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Part I.

Monday afternoon session

Model Predictive Control of a Metal Hydride Hydrogen Storage

Daniel Schwingshackl[a]

The storage of hydrogen using metal hydrides offers significant advantages over high-pressure and liquid hydrogen storage methods. Metal hydride hydrogen storages (*MHHS*) are inherently safer due to their lower operating pressures and temperatures. They also provide higher volumetric energy densities, reduced maintenance and enhanced durability, which are critical for various industrial applications. In a *MHHS*, hydrogen is stored as a solid. This solid is formed by chemical reaction between hydrogen gas and a suitable metal or alloy. The equilibrium of this reaction is influenced by temperature and pressure. When hydrogen is stored, heat is generated which must be dissipated. When hydrogen is released, on the other hand, heat must be added. The efficiency and reliability of such *MHHS* is significantly determined by this necessary thermal conditioning. With the help of a predictive control strategy and available hydrogen consumption/production profiles, the demand of heating/cooling power shall be minimized while increasing the reliability of the hydrogen supply. In Figure 1 the block diagram of the proposed control strategy is shown. The temperature of the *MHHS* is adjusted by a Thermal Management System (*TMS*). Based on a given profile of the hydrogen mass flow $\dot{m}_{H_2}$, the water temperatures ϑ_{in} and ϑ_{out}, the temperature of the metal hydride ϑ_{mh} and the storage pressure p, a new setpoint for the water inlet temperature $\vartheta_{in,set}$ is determined by the suggested control method. The proposed control concept consists of a

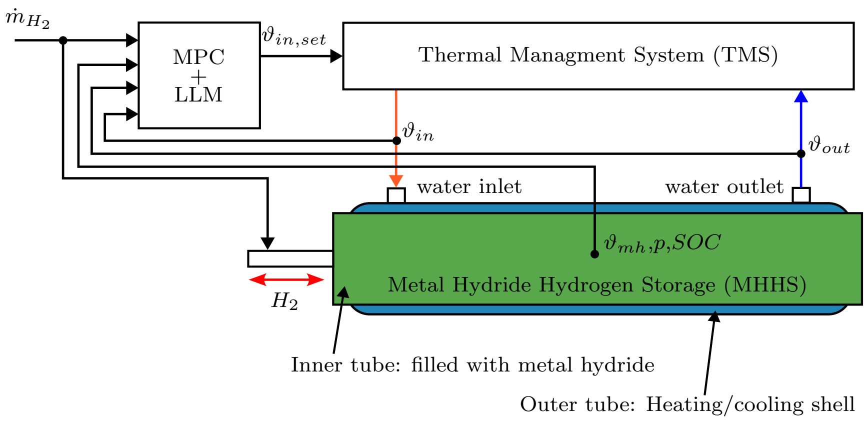

Figure 1: Block diagram of the control strategy.

linear model predictive control (*MPC*) algorithm combined with a network of local linear models (*LLM*). A detailed mathematical model of the *MHHS*, based on physical laws, is validated by measurements. By exciting the detailed model, local linear models are derived using the Local Linear Model Tree (*LoLiMoT*) algorithm [1]. In order to demonstrate the performance of the proposed approach, simulations are conducted and experiments on a real world system are planned.

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A Path Following Model Predictive Controller for Autonomous Truck Navigation in Off-Road Environments

Hamid Didari[a] **Gerald Steinbauer-Wagner**[a]

Off-road driving operations in logistics present various challenges for human operators, including risks of accidents, monotonous tasks, and exposure to strong vibrations, which can impact long-term health [1]. Integrating autonomous trucks into logistics can enhance safety, reduce labor costs, and increase operational efficiency. However, autonomous driving in off-road environments is particularly challenging due to varying surface conditions and types. In this study, our focus was on developing a solution tailored for autonomous trucks. To achieve this, we employed the navigation architecture detailed in a previous work [2]. This architecture comprises two main steps: path planning and controller. Path planning involves planning a path that avoids obstacles and directs the vehicle toward its destination; it plans a new path whenever the current path is driven by the vehicle or becomes invalid due to new obstacles. The controller ensures the vehicle follows the planned path. In prior work, the Stanley Controller [3] was utilized for path following within the described navigation architecture. However, a limitation of this architecture is that it does not account for situations where the vehicle may deviate from the planned path and encounter obstacles that are not directly on the path but are in the way as the controller tries to follow the path.

To address this issue, we have designed a Model Predictive Control (MPC) system to control both the longitudinal and lateral movements of a HX2 truck in offroad environments. Subsequently, we assess the predicted path of the truck for potential collisions with obstacles. If a collision is anticipated, the system requests the planner to generate a new path to avoid the obstacle. We employed the bicycle model for MPC to represent truck movement. The bicycle model is described by the following set of nonlinear differential equations:

$$\begin{aligned}
&x_{k+1} = x_k + v_k \cos(\psi_k + \delta_k)\Delta t, \quad y_{k+1} = y_k + v_k \sin(\psi_k + \delta_k)\Delta t, \\
&\psi_{k+1} = \psi_k + \frac{v_k}{L}\tan(\delta_k)\Delta t, \quad v_{k+1} = v_k + a_k \Delta t, \\
&\theta_{k+1} = \theta_k + v_k \Delta t,
\end{aligned} \tag{1}$$

where x and y are the positions, ψ is the heading angle, v is the velocity, L is the wheelbase of the vehicle, δ is the steering angle, a is the acceleration, and θ is a variable that approximates the progress along the path. The objective of optimization is to minimize the following cost function:

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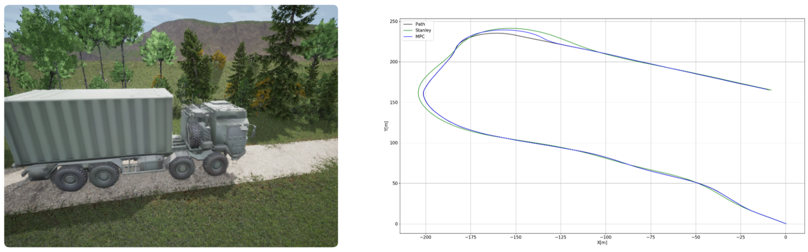

(a) (b)

Figure 1: (a) Image of the truck in simulation (b) Comparison of path following between MPC and Stanley controller.

