# Time Domain Control for Passive Variable Motion and Force Scaling in Delayed Teleoperation

**M. Panzirsch** * **R. Balachandran** *

* *Institute of Robotics and Mechatronics, German Aerospace Center (DLR), 82234 Wessling, Germany (e-mail: michael.panzirsch@dlr.de).*

**Abstract:** Scaling of motion and forces has always been of high relevance in teleoperation setups since it allows the adaptation of workspaces of master and slave devices or to increase precision. Teleoperation setups are often affected by a delay in the communication channel. Most state of the art control approaches that guarantee stability despite delay are based on the passivity criterion which is highly restrictive to standard scaling methods. This paper proposes different time domain control concepts that regulate the motion or force scaling based on the energy flow in delayed teleoperation systems. The approach focuses on setups with motion down-scaling and is applicable to variable motion and impedance scaling. The scaling control is integrated in a state of the art time delay control concept and its performance is analyzed in experiments.

*Keywords:* Scaling, Time Delay, Teleoperation, Time Domain Control

## 1. INTRODUCTION

Teleoperation is a mature technology that has a large variety of application fields ranging from nuclear research to space and the medical sector. Some prefer an up-scaling of the master motions for a large slave robot workspace, others as surgical applications require micro- or nano-manipulation capabilities in the extreme case (Onal and Sitti (2009)) which can be achieved by a motion down-scaling. Apart from motion scaling also force scaling can be helpful, for example, in teleoperation training or for task allocation in multilateral setups (Panzirsch et al. (2018)). Depending on the combination of motion and force scaling factors, so-called power scaling, impedance scaling or pure motion or force scaling can be designed. The works of Colgate (1991), Vander Poorten et al. (2006) and Goldfarb (1998) discuss different force scaling designs according to the properties of the environmental impedance that can be primarily inertial, elastic or exhibit viscous damping.

Scaling factors have been applied within different teleoperation control architectures and with a variety of stability analyzes. In Speich and Goldfarb (2002), the transparency of a scaled position-force architecture with loop-shaping compensators has been evaluated. Also, the $H_\infty$ approach (Yan and Salcudean (1996), Boukhnifer et al. (2004)) and a sliding mode control (Khan et al. (2009)) have been implemented for scaled teleoperation. Power scaling was applied by Boukhnifer and Ferreira (2006), Boukhnifer et al. (2004) and Jazayeri and Tavakoli (2013). Jazayeri and Tavakoli (2013) focused on absolute stability for scaled sampled-data systems. Impedance scaling has been considered by Onal and Sitti (2009). Vander Poorten et al. (2006) performed an absolute stability analysis based on the scattering matrix of a delay-free, fixed-scale teleoperation setup.

A large set of control concepts for delayed teleoperation is based on an energy criterion. Colgate (1991) and Itoh et al. (2000) chose a passivity based design considering a scattering matrix. In the system of Itoh et al. (2000), the scaling design was specific in that it was separated from the telemanipulator. The wave variables method was applied by Boukhnifer and Ferreira (2006). Secchi et al. (2005) designed a scaled teleoperation setup with the port-Hamiltonian system representation. Often, it is assumed that environments are passive (Itoh et al. (2000), Secchi et al. (2005), Onal and Sitti (2009)) which presents a clear limitation for the teleoperation scenario. For example, a beating heart in a medical scenario or a human interacting with a robot in an ambient assisted living scenario presents an active environment. Also, several control approaches require power scaling settings (Boukhnifer and Ferreira (2006)) since it is an intrinsically passive functionality. But the power scaling values differ extremely from impedance scaling values which are often preferable.

Here, we focus on the passivity criterion since most state of the art approaches for time-delayed teleoperation as the wave variables method (Niemeyer (1996)) or the time domain passivity approach (TDPA, Ryu et al. (2010), Panzirsch et al. (2019)) are based on this criterion. The benefit is the high modularity of energy-based concepts which allows, for example, uncomplicated extensions of bilateral to multilateral setups (Panzirsch et al. (2013)). In this paper, we propose a time domain control concept for passive scaling that can be applied in teleoperation scenarios with active environments. In contrast to former approaches, the concept guarantees passivity in setups with pure motion, pure force and impedance scaling, and allows for time-varying scaling designs. Also, we present how the conservatism of time domain passivity control in delayed setups with motion scaling can be reduced.

