Flow Diagram of a PF_{comp} Teleoperation Architecture

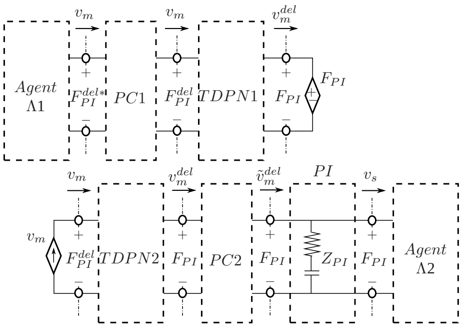

Fig. 2. Network Representation of a PF_{comp} Teleoperation Architecture

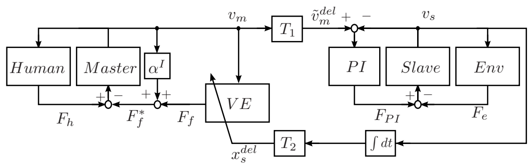

Fig. 3. Signal Flow Diagram of a Model-Mediated Teleoperation Architecture

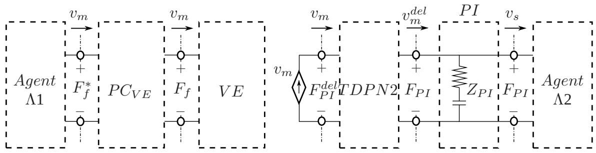

Fig. 4. Network Representation of a Model-Mediated Teleoperation Architecture

two principle branches of research concepts in teleoperation. The proposed method is reasonable up to at least 600ms round trip-delays (compare telemanipulation experiment of [18]) or even more in the teleoperation of mobile-robots. The challenge in the proposed extended model-mediated teleoperation scheme is the stability proof considering the dual coupling to the local robot model and the real remote robot, the interaction with the virtual reality and the model updates.

This paper is structured as follows: Section II explains the functionality and limitations of existing approaches. In Section III, the considered technical setup is introduced. Section IV describes the multilateral coupling and provides the respective stability proofs. Experiments are presented in Section V and Section VI summerizes the results.

II. Problem Definition

This section presents the principles of the two basic teleoperation schemes involving delayed and model-mediated force feedback. The respective control loops and stabilization methods are presented and the limitations are discussed.

A. Delayed Force Feedback

Fig. 1 presents a position-computed force architecture (PF_{comp}) in which the controller force is fed back to the master device through the communication channel (T_1, T_2). The scalings α^I and β^I are the variable damping gains injected by passivity controllers (PC) which are introduced by the Time Domain Passivity Approach (TDPA, [6]) to assure the passivity of the communication channel. The human operator and the environment (Env) act with a force $F_{h/e}$ on master and slave device respectively.

Several approaches to guarantee stability despite time delay, such as the wave variables method [5] or the TDPA, are based on the passivity theorem. Via the so-called network representation [19], the energy behavior of a system can be systematically analyzed. The elements of a control loop can be presented as n-port subsystems with n ports at which flow (velocity) and effort (force) variables can be measured as depicted in Fig. 2. The human and the master are represented as $Agent\ \Lambda 1$ and the slave and the environment as $Agent\ \Lambda 2$ respectively. Applying the TDPA to the PF_{comp} architecture analogous to [20], the control loop can be split up into two parts. The motion demand of the operator is represented by the flow source v_m in the circuit of $Agent\ \Lambda 2$ and the effort source F_{PI} introduces the feedback force into the circuit of $Agent\ \Lambda 1$. The Time Delay Power Networks (TDPN, [20]) representing the communication channels assure the power consistency of the network ports. The delay as an active component generates energy which can lead to instability. This excessive energy can be calculated through the port signals in the network representation. The passivity controllers ($PC1$, $PC2$) dissipate that excessive energy through a variable damping. The reader is referred to [20] and [21] for more details on the TDPA and TDPN functionality. Note that the TDPA methodology also allows the feedback of measured [22] or fictitious forces.

To assure stability, the passivity controller $PC1$ varies the force feedback, which is, furthermore, delayed by the communication channel. Thus, the operator does not receive perfect haptic cues on the slave's interaction with its environment. In the other direction of energy flow, $PC2$ varies the velocity v_m^{del}.

B. Model-Mediated Teleoperation

In [7], MMT has been proposed for setups with large roundtrip-delays. As depicted in the signal flow diagram of Fig. 3, the operator receives force feedback F_f from a virtual reality. The model of this virtual environment (VE) and the state of the robot x_s^{del} within it are updated from the remote side. The functionality of damping α^I (later PC_{VE}) that assures the passivity of the interaction with the VE is described later.