$$\min \sum_{k=1}^{N} \left[\begin{pmatrix} \hat{e}_k^c \\ \hat{e}_k^l \\ \hat{e}_k^v \end{pmatrix}^T \begin{pmatrix} q_c & 0 & 0 \\ 0 & q_l & 0 \\ 0 & 0 & q_v \end{pmatrix} \begin{pmatrix} \hat{e}_k^c \\ \hat{e}_k^l \\ \hat{e}_k^v \end{pmatrix} + \begin{pmatrix} a_k \\ \delta_k \end{pmatrix}^T \begin{pmatrix} r_a & 0 \\ 0 & r_\delta \end{pmatrix} \begin{pmatrix} a_k \\ \delta_k \end{pmatrix} \right] \tag{2}$$

Where $q_c, q_l, q_v, r_a, r_\delta$ are weights for the cost function, subject to the following:

$$\begin{aligned} &\hat{e}_k^c = \sin(\psi^{\text{path}}(\theta_k))(x_k - x^{\text{path}}(\theta_k)) - \cos(\psi^{\text{path}}(\theta_k))(y_k - y^{\text{path}}(\theta_k)) \\ &\hat{e}_k^l = -\cos(\psi^{\text{path}}(\theta_k))(x_k - x^{\text{path}}(\theta_k)) - \sin(\psi^{\text{path}}(\theta_k))(y_k - y^{\text{path}}(\theta_k)) \\ &\hat{e}_k^v = v_k - v^{\text{path}}(\theta_k) \\ &\underline{\delta} \leq \delta_k \leq \overline{\delta}, \quad \underline{a} \leq a_k \leq \overline{a} \end{aligned} \tag{3}$$

Where $\psi^{\text{path}}, x^{\text{path}}, y^{\text{path}}$, and v^{path} are planned path variables by the path planner. The proposed controller has been implemented in C++ and solves the optimization problem using CppAD and the Ipopt solver. Simulation software developed by AVL is utilized to evaluate the controller. In the simulation software, the truck model is simulated using $AVL\ VSM^{tm}$[1], and CARLA simulation is used to simulate off-road environments. Figure 1.a shows an image of the truck in simulation. The performance of the MPC and Stanley controllers can be seen in Figure 1.b. During testing, the truck's speed was 5 m/s. The root mean square of cross-track error for the Stanley Controller was 3.4 m, and for MPC, it was 1.2 m. Further results will be presented in the talk on sensitivity to localization accuracy and delay, as well as different trajectories.

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[2] R. Hoheneder, A. Buchegger, H. Didari, M. Eder, K. Mautner-Lassnig, C. Mühlbacher, and G. Steinbauer-Wagner, "An event-based approach to autonomous navigation," in *Proceedings of the Austrian Robotics Workshop 2023*, 2023.

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[1] https://www.avl.com/de-at/simulation-solutions/software-offering/simulation-tools-a-z/avl-vsm

Innovative control to suppress sloshing in fast transport of liquids

Stefan Jakubek[a] **Christoph Hametner**[a] **Alexander Schirrer**[a]

Rapidly transporting liquids in open containers without sloshing poses significant challenges in numerous industrial applications, such as in chemical processing, food and beverage transport, and laboratory automation. Our research contribution addresses and solves these challenges by an advanced feedforward control design approach combining several innovations: an effective modelling step provides a dynamic surrogate model of the relevant sloshing dynamics in arbitrarily-shaped containers. The liquid container dynamics is virtually mounted on a pendulum whose parameters are specifically chosen so that the primary sloshing mode cannot be excited by horizontal excitation of the pendulum pivot, extending on the idea of the so-called “Moroccan tray”. Furthermore, we devise a differentially flat output formulation for this system, allowing us to formulate a flatness-based feedforward control law to facilitate rest-to-rest transport maneuver planning. The resulting control law is highly effective in mitigating sloshing and computationally efficient, without the need for any optimization in the process. It ensures that the liquid remains stable and undisturbed during fast transport, thus preventing spillage and maintaining the integrity of the liquid.

To verify robustness, the feedforward control approach is thoroughly examined under conditions where the liquid filling level is unknown. Extensive simulations demonstrate the excellent robustness and performance of the control strategy, while experimental validations using an industry-grade research robot confirm its practical efficacy. Video measurements of the experiments acknowledge the achieved real-world sloshing suppression accuracy.

Summing up, our research provides a robust and computationally simple solution for sloshing suppression in the rapid transport of liquids in open containers (Fig. 1). The feedforward control law developed through this study offers reliable performance across varying conditions, making it a valuable tool for industries requiring precise and efficient liquid transport.

Figure 1: Fast non-sloshing rest-to-rest maneuver with a challenging cocktail glass shape

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Modelling, Control and Monitoring of a Renewable Flow Battery

Thomas Reiter-Nigitz[a] **Johannes Niederwieser**[a] **Uwe Poms**[a]
Dominik Wickenhauser[b,c] **Stefan Spirk**[b,c] **Markus Gölles**[a,d]

Redox flow batteries have great potential due to their high capacity to balance fluctuations of volatile renewable energy sources such as wind or solar energy. Redox flow batteries are currently used to a limited extent as large-scale stationary energy storage systems. However, commercially available systems today use materials that are not renewable and not local available. Renewable flow batteries often use local, plant-based compounds. Several years ago, vanillin, a common flavor compound has been described as precursor for the reactants in flow batteries [2]. Vanillin is already produced at large scale from plant-based resources. These organic flow batteries are currently still under research and development, requiring a control and monitoring strategy. The knowledge on control and/or monitoring of organic flow batteries in general is limited.

The aim was to develop a control and monitoring strategy for an organic flow battery, and to demonstrate it at a research demonstrator with an output of around 5 kW and a storage capacity of around 20 kW h. A process diagram of the research demonstrator with installed sensors and actuators is shown in Figure 1.

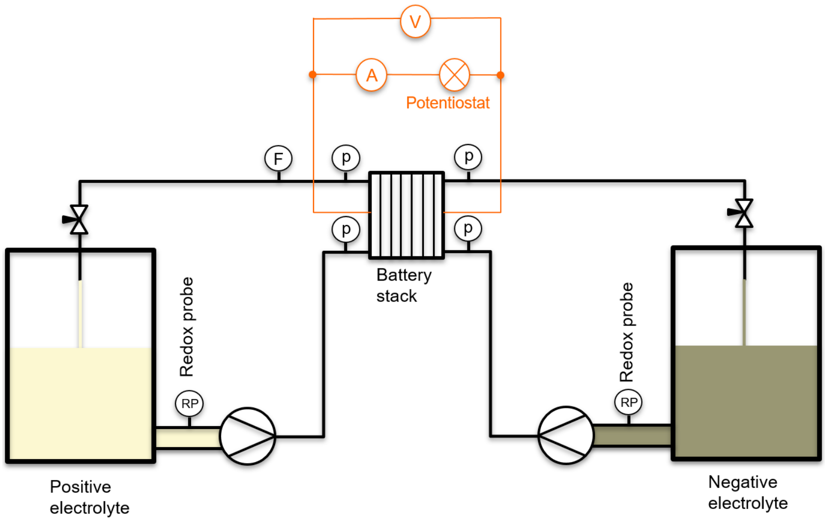

Figure 1: Process diagram of the research demonstrator

The process consists of an electric circuit and two hydraulic circuits, that interact within the battery stack. The electric circuit consists of a potentiostat that acts as current source and sink, as well as the electric side of the battery stack. The two hydraulic circuits are very similar and are filled with the positive electrolyte and the negative electrolyte. The

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electrolytes consist of a weak acid with the two different reactants dissolved respectively in it. Each hydraulic circuit consist of a tank, a pump and the hydraulic side of the battery stack.