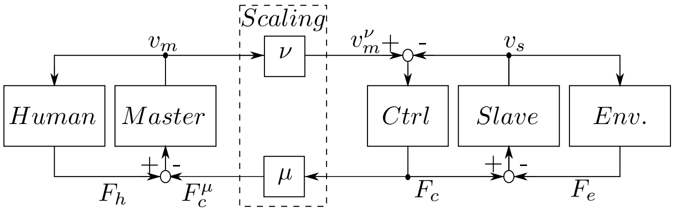


Fig. 1. Signal flow diagram of a 2-Channel architecture with scaling.

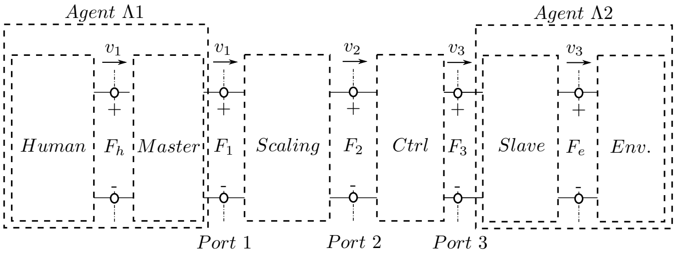


Fig. 2. Network representation of a 2-Channel architecture with scaling.

The method promises high transparency especially during motion down-scaling.

The paper is structured as follows: Section 2 analyzes the energetic behavior of motion and force scalings in control networks. A power-based and an energy-based time domain passivity control for variable motion and force scaling are introduced in Section 3. The experimental evaluation which includes time delay teleoperation setups is presented in Section 4. Finally, Section 5 concludes the work.

## 2. PROBLEM STATEMENT

The signal flow diagram of a scaled teleoperation setup and the respective network representation are depicted in Fig. 1 and Fig. 2 respectively. A *Human* uses a *Master* input device to control a slave robot in its environment. The two devices can be coupled with a PD controller (*Ctrl*). The variables $\nu$ and $\mu$ scale the motion (velocity) and force respectively ($\nu, \mu \in [0, \infty[$). The following relations between the signals holds: $v_1 = v_m$, $v_2 = v_m^\nu$, $v_3 = v_s$, $F_1 = F_c^\mu$, $F_2 = F_3 = F_c$. The network representation is an electrical diagram that allows the power observation at the ports $i$ with power-conjugated signals force $F_i$ and velocity $v_i$. The *Scaling* as well as the *Ctrl* are 2-port networks.

Concerning an analytical analysis of a scaling network in the frequency domain (e.g. Raisbeck's criterion), the scaling subsystem is only passive if the motion and force scaling values are equal (power scaling, $\mu = \nu$). That means that, for the sake of passivity, in case of motion up-scaling, the force feedback has to be scaled up and in case of motion down-scaling, the feedback force has to be scaled down. The experiment in Fig. 4 shows that with equal $\mu$ and $\nu$ ($\mu = \nu = 0.5$), the energy over the scaling 2-port $E_{2port}$ is always zero which confirms its passivity. The experiments were performed with two 1-DoF rotational devices (SENSODRIVE, compare Fig. 3). The coupling software was executed on a QNX host machine at a sampling rate of 1kHz.

With the classical impedance scaling, the slave side impedance ($Z_s = F_c v_s$) can be displayed at the master

Fig. 3. Experimental setup: two 1-DoF rotational devices.

device ($Z_m = \mu F_c v_m$). With $v_m = \nu v_s$, impedance scaling requires $\mu = 1/\nu$ which is highly contradictive to the passive power scaling. The experiment in Fig. 5 presents an impedance scaling teleoperation with $\nu = 0.5$ and $\mu = 2$. The energy plot clearly shows the energy generation during the operation (negative slope of $E_{2port}$) when the slave leads the motion at $t > 3.5s$.

The impedance scaling focuses on the haptic perception of impedance at the master device and neglects the visual feedback. Alternatively, it can be argued that the human operator relates the force displayed at the master device to the motion of the slave robot (instead of the master motion). Then, a force scaling of $\mu = 1$ is reasonable. This may be especially relevant for master and slave systems with similar workspace where a pure motion scaling is applied to increase the precision of the operation. In teleoperation scenarios with free motion and soft walls, the pure motion scaling promises a good perception of the environmental interaction whereas during hard contacts (low slave motion) the impedance scaling might be more intuitive. The reader is referred to the work of Goldfarb (1998) for more details on the choice of force scaling factors depending on the environment contact. As visible from the experiment in Fig. 6 and the energy plot $E_{2port}$, the pure motion scaling ($\mu \neq \nu$, $\mu = 1$, $\nu = 0.5$) is not passive.

