CHAPTER X

A modular passivity framework for multilateral teleoperation applications

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In the past few years multilateral teleoperation systems that enable the interaction and coupling of several robotic devices gained in importance as this concept promises especially an increase of ergonomics and precision in teleoperation systems. The challenge in the control of such multi-robot setups is the generalization of the stability proof independent of the number of robotic agents involved. Particularly in the presence of time delay in the communication channel the use of passivity control methods are widely used in bilateral as well as multilateral systems. In literature it was shown that the passivity concept also provides a modular framework that allows for the generalization of stability proofs rendering a frequency-based analysis unnecessary. This paper provides an overview on the existing framework modules and their application to different bilateral communication architectures.

1 Introduction

The application of teleoperation setups in medical or harmful environments, for the maintenance of oil platforms and in underwater scenarios underlines the importance of the teleoperation concept itself but also the need of ergonomic and highly precise robotic systems. The with respect to the long history of robotics novel concept of multilateral teleoperation promises to provide benefits e.g. in the training of novel users (Feth, 2009), the accurate control of robot configurations by professional operators (Malysz, 2011) and through cartesian task allocation to two input devices (Panzirsch, 2015). In such multilateral systems an arbitrary number of agents can be virtually connected with each other in a way that each agent receives information on the position or the environmental interaction of one or more agents. An agent can be a human operator with the master input device, a slave with its environment or an artificial intelligence. The interconnection of the agents is mostly guaranteed by a virtual spring damper system that punishes the position deviation of the agents.

In order to allow interaction from a distance the use of passivity based approaches that were developed for bilateral control (Niemeyer, 1997, Hannaford, 2002) can be applied also to multilateral systems. A setup based on the wave variables transformation (WVT) has been presented by Kanno et al. (Kanno, 2012) and the time domain passivity approach (TDPA) has been employed by Panzirsch et al. (Panzirsch, 2012). Both concepts act on the communication channel which is a purely active component in a way that the passivity of this subsystem can be achieved.

Multilateral systems that consider passivity concepts to tackle the effects of time delay require the passivity of the overall teleoperation architecture since a system is only passive if every subsystem is passive. Still, this is in terms of effort not a drawback since passivity guarantees stability in the sense of Lyapunov and thus, no additional stability proof for a complex multilateral system in the frequency domain is necessary. Panzirsch et al. (Panzirsch, 2013) showed that the passivity of a generalized multilateral system can be easily proven and that the resulting passive framework which can be combined with TDPA and WVT does not reduce the system performance despite consideration of passivity. The framework in this work is based on the tool called network representation proposed by Anderson et al. for the use in teleoperation systems (Anderson, 1992).

This paper is organized as follows: Section 2 introduces the modular concept based on the network representation. The different modules for the assembly of a multilateral system are presented in section 3. The paper content is summarized to a conclusion in section 4.

2 Modular Framework

The network representation is used as it provides energy related ports at each network subsystem that allow the observation of energy flow in a teleoperation system. At first the signal flow diagram (compare Fig. 1) has to be transduced into its network representation (see Fig. 2). The system can be split up into agent and track subsystems. For simplicity the time delay which would be part of the track subsystem is at first not considered in the network representation. At each port the velocity and force can be measured to observe the power with respect to the flow direction from master to slave (L2R) or from slave to master (R2L):

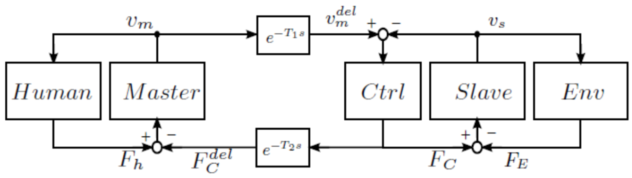

Fig. 1. Signal Flow diagram of a $PF_{computed}$ architecture with communication channel delay.

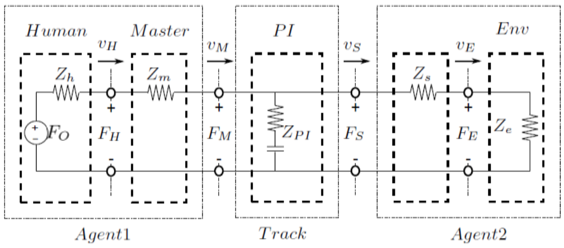

Fig. 2. Network representation of a $PF_{computed}$ architecture without communication channel.

Depending on the chosen architecture and the related force feedback ($PF_{computed}$, $PF_{measured}$, 3Channel or 4Channel) different tracks can be applied in the system. As the widely accepted assumption holds that the agents behave passive in their interactions only the passivity of the track subsystem has to be proven. In a multilateral system (compare Fig. 3) an arbitrary combination of tracks can be straight forwardly used to connect the agents. Panzirsch et al. designed a power control unit (PCU) that represents the sum of forces sent to a device via the tracks. This sum of forces behaves passive as the same velocity is flowing at each port of the PCU (Panzirsch, 2013).