The electric circuit is controlled via the potentiostat, which is a simplification compared to operation at an electric grid.

The hydraulic circuits need to be controlled regarding two objectives. First, the desired volume flow needs to be reached so that enough reactants are inside the battery stack at each time instance, but without wasting electric power for the pumps. Second, the pressure difference across the membrane should be minimized to avoid mechanical stress and reverse osmosis at the membrane. We developed a volume flow controller that ensures both objectives by using a combination of model-based feed-forward controller and two PI-controllers. This volume flow controller is developed using a dynamic model of the hydraulic circuit based on physical equations [3], and is implemented and validated at the research demonstrator. As this volume flow controller fulfills the objectives much better than the pure PI-controller used before, it is used for all further work.

The state-of-charge (SOC) is not directly measureable, but is the main monitoring variable of interest. It is either a qualitative number in % or the energy stored in Wh (or Ah). The SOC depends mainly on the concentration of the reactants within the tanks. One method for the estimation the SOC in % is by using the measurements of the redox potential after each tank via redox probes (compare Figure 1). An advanced method is the estimation of the SOC in Wh via a state-observer as suggested by [1], where the SOC for vanadium flow batteries is observed in simulation studies. Here, the core is a dynamic model of the concentrations of the reactants in the tanks and in the battery stack. Both methods for estimating the SOC are compared and evaluated for the flow battery.

The research leading to these results has received funding from the 14th Call (2021): NEXT GREEN TECH Energy Systems, Green Hydrogen & Green Mobility of Styria. The research demonstrator was set up with the support of the German company Schaeffler and the TU Graz startup Ecolyte.

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Part II.

Tuesday morning session

Observer design for nonlinear heat and mass transfer systems

Alexander Schaum [a]

Heat and mass transport are central mechanisms in process systems, e.g., during the treatment of materials to achieve high-value products or during reaction and combustion processes. Often, besides pure heat and mass transport, that are governed by the mechanisms of convection and diffusion, also nonlinear elements due to structural changes in the material have to be considered, e.g., due to chemical reaction or structural changes between different phases.

Process systems dominated by heat and mass transfer are found in different areas of application, from rapid thermal processing to food production and often go at hand with spatially distributed dynamics, described by partial differential equations (pdes) [2, 1]. Observer design for such systems is a key element, as it is typically not possible to measure spatially distributed parameters completely, but only pointwise or over certain superficial areas. A key question then becomes how to localize sensors and how to design the observer structure and gains. In the talk possible methodological approaches are presented to address these questions for different application scenarios. After a short general introduction to the pde-based setup, first, rapid thermal proccessing of silicon wafers is revisited and the problem of nonlinear observer design is considered. An approach based on pointwise measurement injection with Lyapunov-based stability analysis is followed to ensure observer convergence with explicit sensor localization criteria [4]. In second place a moving boundary problem with coupled heat and mass transfer describing a bread baking process [3] is considered. Moving boundary problems imply the additional difficulty that the spatial domain is time-varying, leading to explicit time-variances in the process model. For the considered model different approximation scenarios are discussed in combination with state and parameter estimation techniques and illustrated with experimental data.

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Observability and High Gain Observer Design for Polynomial Systems

Klaus Röbenack[a] **Daniel Gerbet**[a]

In this talk we consider the problems of observability tests and observer design for nonlinear systems of the form

$$\dot{x} = f(x), \quad y = h(x),$$

where the vector field $f : \mathbb{R}^n \to \mathbb{R}^n$ and the scalar field $h : \mathbb{R}^n \to \mathbb{R}$ are assumed to be polynomial. For nonlinear systems, the concept of observability is based on the indistinguishability of states [6]. In general, it is very difficult to check the observability of a nonlinear system. However, local and global observability can be decided for polynomial systems, see [3] and references cited there. In this talk we present the framework from algebra and algebraic geometry (e.g. polynomial ideals, varieties, radicals) to carry out observability tests for polynomial systems.

Even if a nonlinear system is observable, the design of an observer is not straightforward. The use of normal forms can be helpful for the observer design. In particular, the observability canonical form is often used in high gain observer design [2]. In the transformed coordinates, the observer design procedure itself is comparatively simple. On the other hand, the calculation of the corresponding normal form can be difficult if the system is embedded into a higher dimensional state space as suggested in [1]. Again, methods form algebraic geometry can be employed to compute the transformed system [4, 5].

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Generalized Hybrid-Integrator-Gain System

Christoph Weise[a] **Kai Wulff**[a] **Johann Reger**[a]

Linear time-invariant controllers suffer from fundamental performance limitations in the loop-shaping design method, such as Bode's gain-phase relationship. There have been various approaches to overcome these limitations, e.g. fractional-order controllers [2] or reset controllers [1]. A more recent development is the so-called hybrid-integrator-gain system (HIGS) given by [3]

$$\mathcal{H}: \begin{cases} \dot{x}(t) = \omega_h e(t), & (e, \dot{e}, u) \in \mathcal{F}_1 \quad \text{(I-Mode)} \quad (1a) \\ x(t) = k_h e(t), & (e, \dot{e}, u) \in \mathcal{F}_2 \quad \text{(P-Mode)} \quad (1b) \\ u(t) = x(t) & \quad (1c) \end{cases}$$

with $k_h > 0$ and $\omega_h > 0$ and the sector bound defined by

$$\mathcal{F}_1 = \left\{ (e, \dot{e}, u) \in \mathbb{R}^3 | eu \geq \frac{u^2}{k_h} \wedge (e, \dot{e}, u) \notin \mathcal{F}_2 \right\}, \mathcal{F}_2 = \left\{ (e, \dot{e}, u) \in \mathbb{R}^3 | u = k_h e \wedge \omega_h e^2 > k_h e \dot{e} \right\}.$$