The network representation of this setup (see Fig. 4) shows that the effort or force F_f is generated from the model in the VE. The $TDPN2$ subsystem in the slave side circuit represents the delayed communication. The stability respecting the interaction with the VE has to be assured additionally. In [8], the fictitious force of a virtual potential field was fed back to the operator. The system stability was proven via the Lyapunov approach. However the feedback loop was neglected. An environment model provided a repelling force feedback in [9], but no stability proof was presented. Also, the predictive approach of [4] was proposed without stability proof. The authors of [23] applied fictitious force feedback, but it was mentioned that no physically valid network representation could be found such that no stability proof could be presented. The Routh-Hurwitz criterion [24] and the Llewellyn approach [25] are not applicable here since they are not compatible with passivity-controlled communication channels. A method to guarantee passivity of the fictitious force feedback interaction is introduced in Section IV.

In the model-mediated setup, the operator receives haptic feedback instantaneously on his current commands to the slave and may e.g. recognize the effect of his motion demand earlier than in case of delayed feedback. Still, the model in the VE is affected by errors and the state feedback of the robot is delayed.

III. Technical Setup

A variety of extended model-mediated control schemes with position or rate control, different coupling signals and model types is feasible. In order to determine the required functionalities in a specific setup, this section introduces the focused scenario and the respectively required coupling signals as well as the generation of fictitious force feedback.

The considered scenario is the teleoperation of a rate-controlled wheeled mobile robot (WMR) that is teleoperated at high communication delay (KU Band) in the Kontur-2 setup [26]. The DLR force-feedback joystick (see Fig. 5) serves as the haptic interface to control the DLR light weight rover unit (LRU, Fig. 6). In order to access the three horizontal DoFs of the WMR, here, a car-like interface with curvature and longitudinal velocity command is preferred to a combination of lateral and longitudinal velocity commands, which allows no rotation without interruptions when using a 2-DoF interface.

In case of curvature commands, potential fields can not be applied to generate fictitious force feedback in an intuitive manner. Therefore, in the proposed VE, a predictive method similar to [4] is applied that considers a curvature polygon set as depicted in Fig. 7. Note that no model of the slave is implemented such that the slave dynamics are not considered locally, but the delayed actual pose of the LRU is considered in the local VE map. The polygons are employed to select values from a local danger map, which is computed by classifying the traversability of the terrain surrounding the LRU based on the depth data acquired through its pan/tilt stereo camera system [27]. The value of the fictitious force is determined from the height values of the obstacles that overlap with the polygons. The fictitious force feedback is calculated such that the left set of polygons (violet) produces a force pushing the joystick to the right and vice versa as depicted in Fig. 7. The sum of forces calculated by the left (violet) and right (orange) set of polygons results in a force that acts against the longitudinal driving command.

The LRU generates the danger map with respect to its horizontal plane without consideration of its own slope. Also, the operator's stereo camera feedback may not provide sufficient information on the slope. Therefore, additional haptic feedback should be provided to the operator to display the inclination of the rover. The WMR controller force or the measured wheel torques contain information on the mobility and slope but also on the WMR's inertia such that the resulting feedback force may be disturbing. Since the slope measurement through stereo vision is not accurate, the slope can not be well modeled locally in sufficient quality and thus has to be calculated on the remote side. Here, a feedback generated from the IMU's gravity vector is applied to complement the local model-based feedback.

IV. The Proposed Multilateral Control Approach

Fig. 8 presents the signal flow diagram of the proposed method applied to rate-controlled WMRs. The control loop fuses the delayed feedback force $\boldsymbol{F}^{*}_{m2}$ of the IMU and the local model-based feedback force $\boldsymbol{F}^{\#}_{m1}$. Since the longitudinal DoF of the WMR is rate controlled, the 2-DoF motion command is scaled by $\boldsymbol{\sigma}^1$ and $\boldsymbol{\sigma}^2$ which are denoted by the the superscript $*$ and $\#$. In rate-control teleoperation, the physical interface of the master in the network representation is violated since a master position is translated into a desired velocity. That means that though the human operator is not moving the master device, a power (resulting from desired velocity and force feedback) is sent to the slave robot. To preserve passivity, the r-passivity concept of [28] is applied. Thus, instead of the deflection δ_m of the master input device, the control variable $\boldsymbol{r}_m$ is sent to the remote plant and the local VE. The control variable $\boldsymbol{r}_m = \Gamma\dot{\boldsymbol{\delta}}_m + \Lambda\boldsymbol{\delta}_m$ with the diagonal matrix $\Lambda := diag[\lambda_1, \lambda_2] \in \Re^{nxn} \geq 0$, where $\lambda_j \geq 0$ can be designed to command the longitudinal velocity ($r_{m,1}$) of a WMR and $\Gamma := diag[\gamma_1, \gamma_2] \in \Re^{xxn} \geq 0$, where $\gamma_1 \in \{1, 0\}$ can be set to zero if the corresponding DoF is not rate controlled as the lateral curvature command in this paper. To preserve passivity, the rate control DoFs of a linear master device (constant mass matrix $\boldsymbol{M}$ and no Coriolis and centrifugal effects) require a local spring damper system $PI1$