Depending on the applications, also a variable velocity scaling design can be reasonable. For example, the velocity scaling can be a function of the master velocity ($\nu = f(v_m)$) such that for fast master motion $\nu = 1$ since it can be assumed that the human wants to move far. Whereas at lower master motion, the velocity scaling can be faded down to $\nu = 0.5$ since the human wants to command a precise motion.

In the following, a passivity control for arbitrary and variable scaling values is designed that leads to a passive scaling network subsystem that can be applied to passivity-based control frameworks in a highly modular manner.

## 3. PROPOSED TIME DOMAIN CONTROL APPROACH

As it can be analyzed from the energy plots in Fig. 4 to Fig. 6, the scaling dissipates or generates (positive and negative slope of $E_{2port}$ respectively) energy depending on the scaling values and on which device leads the motion. The power dissipation and generation can be calculated as follows (if $\nu, \mu \neq 0$):

$$P_2 = \frac{\nu}{\mu} P_1 \begin{cases} < P_1 & \text{, if } \nu < \mu \text{ (case 1)} \\ \geq P_1 & \text{, if } \nu \geq \mu \text{ (case 2).} \end{cases} \qquad (1)$$

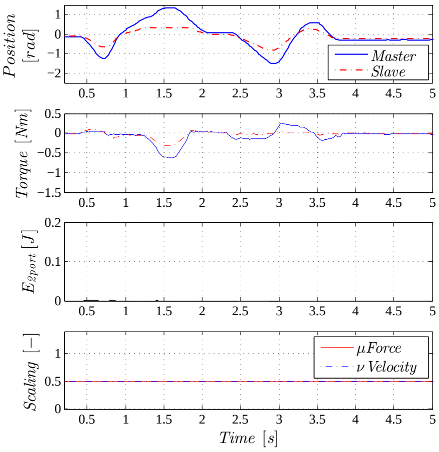


Fig. 4. Power scaling.

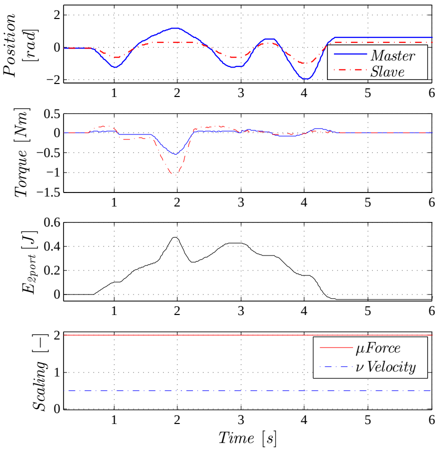


Fig. 5. Impedance scaling.

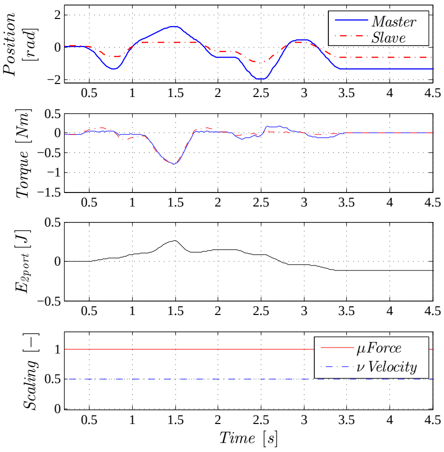


Fig. 6. Pure motion scaling.

In case 1, energy is dissipated in the left to right energy flow direction ($L2R$) and generated in the right to left ($R2L$) energy flow direction. In case 2, it behaves vice versa. The power flow direction can be distinguished by the sign of the power $P_i$. The power values $P_i^{L2R}$ and $P_i^{R2L}$ are positive by definition:

$$P_i^{L2R} = \begin{cases} P_i & \text{, if } P_i > 0 \\ 0 & \text{, if } P_i \leq 0, \end{cases} \tag{2}$$

$$P_i^{R2L} = \begin{cases} -P_i & \text{, if } P_i < 0 \\ 0 & \text{, if } P_i \geq 0. \end{cases} \tag{3}$$

In typical teleoperation setups, the master moves the slave such that in case 1 (for example at pure motion down-scaling) the scaling is mostly overall passive. Still, classical frequency-based stability approaches do not consider this power flow direction dependency and therefore a passive power scaling ($\nu = \mu$) has to be chosen or active environments are not allowed. Applying a time domain energy observation and control, this conservatism can be heavily reduced. In the following, different time domain control approaches for case 1 in (1) will be discussed that consider different power and energy criteria. Furthermore, they differ by the adaptation of motion or force scaling. Finally, the integration of the control approach in a state of the art time delay control approach is presented.