It combines the linear integration within the sector $\mathcal{F}_1$ with a proportional term on the sector bound. This sector boundedness guarantees the strict passivity of the HIGS. Compared to pure reset controllers, a main advantage is the continuity of the controller output $u(t)$. Although non-linear, the parameters ω_h and k_h can be tuned in the frequency domain by using the resulting describing function

$$\mathcal{N}_{\text{IO}}(\mathrm{j}\omega) = \frac{\omega_h}{\mathrm{j}\omega} \left(\frac{\gamma(\omega)}{\pi} + \mathrm{j} \frac{e^{-2\mathrm{j}\gamma(\omega)} - 4e^{-\mathrm{j}\gamma(\omega)} + 3}{2\pi} \right) + k_h \left(\frac{\pi - \gamma(\omega)}{\pi} + \mathrm{j} \frac{e^{-2\mathrm{j}\gamma(\omega)} - 1}{2\pi} \right)$$

with $\gamma(\omega) = 2 \arctan(k_h \omega / \omega_h)$. Fig. 2 shows the Bode-plot of this describing function for $\omega_h = 1$ and $k_h = 1$. The amplitude response corresponds to a first order system low-pass filter with stationary gain k_h and a corner frequency of $\omega_c = |1 + 4\mathrm{j}/\pi| \, \omega_h k_h^{-1}$, whereas the phase response only shows a phase drop of 38°.

Main result

A first generalization has been presented in [4] where the order of integration is adapted. In comparison we generalize the HIGS by combining a reset system with an integrator

$$\begin{aligned} \dot{z}(t) &= A_z z(t) + B_z e(t), && (e, \dot{e}, u, z_\mathrm{m}) \in \bar{\mathcal{F}}_1 \quad \text{(I-Mode)} \\ z(t) &= \begin{pmatrix} 0 & k_h e(t) \end{pmatrix}^\top && (e, \dot{e}, u, z_\mathrm{m}) \in \bar{\mathcal{F}}_2 \quad \text{(P-Mode)} \\ z(t) &= 0 && (e, \dot{e}, u, z_\mathrm{m}) \in \bar{\mathcal{F}}_3 \quad \text{(0-Mode)} \\ u(t) &= \begin{pmatrix} 0 & 1 \end{pmatrix} z(t) \end{aligned}$$

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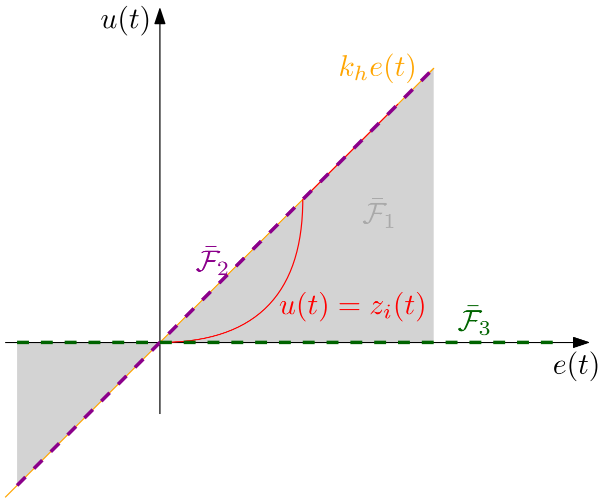

Fig. 1: Sector illustration.

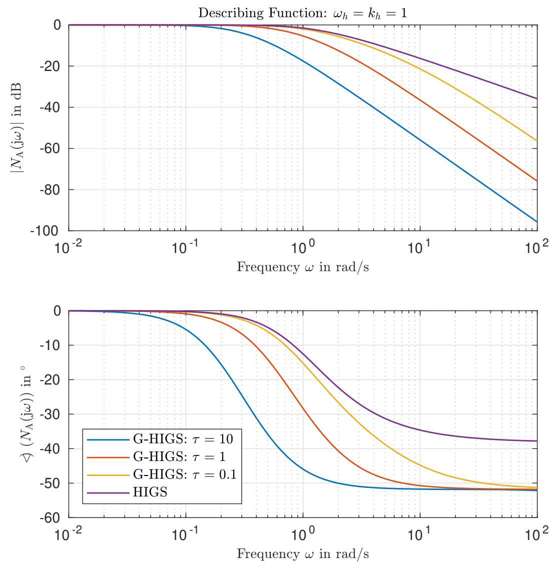

Fig. 2: Amplitude- and phase response of different describing functions.

with the state $z = \begin{pmatrix} z_{\mathrm{m}}^\top(t) & z_{\mathrm{i}} \end{pmatrix}$ consisting of the reset system state z_{m} and the integrator state z_{i} and matrices given by $A_z = \begin{pmatrix} A_{\mathrm{m}} & 0 \\ C_{\mathrm{m}} & 0 \end{pmatrix}$ and $B_z = \begin{pmatrix} B_{\mathrm{m}} \\ D_{\mathrm{m}} \end{pmatrix}$. Note that the underlying baseline system $G_{\mathrm{m}}(s) = C_{\mathrm{m}}(sI - A_{\mathrm{m}})^{-1}B_{\mathrm{m}} + D_{\mathrm{m}}$ should be stable and satisfy $G(0) = \omega_h$. Resetting the states accordingly bounds the control signal to the sector $u(t) \in [0, k_h]$. In comparison to the HIGS, an additional region is required (see Fig. 1)

$$\begin{aligned} \bar{\mathcal{F}}_1 &= \left\{(e, \dot{e}, u, z_{\mathrm{m}}) \in \mathbb{R}^q | eu \geq \tfrac{1}{k_h}u^2 \wedge (e, \dot{e}, u, z_{\mathrm{m}}) \notin (\bar{\mathcal{F}}_2 \cup \bar{\mathcal{F}}_3)\right\} \\ \bar{\mathcal{F}}_2 &= \{(e, \dot{e}, u, z_{\mathrm{m}}) \in \mathbb{R}^q | u = k_h e \wedge (C_{\mathrm{m}} z_{\mathrm{m}} + D_{\mathrm{m}} e)e > k_h e\dot{e}\}\,, \\ \bar{\mathcal{F}}_3 &= \{(e, \dot{e}, u, z_{\mathrm{m}}) \in \mathbb{R}^q | u = 0 \wedge e \neq 0 \wedge (C_{\mathrm{m}} z_{\mathrm{m}} + D_{\mathrm{m}} e)e < 0\}\,. \end{aligned}$$

As the input-output pair remains sector bounded we can show the passivity of the element, which allows the conservative stability assessment of the closed loop.