$$\boldsymbol{M}\ddot{\boldsymbol{\delta}}_m + \boldsymbol{B}\dot{\boldsymbol{\delta}}_m + \boldsymbol{K}\boldsymbol{\delta}_m = \boldsymbol{F}_{FB} + \boldsymbol{F}_h \tag{1}$$

with damping $\boldsymbol{B}$ and stiffness $\boldsymbol{K}$, the human interaction force $\boldsymbol{F}_h$ and the slave's force feedback $\boldsymbol{F}_{FB}$. If the two DoFs of the master device can be regarded as two separate 1-DoF linear systems ($\boldsymbol{M} = diag[m_1, m_2]$), to grant passivity despite rate control, the parameters for both DoFs ($j = 1$, 2) need to be chosen according to

$$b_j \geq \lambda_j m_j \tag{2}$$

with $b_j \geq 0$. Thus, the control loop of Fig. 8 involves one local ($PI1$) and one remote controller ($PI2$). The scalings

Fig. 5. DLR Force-Feedback Joystick

Fig. 6. DLR LRU

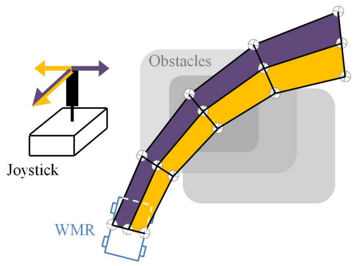

Fig. 7. Generation of Fictitious Force

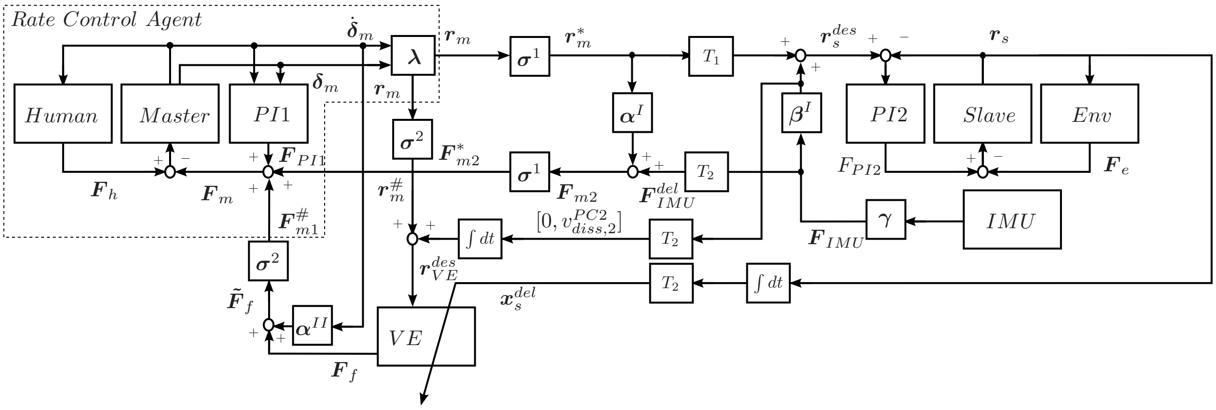

Fig. 8. Signal Flow Diagram of an Extended Model-Mediated Teleoperation Architecture for Rate Control with Passivity Control

$\alpha^{I,II}$ and β^I represent the passivity controllers' damping. α^I and β^I assure the passivity of the communication channel.