### *3.1 Time domain control for passive scaling*

In the following section, we concentrate on case 1 ($\nu < \mu$) settings. The proposed control method preserves passivity through the online adaptation of the velocity or force scaling as soon as passivity is violated. Therefore, considering motion down-scaling, the controller has to increase the velocity scaling or to decrease the force scaling in phases of undesired energy generation to achieve $\nu = \mu$ (passive power scaling). In general, the force scaling should remain constant during teleoperation since the forces are directly perceived at the master device. In contrast, the velocity adaptation is not as obvious and disturbing to the operator since the operator focuses on the position command which is the integral of the adapted variable. On the first sight, the up-scaling of the velocity by the controller may appear as an unintuitive solution. But, a closer analysis reveals that this adaptation is not problematic: In this work, we focus on a down-scaling of the velocity such that the teleoperated slave robot moves slower than the master device. Thus, the controller has to adapt (increase) the velocity scaling if energy is generated by the scaling. As analyzed before, the scaling generates energy if energy is flowing from slave to master, that means if the master device moves out of a wall contact or if the slave leads the motion. If the scaling is not varied (time domain control inactive), the master moves much faster than the slave, which might be dangerous if the slave leads the motion. In contrast, if the velocity scaling is increased in such situations (by the passivity control action), the master device moves as slow and as far as the slave which is a much safer procedure.

Now, two approaches that consider a power-based and an energy-based criterion respectively are presented.

*Power-based passivity criterion (Approach 1):* As explained before, the power flow direction can be analyzed and the focused motion down-scaling produces energy only in the $R2L$ flow direction, which means when the slave leads the master. Therefore, a passivity controller can be designed that adapts the scaling for the sake of passivity to passive power scaling ($\mu = \nu$) if power flows in $R2L$ direction: The velocity scaling

$$\nu(k) = \begin{cases} \nu^{des} & \text{, if } P_1^{L2R} > 0 \\ \mu & \text{, if } P_1^{L2R} = 0, \end{cases} \tag{4}$$

or alternatively, the force scaling can be adapted, therefore:

$$\mu(k) = \begin{cases} \mu^{des} & \text{, if } P_1^{L2R} > 0 \\ \nu & \text{, if } P_1^{L2R} = 0. \end{cases} \tag{5}$$

Note that force scaling may lead to disturbances in the teleoperation setup and therefore, velocity scaling should be favoured. Still, for the sake of completeness, the force scaling is also presented here. Experiments concerning impedance and pure motion scaling are presented in Section 4.

The negative aspect of the power-based controller is that the scaling is not only varied when the slave leads the motion but also when the master leaves a wall contact ($P_1^{L2R} = 0$). Note that if the $\nu$ adaptation is chosen,

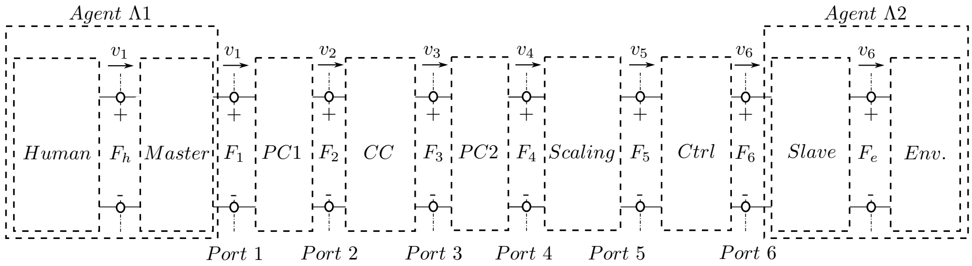


Fig. 7. Network representation of the TDPA (Ryu et al. (2010)) for delayed teleoperation with scaling.

the slave leaves the wall contact faster. As soon as the wall contact is over ($P_1^{L2R} > 0$), the standard scaling is reactivated. For example, in pick and place tasks, the operator wants to feel a wall contact, but also wants to leave it as fast as possible. Then, the power-based velocity adaptation has no negative effect. In soft environments, on the other hand, the slave leaves the wall contact faster and the perception of the wall contact is altered. Still, this may not be critical since the impedance of an object is mainly analyzed in the penetration direction.