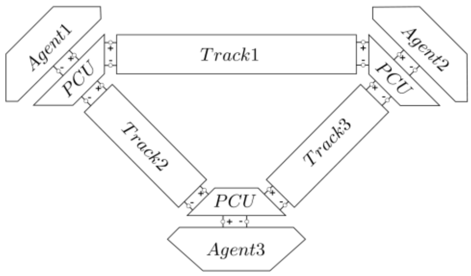

Fig. 3. Network representation of a trilateral teleoperation system (Panzirsch, 2016).

3 Track Design

In the next step the track is divided into its main modules to enable the analysis of their compositions depending on the type of communication channel architecture. Due to space constraints 2-Channel architectures will be focused in the following. Only the time domain passivity control applied to time delay and the measured force feedback are visualized in detail as they depend on the type of architecture chosen.

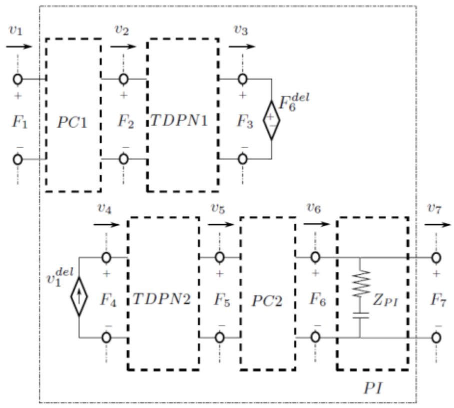

Fig. 4. TDPA applied on the time delay in a $PF_{computed}$ architecture.

The TDPA for a $PF_{computed}$ architecture is presented in Fig. 4. Two passivity controllers PC1 and PC2 dissipate energy generated by the time delay in R2L and L2R direction respectively. The track is split up into those two directions of energy flow and the communication is represented by time domain power networks (TDPN; Artigas, 2011). The dependent velocity (flow) source v_1^{del} injects the energy sent from the master in L2R direction on the slave side whereas the dependent force (effort) source F_6^{del} injects energy from the slave on the master side. The PI Controller is located on the slave side to improve the stability of the system. In contrast to this two PI controllers are considered in the PP architecture (compare Fig. 5). As the additional PI controller is located on the master side of the communication channel the force source of Fig. 4 is replaced by a velocity source v_8^{del}. The force feedback sent to the master is generated by the PI controller on the master side.

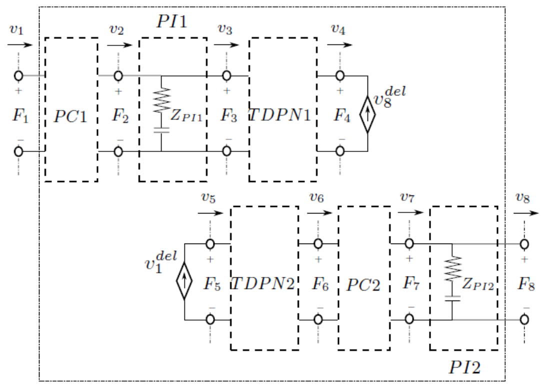

Fig. 5. TDPA applied on the time delay in a PP architecture.

In the following the combination of all modules are presented for different 2-Channel architectures. Besides the time domain passivity control of time delay, scalings α_i of the feedback forces (e.g. for training purposes) and pose projection modules PR are integrated in the following. These passive PR modules serve e.g. the implementation of virtual grasping points (Panzirsch, 2015). As the pose projection does not depend on the communication channel architecture the PR modules are always the outermost modules on each side of the track. The gain α_1 scales down the force feedback in R2L direction to the master and the gain α_2 in direction to the slave respectively. Thus, the scaling behaves passive in the relevant flow direction of the track. Energy that is flowing from master to slave is reduced by the gain α_1 whereas energy that is generated by that gain α_1 in opposite direction is dissipated by the force source F_{10}^{del} (see Fig. 6). Note that the gain on the side of a slave robot is mostly one and can then be neglected.