In the position controlled DoF (curvature in the lateral DoF), the passivity controller $PC2$ (β^I) can introduce a position drift in r_s^{des} that can be compensated [29] to some extent. Here, we propose to consider the drift on the slave side in the local input $r_{VE,2}^{des}$ to the VE. To match the local commanded curvature $r_{m,2}^{\#}$ to $r_{s,2}^{des}$, the velocity $v_{diss,2}^{PC2}$ dissipated by $PC2$ needs to be considered in $r_{m,2}^{\#}$. Therefore, a local curvature command to the VE $r_{VE,2}^{des}$ results from the sum of $r_{m,2}^{\#}$ and the delayed integral of $v_{diss,2}^{PC2}$ over time:

$$r_{VE,2}^{des}(k) = r_{m,2}^{\#}(k) + \sum_{i=0}^{k} v_{diss,2}^{PC2}(i - T_2). \qquad (3)$$

A. Network Representation of the Proposed Extended Model-Mediated Approach

Fig. 9 introduces the network representation of the $Rate\ Control\ Agent$ (RCA) $\Lambda 1$ subsystem. The $PI1$ subsystem with resistor and capacitor represents the local spring damper system. The power control unit (PCU, [13]) fuses the forces or power respectively which is exchanged with the master device. Since r_m is an artificial signal, a dependent flow source is necessary to define a physically valid port representing the user input in direction to the slave and the virtual environments. The flow source introduces energy resulting from the desired rate signals and F_{FB}. The control loop to the master device is closed via the dependent effort source F_{FB} that represents the force feedback to the master device. Note choosing $\lambda_j = 1$ and $\gamma_j = 0$, the RSA can be turned into a position control agent for the lateral DoF. The overall network representation of the extended MMT architecture for WMRs is depicted in Fig. 10. To fuse the force feedback, another PCU module has been introduced. Due to the longitudinal rate-control architecture, a RCA $\Lambda 1$ is considered and the scaling subsystems $\boldsymbol{\sigma}^1$ and $\boldsymbol{\sigma}^2$ are integrated. The circuit of $Agent\ \Lambda 1$ is terminated by a virtual environment VE and the IMU on the right side. In the network representation, the position update of equation (3) can be integrated in the VE subsystem since the VE is treated by the control approach as a black box.