*Energy-based passivity criteria (Approach 2):* This negative aspect of the power-based controller motivates for another solution that circumvents the scaling adaption during one wall contact. In contrast to the power-based design (Approach 1), the following concept considers the potential energy storage in the coupling controller that results from the coupling controller's spring-like element.

This energy storage $E_{st}$ is built up, for example, during a wall contact:

$$E_{st}(k) = E_{st}(k-1) + (P_2^{L2R}(k) + P_3^{R2L}(k) - P_3^{L2R}(k) - P_2^{R2L}(k))T_s,$$

with the sampling time $T_s$ (compare Fig. 2).

During a wall contact, energy is charged into the coupling controller's spring. The same amount of energy is released when the penetration into the wall is reduced. Therefore, a time domain controller for passive scaling that considers the energy $E_{St}$ instead of power does not vary the scaling during the wall contact (in contrast to Approach 1).

The velocity scaling

$$\nu(k) = \begin{cases} \nu^{des} & \text{, if } E_{st}(k) \geq 0 \\ \mu & \text{, if } E_{st}(k) < 0, \end{cases} \tag{6}$$

or alternatively, the force scaling can be adapted therefore:

$$\mu(k) = \begin{cases} \mu^{des} & \text{, if } E_{st}(k) \geq 0 \\ \nu & \text{, if } E_{st}(k) < 0. \end{cases} \tag{7}$$

To assure that the scaling switches when the leading role switches from master to slave or vice versa, the reference energy storage $E_{St}^*$ has to be reset when $x_m = x_s$ (with a certain threshold). If $E_{st}(k) = 0$, the old values of $\nu$ and $\mu$ have to be set. In contrast to the power-based adaption (Approach 1), force scaling may lead to lesser disturbances in Approach 2 since the scaling is not adapted during a wall contact.

### *3.2 Scaling in Time Delay Setups*

Figure 7 presents the network representation of a delayed teleoperation setup with communication channel $CC$ and time domain passivity control (TDPA, Ryu et al. (2010)). The TDPA introduces passivity observers that measure the energy that has been generated by the $CC$ and passivity controllers (PC) that dissipate energy to ensure the passivity of the two-port between ports 1 and 4. This approach also considers two directions of energy flow and therefore, two PCs are implemented. An impedance-type $PC1$ varies the force which is sent to the master side with a variable damping $\alpha$ that depends on the energy that has to be dissipated and on the velocity $v_2$ at the $PC1$ port. An admittance-type $PC2$ varies the velocity ($v_4 = v_3 - v_m^{PC}$) which is sent to the slave side with a variable damping $\beta$ that is calculated from the energy that has to be dissipated and the force $F_3$ at the $PC2$ port. Since this variation can be interpreted as a down-scaling $\nu^{PC}$

$$\nu^{PC} = min(v_m^{PC}/v_m^{del}, 1), \tag{8}$$

(calculated from the delayed master reference velocity $v_m^{del} = v_3$ and the velocity output $v_m^{PC}$ of the $PC2$), it can be considered for the desired velocity scaling $\nu^*$ that acts on $v_m^{PC}$ in case of velocity scaling adaptation (4) or (6):

$$\nu^* = \begin{cases} 1 & \text{, if } \nu^{PC} < \nu^{des} \\ min(1, \nu^{des}/\nu^{PC}) & \text{, if } \nu^{PC} \geq \nu^{des}, \end{cases} \tag{9}$$

such that the effective overall scaling $\nu^*\nu^{PC}$ of the delayed master velocity $v_m^{del}$ is not higher than $\nu^{des}$ (if the time domain controller for passive scaling is not active, otherwise $\nu = \mu$). The consideration of the $PC2$ scaling in the desired motion scaling $\nu$ leads to a less conservative passivity control since the $PC2$ dissipation leads to a position drift ($p_4 \neq p_3$) after integration of $v_4$. If the PC dissipation would not be considered in $\nu = \nu^*\nu^{PC}$, the velocity would be further reduced and position drift increased. The consideration of a force scaling adaptation (5) or (7) in $PC1$ is not presented here.