To tune the parameters in the frequency domain we derive a method to compute the describing function of this generalized HIGS element in terms of matrix exponentials. For example Fig. 2 shows the Bode plot including a first-order lowpass filter $G_{\mathrm{m}} = (\tau s + 1)^{-1}$ for different values of τ. In comparison to the standard HIGS the amplitude response shows a steeper decent at high frequencies, whereas the phase drop increases only slightly. We demonstrate the potential of this element by simulations.

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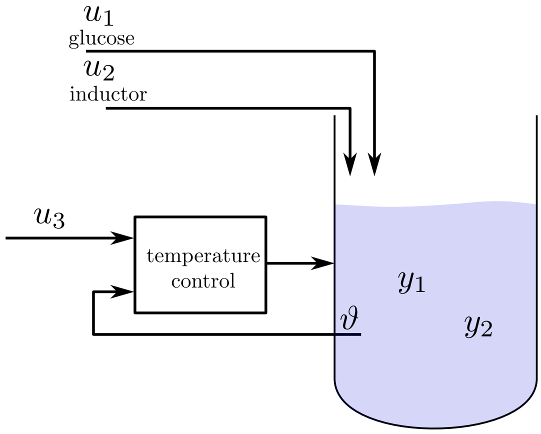
Efficient operation of pharmaceutical processes via model based approaches

Selma Celikovic[ab] **Katrina Wilfling**[a] **Atabak Azimi**[ab] **Jakob Rehrl**[ac]

Manufacturing of pharmaceuticals covers a broad variety of processes. In recent years, the implementation of process- and quality control concepts to such processes was pursued by the regulatory agencies [3, 5]. A strong focus was put on the transition from batch to continuous manufacturing, which opened many potential use cases for the implementation of advanced process control concepts [4], as well as the development and integration of soft-sensors [2]. Consequently, for the commonly used continuous unit operations, process models are available and control concepts have been developed.

However, there are still processes operated in batch-mode, for example fed-batch fermentation in bioreactors, see Figure 1. They are conventionally run at pre-defined, constant operating conditions, which are typically not fully exploiting the process potential. This talk will present model-based concepts designed to improve the process behavior.



u_1 ... glucose feed
u_2 ... inductor feed
u_3 ... temperature setpoint
y_1 ... biomass concentration
y_2 ... product concentration
ϑ ... temperature

Figure 1: Sketch of a fed-batch reactor.

The considered fermentation consists of two phases. In phase 1, the biomass concentration y_1 is increased. For that purpose, an initial number of cells (quantified in terms of biomass concentration $y_{1,0}$) is provided. By adding glucose at a certain feed-rate u_1 and keeping the temperature ϑ of the reactor at a desired level u_3, the biomass concentration is increased. After the concentration has doubled, phase 2 of the process starts and an inductor is fed at a rate of u_2, causing the cells to create the desired product and to increase the product concentration y_2. In phase 2, all three actuating signals are affecting the biomass- and product concentration.

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Traditionally, the choice of the actuating signals is typically based on (i) assumptions on the growth behavior of the cells and (ii) experimental data obtained from systematic designs of experiments (DoEs). This talk presents model-based concepts that utilize the hybrid modelling approach proposed in [1] to compute the actuating signals. Although some aspects of the process can be modeled by first principles (e.g., mass-balance, dilution), there is no mechanistic model available to describe the growth rate of the cells as a function of temperature, biomass- and product concentration. These rates are computed via data-driven models.

The resulting model of the fed-batch reaction is part of the process optimization approach that is presented in this talk. The performed simulation studies show the achievable performance gain (in terms of, e.g., reduction of production time) compared to the traditional concepts mentioned above. Besides the proposed process optimization, the application of the models in fault detection and identification concepts was investigated, too.

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Part III.

Wednesday morning session

Event-triggered control approach for time-critical dynamic systems

Andrej Sarjaš[a] **Dušan Gleich**[a]

1 Introduction

The time-critical feedback dynamics systems require accurate and incessant monitoring to ensure proper behavior. The stability becomes critical due to the tight constraints on reaction time [5]. Many time-critical systems are driven by complex embedded systems with scheduled tasks and advanced power management over the network, distributed systems, etc... All the significant priorities can be assigned as a Deadline-driven performance, which means that the system operates within strict time limitations. Most control algorithms are designed to produce the output in an adequate time sequence, known as a sampling time. Such strict time conditions ensure the stability and desired performance of the time-critical systems. On the other hand, the excessive usage of resources can lead to the lowered performance of the whole supervision system and the required demand for systems with higher speed or a tendency to use high-performance communications networks. In many cases, when the system approaches or reaches the desired value, the fixed time triggering is unnecessary, and the computational burden or network usage can be lowered [2],[1]. The novel paradigms introduce the feedback algorithm with an event execution policy, which is not time-dependable. The execution rule is set on the request 'update when necessary.' Figure presents the classic time execution and event-triggering approach with introduced boundary δ.

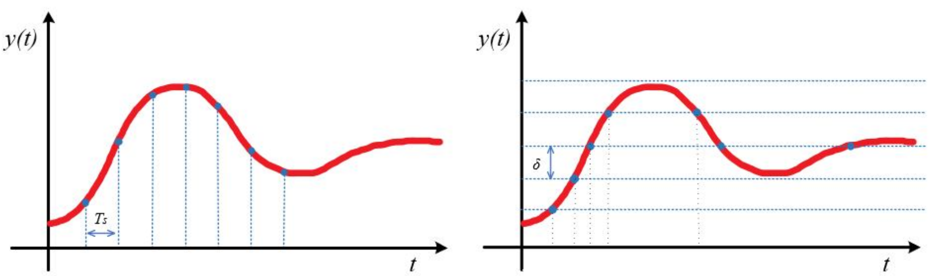

Figure 1: Timer-triggering and Event-triggering approach.