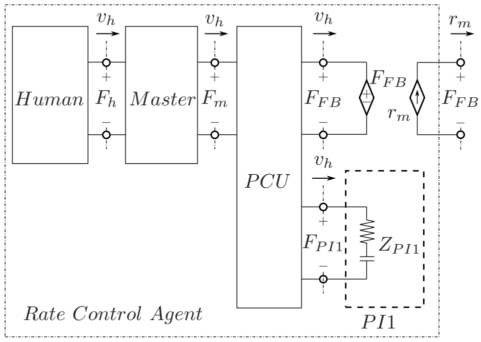

Fig. 9. Agent Preserving Passivity in Teleoperation with Rate Control

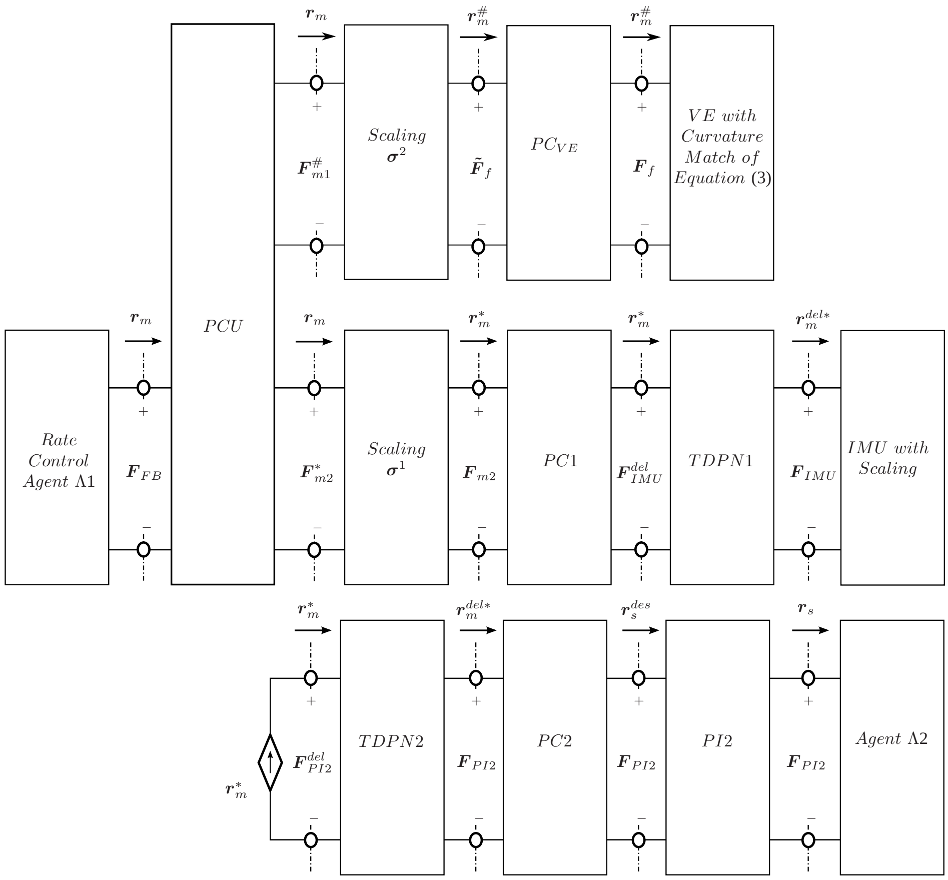

Fig. 10. Network Representation of an Extended Model-Mediated Teleoperation Architecture for Rate Control with Passivity Control

B. Stability Discussion

According to [19], the interconnection of passive n-ports results in a passive and thus $\mathscr{L}_2$-stable system. Therefore, in the following, the passivity of the submodules has to be proven: The RCA $\Lambda 1$ subsystem is designed in a passive manner as described above. The values $\lambda_{1/2}$ have to be determined via the r-passivity approach in order to achieve a passive master subsystem according to (2). The *scaling* subsystems $\boldsymbol{\sigma}^{1/2}$ have an intrinsically passive behavior since the velocity $\boldsymbol{r}_m^{*/\#}$ as well as the force feedback $\boldsymbol{F}_{m2/m1}^{*/\#}$ at the scaling subsystems' ports are affected by the scaling. The active behavior of the *time delay* is considered via the TDPN and controlled by the TDPA ($PC1$,$PC2$). The passivity of *power control units* has been proven in [13].

In order to guarantee overall stability, the passivity of the slave and environment subsystems, the model update via the delayed state feedback x_s^{del} and the passivity of the interaction with the virtual environments remain to be analyzed.

The WMR controller sets the desired curvature κ or yaw-rate $\dot{\psi}$ respectively via the wheel steering angle δ_{WMR} depending on the current longitudinal velocity. Considering the dynamic equations of the bicycle model in terms of sideslip angle and yaw-rate, the authors of [30] have shown that the map $\delta_{WMR} \rightarrow \dot{\psi}$ is strictly passive. The steering angle δ_{WMR} and the longitudinal WMR velocity is set by the controller $PI2$ which can be designed as a passive spring-damper system. Thus, taking into account the generally accepted assumption that the operator and the environment behave passive in their interaction, the subsystems $Agent\ \Lambda 2$ and $PI2$ do not disturb the passivity condition of the overall system.

The passivity controller PC_{VE} ($\boldsymbol{\alpha}^{II}$) assures the passivity of the interaction with the virtual environment despite model updates and discretization. In contrast to the computed force feedback in the control of a stationary robotic manipulator, fictitious forces calculated e.g. from a potential field of obstacles in a modeled environment have no physical relation to the control forces of the slave's actuator. That means, though the mobile robot is moving e.g. in a planar area requiring low traction and steering torques, the potential field of a close object, such as a hill may produce a repelling force. Therefore, it has to be assured that the power exchange resulting from $\boldsymbol{F}_f$ and $\boldsymbol{r}_m^{\#}$ is passive.

The PC acts as a variable damper that reduces the fictitious forces in case more energy exits at the single port of the virtual environment than has been introduced in advance. A similar method for passive model update has been introduced in [10], but that concept is limited to the update of stiffnesses modeled in a local virtual environment. In contrast, the proposed approach is applicable to a large variety of feedback generation types.

The proposed generation of a fictitious force can result in a non-passive interaction without PC. At zero velocity, the lateral motion of the master device may lead to an overlap of the polygon area and obstacles in the map. The resulting force feedback is approximately passive since the environment acts as a spring. Still, the discretization of the map, the delay in the force calculation as well as the model update may introduce energy into the system. Here, the model update is realized through the reloading of the danger map.

Since the longitudinal velocity and the yaw-rate are coupled, the DoFs can be considered together in the passivity analysis. The fictitious force in the longitudinal DoF is always acting against the velocity command such that the power flow is unidirectional and an energy storage can be calculated for the VE subsystems. The power output of the VE has to be limited by a passivity controller PC_{VE} if more energy than available is extracted from the energy storage.