## 4. EXPERIMENTAL EVALUATION

The first experiment (see Fig. 8) presents the power scaling method (Approach 1) with pure motion scaling ($\nu^{des} = 0.5$, $\mu^{des} = 1$) and velocity scaling adaptation (4). The master moves the slave device in free motion and against a wall ($t = [2s - 6s]$). The velocity scaling is adapted when the master leaves the wall penetration, since power is flowing from slave to master ($P_1^{L2R} = 0$). Afterwards ($t = [6s - 7.5s]$), the slave moves the master and the velocity scaling is set to 1 ($P_1^{L2R} = 0$). With this control strategy, a passive scaling can be achieved, as it is confirmed by the purely positive 2-port energy $E_{2port}$ of the scaling subsystem.

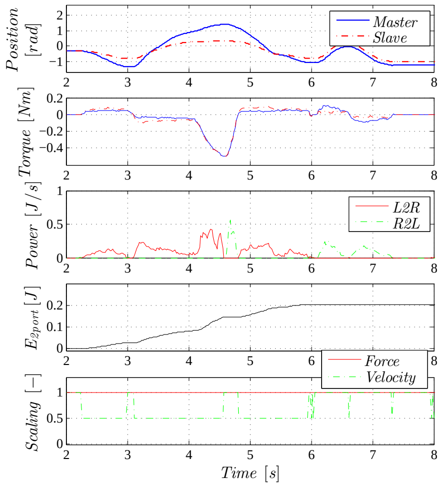


Fig. 8. App1: Power Control with pure motion scaling and velocity scaling adaptation.

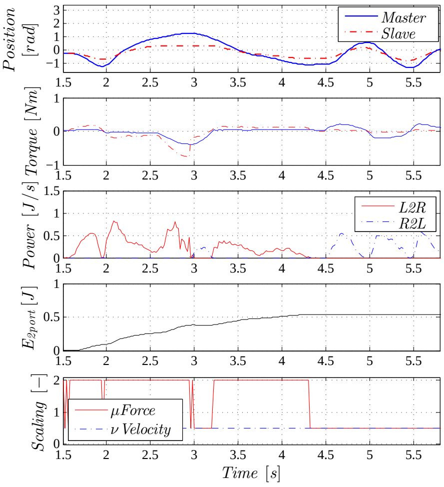


Fig. 9. App1: Power control with impedance scaling and force scaling adaptation.

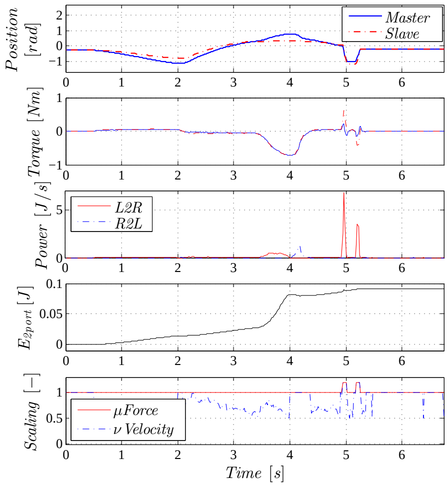


Fig. 10. App1: Power control with variable motion scaling and velocity scaling adaptation.

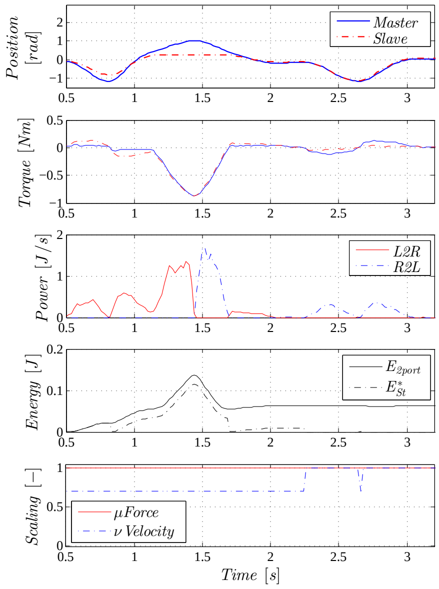


Fig. 11. App2: Energy control with motion scaling and velocity scaling adaptation.