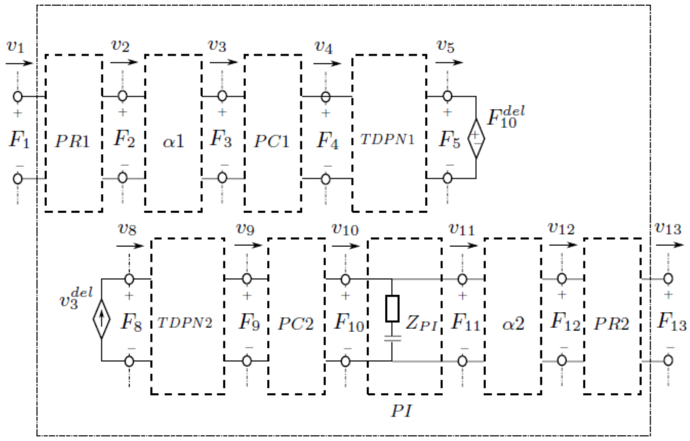

Fig. 6. Combination of modules in a $PF_{computed}$ architecture.

The wave variables transform can be integrated in the network of Fig. 6 by replacing the force and velocity source, the TDPN and PC subsystems with the WVT structure. Fig. 7 presents the composition of all relevant network subsystems in a PP architecture track. The PR and scaling subsystems are located analogously to the $PF_{computed}$ architecture. To the best of the author's knowledge no WVT has been presented for PP architecture yet.

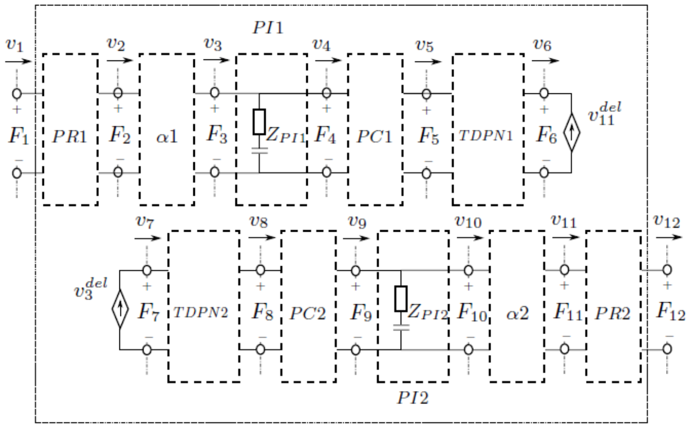

Fig. 7. Combination of modules in a PP architecture.

In literature (Panzirsch, 2016) it was shown that the approach guaranteeing passivity of measured force feedback in bilateral systems proposed by Willaert et al. (Willaert, 2009) cannot be applied to multilateral systems. Panzirsch et al. proposed two passivity controllers PC_L and PC_R (see Fig. 8) that dissipate excessive power introduced by the measured force feedback to achieve passivity. Fig. 9 presents the combination of the two pairs of time domain passivity controllers that consider time delay and measured force feedback respectively.

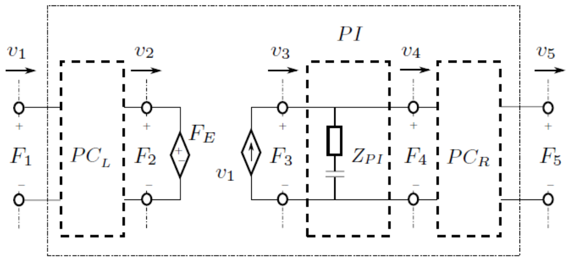

Fig. 8. Passivity of a track with measured force feedback (Panzirsch, 2016).

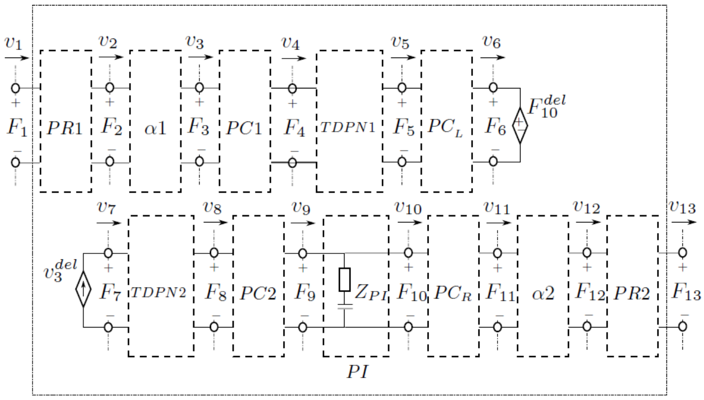

Fig. 9. Combination of modules in a $PF_{measured}$ architecture.

4 Conclusion

The latest results in the developments of new track modules of a passivity based framework for multilateral teleoperation have been summarized in the present work. It was shown that the time domain passivity control architecture can be integrated in the track design for the computed as well as the measured force feedback and the position-position architecture. The wave variables transformation concept can be easily integrated in the computed force feedback architecture, but the aptitude to the measured force feedback architecture has to be investigated. Future work has to focus the development of new tracks for the 3-Channel and 4-Channel control architectures.

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