For example, the energy storage $E_{VE}(k)$ of the VE subsystem of Fig. 10 at time step k can be calculated as follows:

$$\begin{aligned} E_{VE}(k) =& E_{VE}(k-1)+ \\ & (P_1^{L2R}(k)+P_2^{L2R}(k))T_s \end{aligned} \tag{4}$$

with sampling time T_s and the power P_i^{L2R} flowing from left to right ($L2R$) in the first (longitudinal, $i=1$) and second (lateral, $i=2$) DoF

$$P_i^{L2R}(k) = \begin{cases} -r_{m,i}^{\#}(k)F_{f,i}(k) & \text{, if } r_{m,i}^{\#}(k)F_{f,i}(k) \leq 0, \\ 0 & \text{, if } r_{m,i}^{\#}(k)F_{f,i}(k) > 0. \end{cases} \tag{5}$$

If the sum of desired output power $P^{R2L}(k) = P_1^{R2L} + P_2^{R2L}$ in right to left direction ($R2L$), with

$$P_i^{R2L}(k) = \begin{cases} r_{m,i}^{\#}(k)F_{f,i}(k) & \text{, if } r_{m,i}^{\#}(k)F_{f,i}(k) \geq 0 \\ 0 & \text{, if } r_{m,i}^{\#}(k)F_{f,i}(k) < 0 \end{cases} \tag{6}$$

violates the storage $E_{VE}(k)$, the power $P_{d,i}^{PC_{VE}}(k)$ has to be dissipated by PC_{VE} in the ith DoF:

$$P_{d,i}^{PC_{VE}}(k) = \begin{cases} P_d(k)\frac{P_i^{R2L}(k)}{P^{R2L}(k)} & \text{, if } \frac{E_{VE}(k)}{T_s} < P^{R2L}(k) \\ 0 & \text{, if } \frac{E_{VE}(k)}{T_s} \geq P^{R2L}(k) \end{cases}$$

with the power P_d that has to be dissipated overall

$$P_d(k) = E_{VE}(k)/T_s - P^{R2L}(k). \tag{7}$$

$P_{d,i}^{PC_{VE}}$ has to be dissipated by an impedance type PC in both DoFs. An impedance type PC dissipates energy by a variation of the fictitious output force F_f:

$$\tilde{F}_{f,i}(k) = F_{f,i}(k) + \alpha_i^{II}(k) r_{m,i}^{\#}(k) \tag{8}$$

with

$$\alpha_i^{II}(k) = \frac{P_{d,i}^{PC_{VE}}(k)}{r_{m,i}^{\#}(k)^2}. \tag{9}$$

Then, the energy storage $E_{VE}(k)$ needs to be updated since the power $P^{R2L}(k)$ left the VE

$$\begin{aligned} E_{VE}(k) =& E_{VE}(k-1) + (P_1^{L2R}(k) + P_2^{L2R}(k) \\ & - P_1^{R2L}(k) - P_2^{R2L}(k))T_s. \end{aligned} \tag{10}$$

Through the dissipation of impedance type PC_{VE}, the passivity of the interaction with the VE and the model update can be assured. Note that the usage of a PC allows a flexible design of the fictitious force feedback. For example, the fictitious forces can be smoothened by filters inside the VE one-port network without violation of passivity. Here, the summation of $r_{m,2}^{\#}$ and $v_{diss,2}^{del}$ of equation (3) is considered in the VE subsystem without violating the passivity condition since the PC_{VE} assures the passivity of the VE subsystem.

In contrast to the VE force feedback, the force F_{IMU} is not affected by discretization or model updates. Since, in addition, the energy exchange with the IMU subsystem is passive, no PC is required for that one-port network. Considering the car-like interface with longitudinal velocity v_x and curvature κ, the passivity of the IMU subsystem is not obvious. But, analyzing the decoupled interface of v_x and yaw-rate $\dot{\psi}$ ($\dot{\psi} = \kappa v_x$), it is clear that no energy can be introduced by the IMU subsystem that has the energetic behavior of a potential energy storage. Even, the initial potential energy which appears if the WMR starts on a high place is accounted in the passivity criterion.

The experiment Exp1 serves the validation of the passivity control of the virtual environment and its fictitious force feedback. As can be seen in Fig. 11, a random motion is commanded to the WMR at 800ms roundtrip-delay with pure local feedback. Especially in the beginning ($t = [0s, 10s]$), energy is dissipated by PC_{VE} ($F_{PC,1/2}$) since the virtual environment including the model update behaves active. Afterward ($t > 10s$), the VE force $\tilde{F}_f$ is not varied by the PC. The energy plot E_{PP} shows that the passivity controller assures the passivity of the fictitious force feedback since the energy is never negative.