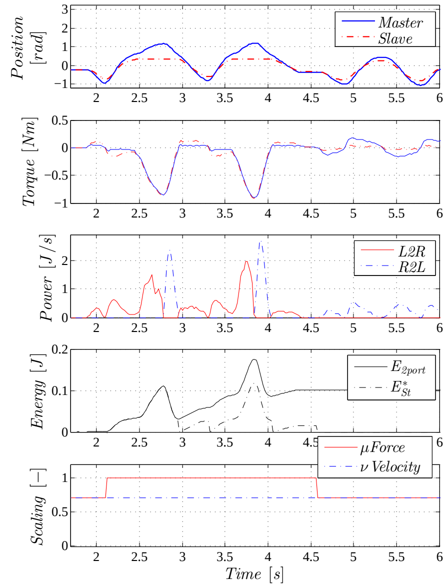


Fig. 12. App2: Energy control with force scaling and force scaling adaptation.

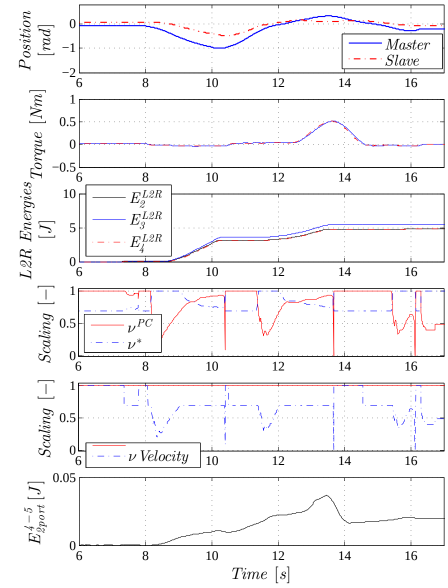


Fig. 13. TDPA with Approach 1 and velocity scaling adaptation at 100ms roundtrip-delay

In the second experiment (see Fig. 9), an impedance scaling ($\nu^{des} = 0.5$, $\mu^{des} = 2$) with force scaling adaptation (5) is presented. The master moves the slave $t = [1.5s - 4.3s]$ and the slave overtakes the lead at $t = [4.3s - 6s]$. Comparing the power and scaling plots, it is obvious that the force scaling is adapted when energy flows from slave to master ($R2L$ direction, $P_1^{L2R} = 0$). It can be seen from the energy plot that also the force adaptation leads to a passive scaling 2-port.

The third experiment in Fig. 10 presents a variable motion scaling and power-based velocity scaling adaptation (4). The velocity scaling depends on the master velocity $\nu = f(v_m)$:

$$\nu^* = \begin{cases} \nu^{des} & , \text{ if } |v_m| < v_{min} \\ \nu^{\ des} + (1 - \nu^{des})\frac{|v_m| - v_{min}}{v_{max} - v_{min}} & , \text{ if } v_{min} \le |v_m| < 2\frac{rad}{s} \\ 1.2 & , \text{ if } |v_m| \ge 2\frac{rad}{s}. \end{cases}$$

The variable scaling was designed such that at fast motions, the velocity scaling is $\nu = 1.2$. If $\nu > 1$ ($t = [4.8s - 5.2s]$), the time domain scaling controller has to set the force scaling to $\mu = \nu$ independent of the power flow to maintain passivity. High master velocities appear at free motions and therefore, the increase of force scaling has no unintuitive effect. If the controller has to act, the velocity scaling is set to $\nu = \mu$ ($t = [5.5s - 6.8s]$). Again, the energy plot $E_{2port}$ confirms the passivity of the time domain scaling controller.

Figure 11 and Fig. 12 present the energy-based Approach 2 with velocity (6) and force scaling adaptation (7) respectively. The passivity of the scaling is confirmed by the solid energy plot $E_{2port}$. The dashed energy plot $E^*_{St}$ presents the reference energy which is reset when the positions of master and slave match. The master leads in Fig. 11 at $t = [0.5s - 2.25s]$ and in Fig. 12 at $t = [2.1s - 4.6s]$. The positive aspect of Approach 2 is that the scaling does not change during the wall contact in contrast to the power-based approaches.

The experiment in Fig. 13 presents a delayed setup with TDPA at 100ms roundtrip-delay with power-based scaling (Approach 1) and velocity scaling adaptation (4). A pure motion scaling ($\nu^{des} = 0.7$, $\mu^{des} = 1$) has been applied. Since $E_4^{L2R} \leq E_2^{L2R}$ (compare Fig. 7) the energy plot confirms that the admittance type PC ensures a passive communication. The scaling $\nu^*$ acts on the velocity output of the PC. The resulting velocity scaling $\nu$ is $\nu^{PC}$ when $\nu^{PC} < \nu^{des}$ and $\nu^{des}$ when $\nu^{PC} > \nu^{des}$. When power flows from slave to master in $R2L$ direction, the velocity scaling is deactivated ($\nu = 1$). The consideration of the PC dissipation in the motion scaling leads to lower conservatism.