2 Event-triggering approach

Event-triggering control is an approach used in control systems to optimize the utilization of resources and reduce communication or computation overhead by triggering control actions only when necessary. Unlike the traditional approach with equidistant time triggering

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execution, event-triggering control dynamically adjusts the timing of control actions based on the system's behavior and selected triggering law. Such an approach can also be applied to time-critical dynamics systems, where stability and performance can also be ensured during the event-triggering execution [3],[4]. The control design with selected triggering law involves the stability check, where the lower positive execution time has to be ensured. The presented work will discuss the different approaches of the event-triggering controller design over different feedback structures. The stability issue and performance criteria for different types of controllers will be discussed. Some additional attention will be given to sliding mode controllers. The event-triggering approach improves sliding mode controller performance, where the chattering phenomena can be effectively suppressed during the event-triggering operation. Nevertheless, the utilization of the resources has to be preserved or even improved in contrast to the time-triggered execution of the sliding mode controllers. The presentation will cover:

- Comparison of time-triggering with event-triggering approach.
- Linear state-space controller for unstable system in event-triggering execution.
- The sliding mode controller is in the event-triggering mode for the distributed system over the standard communication network.
- Dynamic event-triggering approach with additional internal dynamics.

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A Lyapunov Function-Based Control Concept for Networked Systems

Katarina Stanojević[a]

The increasing complexity of modern systems together with the rapid development of communication technologies, cloud computing and cybersecurity have led to a tendency for replacement of traditional point-to-point wiring with communication networks, thereby redefining the boundaries of modern engineering. Nevertheless, the main challenges which arise when controlling the system over a network are communication constraints such as limited bandwidth and unreliability of the communication channel. The resulting random time delays and data loss have a great impact on the control design, since they don't in general allow direct application of the conventional control laws, thus leading to the need for new strategies which take these into account. The stability analysis and controller design for a time-variant networked control systems (NCS) model combining all relevant network uncertainties results in a very high complexity of the proposed method. Given the current state of research, an appropriate polytopic model derived using overapproximation techniques is required, while the number of linear matrix inequalities (LMIs) needed to compute a control law increases exponentially with the maximum allowable delay, see [1].

In this talk, a Lyapunov function-based control strategy for NCS affected by unknown variable time delays and data loss is presented [2]. A special focus is put on the reduction of the computational complexity of the proposed approach. The crucial step to achieving computational efficiency involves defining a specific buffering mechanism, which not only simplifies the discrete-time model of the NCS significantly but limits the additional buffer delay to one sampling time as well. The resulting buffered NCS can therefore be described as a switched system even though NCS practically does not involve switching. The novel approach does not only circumvent the need for any over-approximation technique but also leads to a strongly decreased number of optimization variables and LMIs, allowing hereby greater flexibility with respect to additional degrees of freedom affecting the transient behavior. The performance and computational effort of the proposed control approaches are evaluated in a simulation study which not only highlights the achieved computational simplicity but demonstrates the greater flexibility of the proposed laws with respect to the transient behavior as well. The potential for representation of the NCS as a switched system is further exploited for the observer design with a focus on developing a framework which allows treating out-of-order arrival of the data packets and data loss as well.

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Local stability analysis of sliding-mode control approaches within the model-following control architecture

Niclas Tietze[a] **Kai Wulff**[a] **Johann Reger**[a]

We consider the model-following control structure [1], [2] depicted in Fig. 1, which is a two-degrees of freedom control structure consisting of the model control loop (MCL) and the process control loop (PCL), using a linear state-feedback in the MCL loop and a sliding-mode controller in the PCL. The process is represented by an integrator chain with time- and state-dependant perturbation

$$\dot{x} = A\,x + B\,(u + \Delta(x,t))\,,$$

with (A, B) in Brunovský-form for state $x(t) \in \mathbb{R}^n$ and input $u(t) \in \mathbb{R}$. The function $\Delta : \mathbb{R}^n \times \mathbb{R} \mapsto \mathbb{R}$ represents an unknown perturbation satisfying some norm-bounding condition locally. The goal is to locally stabilise the origin assuming that the state $x(t)$ is available for control.

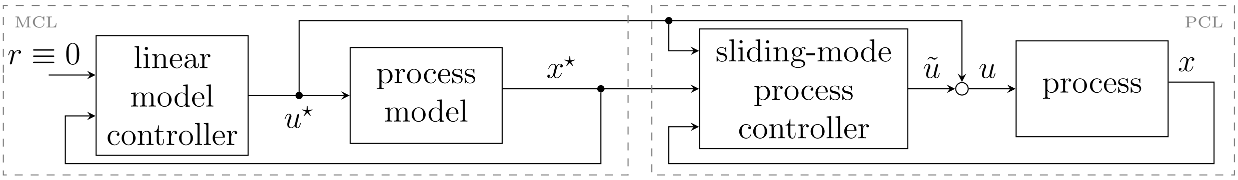

Figure 1: Model-following control (MFC) block diagram with sliding-mode process controller.

The MFC structure consists of two control loops. The open-loop dynamics are given by

$$\dot{x}^\star = A\,x^\star + B\,u^\star, \qquad\qquad \dot{\tilde{x}} = A\,\tilde{x} + B\,\left(\tilde{u} + \Delta(x,t)\right),$$

where $x^\star(t) \in \mathbb{R}^n$ denotes the state of the model with input $u^\star(t) \in \mathbb{R}$ for the MCL, and for the PCL we consider the error-state $\tilde{x} := x - x^\star$, with input $\tilde{u} := u - u^\star$. In the MCL we apply a linear state feedback $u^\star = k^{\star\top} x^\star$ with $k^\star \in \mathbb{R}^n$. For the PCL we consider a first-order as well as a super-twisting sliding-mode control (SMC). We analyse the stability of the closed-loop system and provide an estimate for the region of attraction (ROA), which depends on the initial state $x_0^\star \in \mathbb{R}^n$ of the MCL.

First-order sliding-mode control: Let the perturbation Δ be locally bounded such that $|\Delta(x,t)| \leq \delta$ for all $x \in \mathcal{D} \subset \mathbb{R}^n$ and all $t \geq 0$. We apply a first-order SMC law with gain $\tilde{\rho} > \delta$ and sliding-variable $\tilde{s}(\tilde{x})$. For our local stability analysis we consider three different cases for the selection of the initial state $x_0^\star$ in the MCL.

$\boldsymbol{x_0^\star = 0}$**:** For $x_0^\star = 0$, we obtain a trivial solution for the MCL, i.e. $x^\star \equiv 0$, $u^\star \equiv 0$. Thus, the MFC behaves like a single-loop first-order SMC which stabilises the origin $\tilde{x} = 0$ of the PCL locally. An estimate of the ROA is given by

$$\tilde{\Omega}_{\tilde{c},\tilde{c}_z} := \left\{\tilde{x} \in \mathbb{R}^n \,\middle|\, |\tilde{s}(\tilde{x})| \leq \tilde{c} \wedge \tilde{V}_z(\tilde{z}) \leq \tilde{c}_z\right\} \subseteq \mathcal{D}, \qquad \tilde{c} \geq 0, \quad \tilde{c}_z \geq \tilde{a}\,\tilde{c},$$

where $\tilde{V}_z$ is a Lyapunov function for the dynamics of the reduced system state $\tilde{z} = [\tilde{x}_1, ..., \tilde{x}_{n-1}]^\top$ and $\tilde{a} > 0$ is an appropriately selected constant.