V. Experiments

The following experiments have been performed with the DLR LRU and the DLR Force-Feedback Joystick (see Fig. 5 and Fig. 12). The control software has been implemented in Matlab/Simulink with a simulated constant delay in a UDP communication. The scalings $\sigma_{1,1}$ and $\sigma_{2,1}$ were set to 4, such that the maximum deflection of 20 degrees was mapped to $1.4m/s$ longitudinal velocity. Whereas the scaling $\sigma_{1,2}$ and $\sigma_{2,2}$ were chosen as 1.5, such that maximally a curvature of approximately $0.5/m$ could be commanded. Since the joystick's moment of inertia equals $0.0003\frac{kg}{m^2}$ and $\gamma_1 = 1$, $\lambda_1 = 10$, a damping of $b_1 = 0.07\frac{Nms}{rad}$ and a stiffness of $k_1 = 0.1\frac{Nm}{rad}$ were chosen.

In experiment Exp2, a longitudinal motion is commanded to the WMR which is standing on an inclined surface in front of an obstacle as depicted in Fig. 12. Especially, when driving downwards, the IMU feedback and the fictitious feedback might act in opposing directions. Here, the force scalings

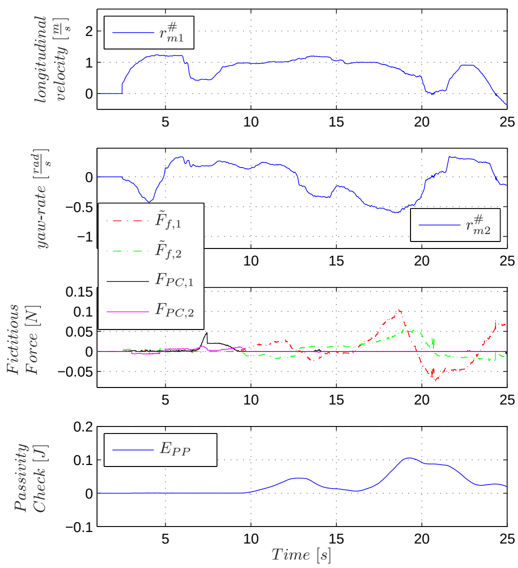

Fig. 11. Exp1: Passivity Proof of Virtual Environment at 800ms Roundtrip-Delay

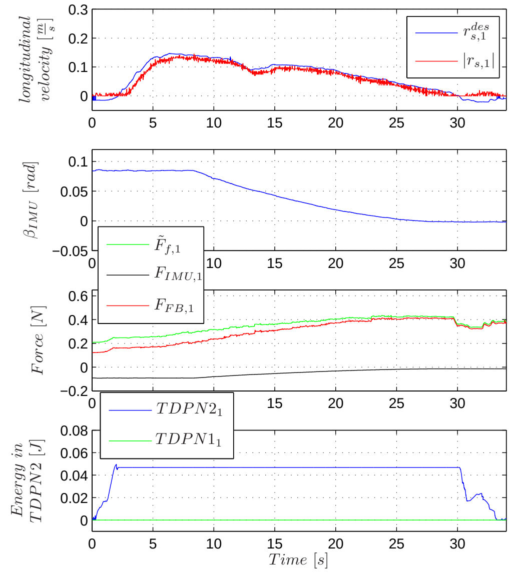

Fig. 13. Exp2: Pure Longitudinal Motion at 400ms Roundtrip-Delay

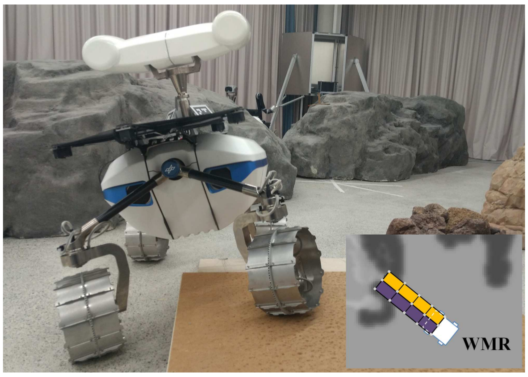

Fig. 12. LRU Scenario with Grid Map and Polygon

were designed such that $max(\tilde{F}_{f,1})/max(F_{IMU,1}) = 2$. Therefore, the fictitious force feedback $\tilde{F}_{f,1}$ outweighs the IMU feedback $F_{IMU,1}$ significantly when coming close to the obstacle. In addition, a nonlinear, obstacle distance dependent force weight in the VE force generation can be considered. Also, a top view visualization of the LRU motion and the polygons in the danger map support the operator's awareness of impeding obstacles. The fictitious force feedback $\tilde{F}_{f,1}$ and the IMU feedback $F_{IMU,1}$ have different signs such that the perception of the obstacle through $\tilde{F}_{f,1}$ is constrained ($t = [0s, 30s]$). It can be analyzed from Fig. 13 that the operator is pushed away from the obstacle and that the IMU feedback pushes the operator down the slope during standstill ($t = 0s$). The velocity command $r^{des}_{s,1}$ as well as the force feedback $F_{FB,1}$ are not heavily affected by the passivity controllers $PC1$ and $PC2$ respectively such that the current velocity of the slave $r_{s,1}$ is close to the commanded value $r^{des}_{s,1}$. The energies in the passivity controlled TDPN1 and TDPN2 are purely positive which proofs the passivity of the communication channels. The