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Control of a magnetic levitation system with communication imperfections: A model-based coupling approach

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ABSTRACT

This work presents a control strategy to control a magnetic levitation system under the influence of coupling imperfections (disturbances). To overcome problems arising whenever the interconnections between plant and controller have a non-negligible influence on the control-loop behavior a so-called model-based coupling approach is used. The main idea of this coupling approach is to use prediction schemes based on recursively identified plant and controller models which compensate for performance degradation due to coupling imperfections. Coupling failures such as time-delays, data-losses and noise drastically influence the control-loop performance. Especially when systems in form of real hardware (real-time systems) are present such disturbances have to be handled adequately. To demonstrate the effectiveness of the model-based coupling approach, a control-loop of a magnetic levitation system is analyzed in simulation as well as in real world laboratory setup (HiL simulation). Furthermore a first insight into the stability analysis of closed-loop systems including the model-based coupling technique is performed for a simplified configuration.

1. Introduction

This work deals with the integration of a model-based coupling technique into control-loops to reduce the influence of disturbances caused by real communication media. It is designed to compensate effects of coupling failures to maintain the specified and desired control-loop properties. The performance improvement is analyzed via a magnetic levitation control-loop in simulation and real-world experiment. Communication imperfections are well studied in the field on networked control systems (NCS) which received considerable attention in recent years (Antsaklis & Baillieul, 2007; Baillieul & Antsaklis, 2007; Xia, Gao, Yan, & Fu, 2015; YOU & XIE, 2013). In this area, the control algorithms are designed to cope with these imperfections and constraints. The stability issue is also typically handled via stabilizing control design techniques (Bauer, Maas, & Heemels, 2012; Dasgupta, Halder, Banerjee, & Gupta, 2015; van de Wouw, Nesic, & Heemels, 2012). Network-induced imperfections can be categorized into five different types (Heemels, Teel, van de Wouw, & Nesic, 2010; Zhang, Gao, & Kaynak, 2013):

- quantization errors caused by finite word length;
- packet dropouts caused by unreliability of the used network;
- variable sampling/transmission intervals;
- variable communication delays;
- and communication constraints caused by shared networks.

These mentioned network imperfections significantly degrade the performance of control-loops which can even lead to instabilities in the worst case. Such a worst case scenario is addressed in Cloosterman, van de Wouw, Heemels, and Nijmeijer (2009). Up to date NCS approaches focus on one or more special types of the network-induced imperfections while ignoring the other ones. For instance (Garcia & Antsaklis, 2013; Kang & Ishii, 2015; Yang, Shi, Liu, & Gao, 2011) deal with the effects of quantization, Liu, an Zhang, Yu, Liu, and Chen (2015),Rahmani and Markazi (2013), Gommans, Heemels, Bauer, and van de Wouw (2012) address the packet dropout issue, Ren, Zhang, Jiang, Yu, and Xu (2015), YOU and XIE (2013) consider also noisy digital channels while (Gielen et al., 2010; Luan, Shi, & Liu, 2011; Mahmoud & Sabih, 2014; Vatanski, Georges, Aubrun, Rondeau, & Jms-Jounela, 2009) focus on time-varying transmission delays. Beside the mentioned approaches, NCS are also studied using techniques from time-delay system theory as e.g. discussed in Liu et al. (2014). Beside

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the NCS theory, decentralized control techniques are dealing with the same difficulties. In this field an entire system is considered large-scale if it is advantageous to partition the given analysis and synthesis into manageable subproblems with decreased complexity. This concept leads to a distributed system of systems e.g. the overall plant is no longer controlled by a single controller but by several independent controllers which all together represent a decentralized controller. In this area, more and more emphasis is put on decentralized and distributed control design techniques considering the interconnections explicitly. Typically the network properties including the problem of delay and packet dropouts are considered explicitly in the controller design (Bakule & Papk, 2012; Halder et al., 2016; Donkers, Heemels, van de Wouw, 2011; Lim & Ahn, 2013; Peng, Han, & Yue 2013; Shi, Yang, Basin, & Karimi, 2012; Shu & Lin, 2014; Zhang & Liu, 2014). In contrary to the NCS and decentralized control approaches, the model-based coupling approach can be integrated into existing control-loops without any subsystem modification. This means the controller design is independent of the used communication media and can therefore be performed as if no coupling imperfections were present. Hence the model-based coupling approach represents the most flexible approach and no application specific solution. Due to this universal applicability, the model-based coupling approach can easily be applied to a variety of applications in different domains like Real-Time Co-Simulation (Stettinger, Horn, Benedikt, & Zehetner, 2014a, 2014b) where no subsystem adaptation according to the expected coupling imperfections is possible/desirable, Li, Zhang, and Li (2014) motivates the application of co-simulation platforms for co-design of NCS, NCS without any subsystem modification in both the sensor-to-controller as well as the controller-to-actuator channel (Gommans et al., 2012; Lin, Chen, & Huang 2008), Time-Delay Systems (Fridman, 2014; Efimov, Polyakov, Fridman, Perruquetti, & Richard, 2014) to compensate effects of delays, Systems of Systems (Galor, 2014; Holt et al., 2015; Mostafavi, Abraham, DeLaurentis, & Sinfield 2011) to ensure an exact entire system simulation, Consensus Control (Guo, Ding, & Han, 2014; Huang, Wen, Wang, & Song, 2015; Kar & Moura, 2009; Zhu & Jiang, 2015) for coordination of multi-agent systems to ensure a consistent view of the objectives and the world, Smart Grid Applications (Erol-Kantarci & Mouftah, 2015; Mets, Ojea, & Develder, 2014; Qu & Simaan, 2014) to compensate performance degradation caused by transmission delays and Signal-Conditioning (Bansal et al., 2014; Karthik, Fathima, Rahman, Ahamed, & Lay-Ekuakille, 2013) for model-based noise filtering tasks.