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$\boldsymbol{x_0^\star = x_0}$**:** When selecting $x_0^\star = x_0$, we have $\tilde{x}_0 = 0$ such that $\tilde{x} \equiv 0$ whenever $x^\star$ remains in $\mathcal{D}$. Then, the PCL tracks the solution of the MCL without any deviations. An estimate of the ROA is given by sets which are positively invariant w.r.t to the dynamics $\dot{x}^\star = (A + B\, k^{\star\top})\, x^\star$, e.g. level-sets $\Omega^\star_{c^\star} := \{x^\star \,|\, V^\star(x^\star) \leq c^\star\}$, $c^\star \geq 0$ of a Lyapunov function $V^\star$ for the MCL.

$\boldsymbol{x_0^\star \neq x_0}$**:** If $x_0^\star \neq 0$ and $\tilde{x}_0 \neq 0$, the first-order SMC stabilises the PCL whenever the solution $x = x^\star + \tilde{x}$ remains in $\mathcal{D}$ such that $|\Delta(x,t)| = |\Delta(x^\star + \tilde{x}, t)| \leq \delta$. Thus, the MFC stabilises the origin $x = 0$ whenever the process controller stabilises the origin $\tilde{x} = 0$ of the PCL along the entire solution $x^\star$ of the MCL. Noting that the solution $x^\star$ of the MCL remains in the set $\Omega^\star_{c^\star}$, $c^\star \geq 0$ whenever $x_0^\star \in \Omega^\star_{c^\star}$, we obtain an estimate of the ROA of the MFC using the Minkowski sum of the sets $\Omega^\star_{c^\star}$ and $\tilde{\Omega}_{\tilde{c},\tilde{c}_z}$. We obtain the following stability statement.

Theorem ([3])**.** *Let $c^\star, \tilde{c} > 0$ and $\tilde{c}_z \geq \tilde{a}\,\tilde{c}$ be given such that $\Omega_{c^\star,\tilde{c},\tilde{c}_z} = (\Omega^\star_{c^\star} \oplus \tilde{\Omega}_{\tilde{c},\tilde{c}_z}) \subseteq \mathcal{D}$. Then the solution $x = x^\star + \tilde{x}$ remains in $\Omega_{c^\star,\tilde{c},\tilde{c}_z}$ and $\lim_{t\to\infty} x(t) = 0$. For each $x_0 \in \Psi$ with*

$$\Psi := \bigcup_{c^\star,\tilde{c}\geq 0,\tilde{c}_z \geq \tilde{a}\,\tilde{c}} \left\{\Omega_{c^\star,\tilde{c},\tilde{c}_z} \,\middle|\, \Omega_{c^\star,\tilde{c},\tilde{c}_z} \subseteq \mathcal{D}\right\}$$

the convergence to the origin can be guaranteed by an appropriate choice of the initial state $x_0^\star$ of the model. Thus, the initial state $x_0^\star$ can be considered as an additional degree of freedom.

We consider a second-order system and compare the obtained ROAs for different initialisations $x_0^\star$. For $x_0^\star = 0$ we obtain an estimate of ROA Ψ_{SL} by restricting the definition of Ψ above to $c^\star = 0$. Fig. 2 shows the sets Ψ and Ψ_{SL} and the largest level-set $\Omega^\star_{c^\star} \subseteq \mathcal{D}$. It holds that $\Psi_{\mathrm{SL}} \subset \Psi$ and $\Omega^\star_{c^\star} \subset \Psi$.

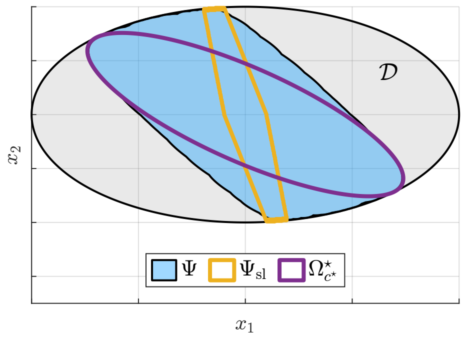

Figure 2: Estimates of the ROA.

Super-twisting SMC: Let the perturbation $\Delta(x,t)$ and its partial derivatives w.r.t. x and t be bounded. We consider a super-twisting SMC as proposed in [4] to overcome the problem of algebraic loops that occurs for super-twisting with state-dependant perturbations, see [5]. We show that, given some $c^\star \geq 0$ such that $\Omega^\star_{c^\star} \subseteq \mathcal{D}$, there exists some scaling $\tilde{\mu} > 0$ such that the control law

$$\tilde{u} = -[0\ \tilde{m}^\top]\,\tilde{x} - \tilde{\mu}^{-1}\,|\tilde{s}(\tilde{x})|^{1/2}\,\mathrm{sgn}(\tilde{s}(\tilde{x})) + \tilde{v}, \quad \dot{\tilde{v}} = -0.5\,\tilde{\mu}^{-2}\,\mathrm{sgn}(\tilde{s}(\tilde{x})), \quad \tilde{s}(\tilde{x}) = [\tilde{m}^\top\ 1]\,\tilde{x},$$

$\tilde{m} \in \mathbb{R}^{n-1}$, enforces $\lim_{t\to\infty} x(t) = 0$ for all $x_0 \in \Omega^\star_{c^\star}$ with initialisation of the MCL $x_0^\star = x_0$.

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Super-Twisting Control in Practical Applications: An Alternative to PI-Control?

Benedikt Andritsch[a] **Stefan L. Hölzl**[a,b] **Stefan Koch**[a]
Markus Reichhartinger[a] **Martin Horn**[a]

PI-Control is used extensively in the industry for output feedback stabilization and reference tracking applications. It works great in many applications with piece-wise constant or at least sufficiently slow reference trajectories. However, in case of fast reference trajectories or in presence of input disturbances PI-control loses its beneficial properties. Hence, there is a need for a different control strategy. Extending the control law by more involved knowledge of the plant and adding a feed-forward control action improves the tracking behavior, but still the closed loop is not robust against unknown input disturbances. Thus, in case of input disturbances PI-control only yields bounded-input bounded-state stability.