velocity and force signals closing the control loop do not show any oscillations which promises a good operating performance despite a roundtrip-delay of 400ms. Therefore, the setup can be applied even with a high delay KU-Forward link with geostationary satellites. Here, we present a proof of concept in a simplified environment. In case of higher slopes which are within the maneuverability range of the WMR, the IMU scaling can be adjusted without violating the passivity condition.

In experiment Exp3 ($\gamma_2 = 0$, $\lambda_2 = 1$, $b_2 = k_2 = 0$, Fig. 14) a combined longitudinal and lateral motion was performed at 800ms roundtrip-delay. The LRU is driving down a slope and enters a canyon-like structure (compare Fig. 12). The curvatures $r^{des}_{s,2}$ and $r^{des}_{VE,2}$ are equal, thanks to the functionality of equation (3). Therefore, the local VE provides reasonable force feedback in the lateral DoF. Especially in free motion, the IMU feedback is clearly perceived by the operator. The force plots in Fig. 14 show that, as desired, the obstacles are displayed with higher priority to the operator. Again, the passivity controllers $PC1$ and $PC2$ do not seriously disturb the velocity and curvature commands $\boldsymbol{r}^{des}_{s}$ and the force feedback $\boldsymbol{F}_{FB}$. The positive energy plots of the communication channel TDPN2 prove the passivity despite time delay.

VI. Conclusion

In this paper, a concept for extended model-mediated teleoperation of mobile robots incorporating local and remote force feedback was introduced. Due to the modularity of the network representation, the proposed concepts can be applied to a variety of fictitious forces and combined with other control architectures involving position or rate control and computed or measured force feedback architectures. Also, the wave variables approach can be used instead of the TDPA.

The passivity of the proposed setup was guaranteed via the TDPA and the r-passivity approach for rate-control teleoper-

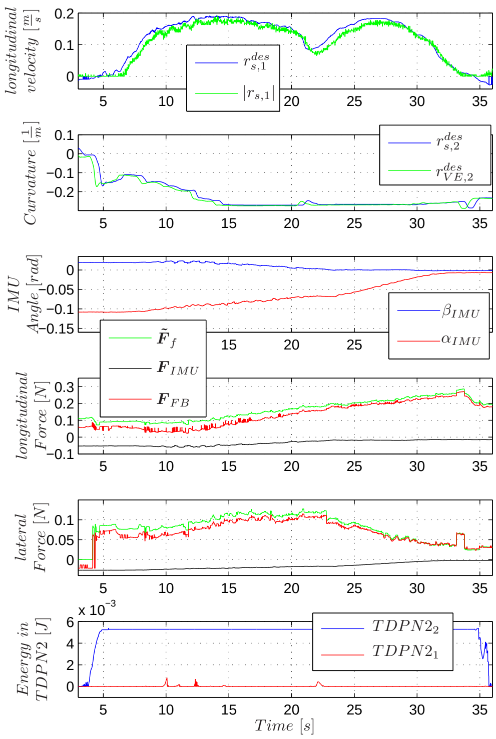

Fig. 14. Exp3: Combined Longitudinal and Lateral Motion at 800ms Roundtrip-Delay

ation. Furthermore, a new method to guarantee passivity of fictitious force feedback and permanent model updates has been proposed and validated.

Experiments showed that stability of the new extended model-mediated teleoperation scheme could be guaranteed and the fused local and remote force feedback promise a performance increase.

In future work, the setup should be tested in position control telemanipulation applications.

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