## 5. CONCLUSION

A new time domain passivity control for scaling subsystems has been proposed that focuses on setups that require a down-scaling of motions for higher precision or a smaller workspace of the slave robot. A power- and an energy-based control approach have been presented that can be applied for impedance and pure motion scaling with adaptation of force or velocity. The user has to decide for a force or velocity adaptation according to the respective teleoperation application. A time delay control approach has been extended with the proposed scaling method. The time domain control approach has been successfully validated in experiments. In contrast to former approaches, in the proposed method, a variable scaling is feasible, which is otherwise very difficult to integrate in an alternative frequency based stability analysis. Furthermore, no passivity assumptions for environments have to be made.

## REFERENCES


Boukhnifer, M. and Ferreira, A. (2006). Stability and transparency for scaled teleoperation system. In *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 4217–4222. IEEE.

Boukhnifer, M., Ferreira, A., and Fontaine, J.G. (2004). Scaled teleoperation controller design for micromanipulation over internet. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004*, volume 5, 4577–4583. IEEE.

Colgate, J.E. (1991). Power and impedance scaling in bilateral manipulation. In *Proceedings. 1991 IEEE International Conference on Robotics and Automation*, 2292–2297. IEEE.

Goldfarb, M. (1998). Dimensional analysis and selective distortion in scaled bilateral telemanipulation. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation*, volume 2, 1609–1614. IEEE.

Itoh, T., Kosuge, K., and Fukuda, T. (2000). Human-machine cooperative telemanipulation with motion and force scaling using task-oriented virtual tool dynamics. *IEEE Transactions on robotics and automation*, 16(5), 505–516.

Jazayeri, A. and Tavakoli, M. (2013). Absolute stability analysis of sampled-data scaled bilateral teleoperation systems. *Control Engineering Practice*, 21(8), 1053–1064.

Khan, S., Sabanovic, A., and Nergiz, A.O. (2009). Scaled bilateral teleoperation using discrete-time sliding-mode controller. *IEEE Transactions on Industrial Electronics*, 56(9), 3609–3618.

Niemeyer, G.D. (1996). *Using wave variables in time delayed force reflecting teleoperation.* Ph.D. thesis, Massachusetts Institute of Technology.

Onal, C.D. and Sitti, M. (2009). A scaled bilateral control system for experimental one-dimensional teleoperated nanomanipulation. *The International Journal of Robotics Research*, 28(4), 484–497.

Panzirsch, M., Artigas, J., Ryu, J.H., and Ferre, M. (2013). Multilateral control for delayed teleoperation. In *Proc. of 2013 International Conference on Advanced Robotics*, 1–6.

Panzirsch, M., Balachandran, R.R., Weber, B., Ferre, M., and Artigas, J. (2018). Haptic augmentation for teleoperation through virtual grasping points. *IEEE Transactions on Haptics*, 11(3), 400–416.

Panzirsch, M., Ryu, J.H., and Ferre, M. (2019). Reducing the conservatism of the time domain passivity approach through consideration of energy reflection in delayed coupled network systems. *Mechatronics*, 58, 58–69.

Ryu, J.H., Artigas, J., and Preusche, C. (2010). A passive bilateral control scheme for a teleoperator with time-varying communication delay. *Mechatronics*, 20(7), 812–823.

Secchi, C., Straimgioli, S., and Fantuzzi, C. (2005). Power scaling in port-hamiltonian based telemanipulation. In *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1850–1855. IEEE.

Speich, J.E. and Goldfarb, M. (2002). Implementation of loop-shaping compensators to increase the transparency bandwidth of a scaled telemanipulation system. In *Proceedings 2002 IEEE International Conference on Robotics and Automation*, volume 3, 2886–2893. IEEE.

Vander Poorten, E.B., Yokokohji, Y., and Yoshikawa, T. (2006). Stability analysis and robust control for fixed-scale teleoperation. *Advanced Robotics*, 20(6), 681–706.

Yan, J. and Salcudean, S.E. (1996). Teleoperation controller design using h-infinity optimization with application to motion-scaling. *IEEE Transactions on control systems technology*, 4(3), 244–258.