A sliding-mode control strategy applicable to the same type of plants is super-twisting control, which can be regarded as nonlinear PI-control. It can robustly stabilize a tracking error with relative degree one against a matched input disturbance. To achieve a proper control performance, the nominal plant dynamics must be known sufficiently well to be compensated. Recent research successfully mitigated the problem of discretization chattering by employing an implicit discretization [1, 2]. However, for a satisfactory performance in practical application of super-twisting control, still other sources of chattering must be accounted for, which is the aim of this talk.

The difficulty of handling unmodeled dynamics in the plant is demonstrated. Ways to mitigate the effects are discussed and state-of-the-art solutions are presented. A reduced chattering variant of discrete-time super-twisting control will be introduced. This controller is usable in practical applications that may also contain unmodeled actuator or sensor dynamics (e.g. cascaded control or sensor with low-pass characteristic) and does not result in undesired oscillations. The resulting super-twisting controller is able to outperform the classical PI-controller. Furthermore, it is beneficial in comparison to other state-of-the-art implementations of super-twisting-control.

Reduced Chattering Variant of Super-Twisting Control

When interpreting the control loop under super-twisting control as a pseudo-linear system, the state-dependent controller gains continuously increase as the sliding variable decreases. In case of Euler forward discretization, they increase unboundedly. In case of proper implicit discretization, they increase and stop at gains imposing deadbeat dynamics, which are high-gain controller gains that depend on the discretization time. However, these deadbeat gains may be too large in case of unmodeled dynamics in the plant. The reduced chattering

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[b]Kristl, Seibt & Co G.m.b.H., Baiernstrasse 122a, 8052 Graz, Austria

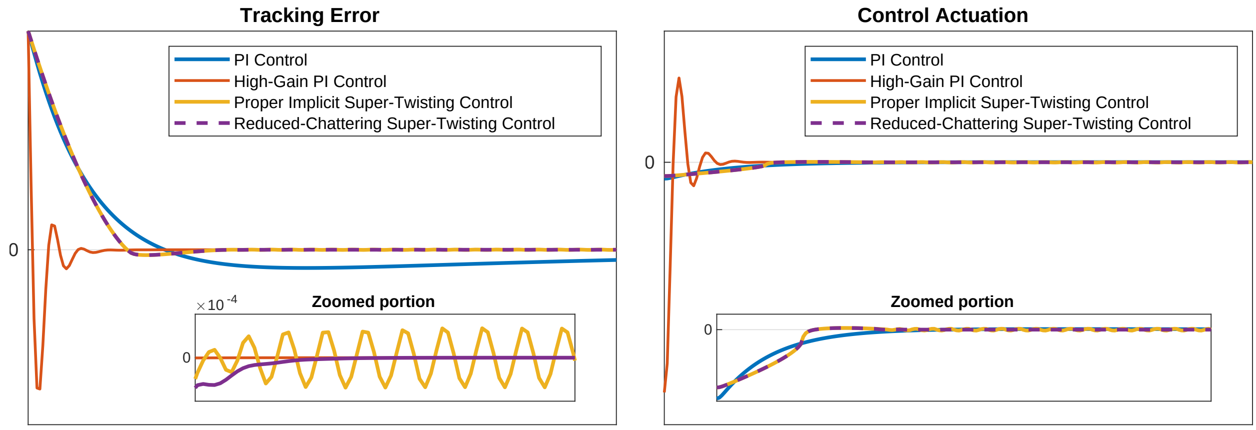

Figure 1: Control of an integrator with a first-order lag-element as unmodeled dynamic.

variant therefore stops the gain increase earlier at a stage that yields an asymptotically stable closed-loop system, similar to the ideas in [3, 4].

Effectively, this yields a linear controller in a vicinity of the origin, and thus does not deviate from a specifically tuned PI-controller in this region. However, with reduced chattering super-twisting control the maximum gains can be selected in an optimal sense for the nominal case. A PI-controller tuned in this way would produce large control actuation in the transient phase, which is not the case with super-twisting control.

The effectiveness of the reduced chattering super-twisting control is shown in simulation studies as well as experiments. The benefits in comparison to PI-control are demonstrated. Additionally, an intuitive tuning procedure is presented, explaining the role and effect of all three involved parameters, of which two are heavily related to the plant.

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Institute of Automation and Control
Graz University of Technology

23rd Styrian Workshop on Automatic Control

September 9–11, 2024, Schloss Retzhof, Austria

PROGRAM

Monday Sep 9, 2024

14:00 – 15:00	Registration + coffee
15:00 – 15:05	Opening
15:05 – 15:45	Daniel Schwingshackl *Model Predictive Control of a Metal Hydride Hydrogen Storage*
15:45 – 16:25	Hamid Didari, Gerald Steinbauer-Wagner *A Path Following Model Predictive Controller for Autonomous Truck Navigation in Off-Road Environments*
16:25 – 16:50	Coffee break
16:50 – 17:30	Stefan Jakubek, Christoph Hametner, Alexander Schirrer *Innovative control to suppress sloshing in fast transport of liquids*
17:30 – 18:10	Thomas Reiter-Nigitz, Johannes Niederwieser, Uwe Poms, Dominik Wickenhauser, Stefan Spirk, Markus Gölles *Modelling, Control and Monitoring of a Renewable Flow Battery*
18:30	Dinner

Tuesday Sep 10, 2024

08:30 – 09:10	Alexander Schaum *Observer design for nonlinear heat and mass transfer systems*
09:10 – 09:50	Klaus Röbenack, Daniel Gerbet *Observability and High Gain Observer Design for Polynomial Systems*
09:50 – 10:20	Coffee break
10:20 – 11:00	Christoph Weise, Kai Wulff, Johann Reger *Generalized Hybrid-Integrator-Gain System*
11:00 – 11:40	Jakob Rehrl *Efficient operation of pharmaceutical processes via model based approaches*
12:00	Lunch
16:00	Social program (in Graz)
18:00	Dinner (in Graz)

Wednesday Sep 11, 2024

08:30 – 09:10	Andrej Sarjas, Dusan Gleich *Event-triggered control approach for time-critical dynamic systems*
09:10 – 09:50	Katarina Stanojevic *A Lyapunov Function-Based Control Concept for Networked Systems*
09:50 – 10:30	Coffee break + check out option
10:30 – 11:10	Niclas Tietze, Kai Wulff, Johann Reger *Local stability analysis of sliding-mode control approaches within the model-following control architecture*
11:10 – 11:50	Benedikt Andritsch, Stefan L. Hölzl, Stefan Koch, Markus Reichhartinger, Martin Horn *Super-Twisting Control in Practical Applications: An Alternative to PI-Control?*
12:00	Lunch