1.1. Considered coupling imperfections

The interaction between the controller (C) and the plant (P) via different communication media is commonly characterized by introduced communication time-delays, see Fig. 1. These time-delays (labeled with "delay") represent dead-times in the control-loop and result in so-called round-trip-times (RTTs) which may be time-variant depending on the communication media utilization. Introduced RTTs prohibit a time-correct coupling. Significant RTTs impose a serious limitation on the control performance of closed-loop systems as closed-loop bandwidth is limited to be approximately less than 1/RTT (Skogestad & Postlethwaite, 2005). Another important aspect are noisy coupling signals, introduced by sensors installed in real-time systems, see Fig. 1. Noisy measurements are especially problematic if signal-based coupling schemes are used due to their tendency of noise-level amplification which is a potential threat to stability (Wiener, 1964). Data-losses (see Fig. 1), caused by disturbances, transmission failures, message collisions or overload of communication capacity are additional phenomena occurring in coupled systems. These corrupted coupling signal values may lead to a distorted behavior of the control-loop. In the worst case, unstable control-loops result as data losses have a similar effect as dead-times.

1.2. Handling of coupling imperfections

The model-based coupling scheme is implemented in a so-called coupling element (denoted by MBC) which is inserted between controller and plant, see Fig. 2. At every sampling instant (denoted by ΔT), coupling data is exchanged to synchronize the subsystems. The coupling element divides the round-trip-time (RTT) into sending $(d_{s,1}, d_{s,2})$ and receiving $(d_{r,1}, d_{r,2})$ time-delays in multiples of ΔT from its perspective:

$$\begin{aligned} &d_{s,1} = t_{s,1} \times \Delta T,\ \ d_{s,2} = t_{s,2} \times \Delta T \text{ with } t_{s,1}, t_{s,2} \in \mathbb{Z} \\ &d_{r,1} = t_{r,1} \times \Delta T,\ \ d_{r,2} = t_{r,2} \times \Delta T \text{ with } t_{r,1}, t_{r,2} \in \mathbb{Z}. \end{aligned} \tag{1}$$

To ensure a time-correct interaction, the controller output u_k must arrive at the plant input without any delay. This is also true for the plant output y_k. Communication media typically violate this request due to their finite communication speed. To compensate the destabilizing effect of RTTs and to ensure a time-correct interaction, the model-based coupling algorithm extrapolates the coupling signals $(u_{k-t_{r,1}}, y_{k-t_{r,2}})$ to $(\hat{u}_{k+t_{s,1}}, \hat{y}_{k+t_{s,2}})$. This means that at discrete time instant k extrapolated values $\hat{u}_k$ and $\hat{y}_k$ are already present at the controller and plant inputs. In this way the effect of the RTTs is compensated. Coupling data-losses have a very similar effect as dead-times and can therefore be compensated via additional model-based extrapolations according to the amount of lost data. In addition, noisy measurements can be treated via adequate parametrizations of recursive system identification algorithms (model-based filtering).

2. Model-based coupling approach

2.1. Motivation

To compensate undesirable effects of coupling imperfections, coupling elements, including the model-based coupling approach, are integrated in control-loops to solve this issue. To achieve this goal, the extrapolation functionality of the coupling elements is one of the keys to handle them efficiently. To perform these extrapolations, the model-based coupling approach uses internal identified models of the controller and plant to predict future coupling signals. These internal models of the control-loop are updated at every sampling time instant to ensure an adequate approximation of the subsystem behavior. The prediction process is based on the assumption that the subsystem dynamics doesn't change drastically during the extrapolation horizon.

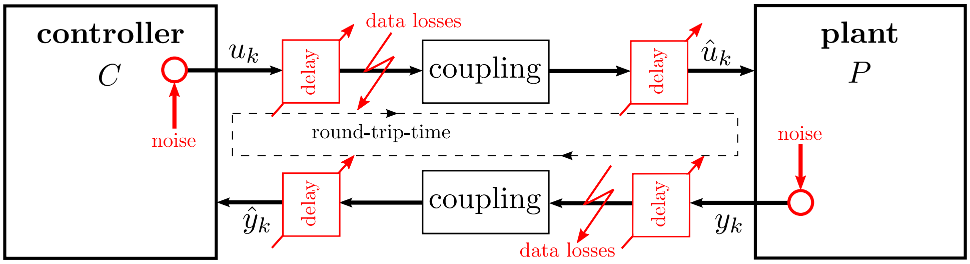

Fig. 1. Considered coupling imperfections in control-loops (Stettinger et al., 2014a, 2014b).