12th IFAC International Symposium on
Advanced Control of Chemical Processes
July 14-17, 2024. Toronto, Canada

Enhancing Closed-Loop Performance in Manufacturing Processes Using Universal Controller Tuning for Industrial Practice

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Abstract:
This research paper introduces a novel approach to enhance closed-loop performance in manufacturing processes, catering specifically to industrial practice. The primary objective is to design a supervisory controller capable of shaping the response of an existing yet rigid, closed-loop system while adhering to crucial criteria like respecting process constraints or allowing for simple synthesis of the tuning options. The manuscript shows how to extend the universal tuning strategy with a lead-lag compensator, which decreases the rise time and removes possible oscillations. Two experiments are conducted: one employs a traditional approach, and the second verifies the lead-lag extension. Experimental results demonstrate the significant impact of the universal tuner on closed-loop performance, particularly in the overall effect on quality criteria of control performance.

Keywords: reference governor, controller tuning, experimental results

1. INTRODUCTION

Operators and control engineers responsible for industrial plant operations often need to adjust control performance within specific control loops. In straightforward cases involving controllers of the PID family, online tuning is a simple and intuitive process involving the customizing of three coefficients. Nowadays, however, the control loops consist of advanced process control strategies, like model predictive controllers (MPC), fuzzy controllers, or other form of multiple-input-multiple-output strategies. For such control strategies, it becomes nearly impossible to formulate straightforward and effective tuning guidelines for operators. Additionally, tuning closed-loops with MPCs, particularly when employing explicit model predictive control for plant operation, presents significant challenges, as outlined by Oravec and Klaučo (2022).

Our approach aims to design a universal tuner of the existing closed-loop performance by straightforward rules, without changing the architecture of the nominal control system. We follow and expand the theoretical concepts presented in the work of (Fikar et al., 2023), which presents an extension of the nominal control system with a single gain component that shapes the setpoint for the nominal system.

The organization of individual control blocks is heavily inspired by traditional reference governor control setup, popularized by works (Liu and Ossareh, 2021; Pilbauer et al., 2018; Cavanini et al., 2021) and references therein. All mentioned approaches have several drawbacks, which our approach remedies to some extent. The drawbacks of existing reference governor control strategies are mainly as follows:

(1) model knowledge of the existing closed-loop control system si required, as presented by Klaučo and Kvasnica (2019) or by Burlion et al. (2022),
(2) requirement of advanced knowledge about synthesis and/or tuning procedures of the reference governor as suggested e.g. by Kalabić and Kolmanovsky (2014).

The proposed manuscript addresses all aforementioned drawbacks by introducing the input shaper of several variants that merely supply a weighted set point for the nominal control system while still preserving the underlying features of the primary controller in the existing closed-loop system.

The manuscript is organized as follows. The Section 2 formulates the problem statement, preliminaries, and the nominal controller. Next, in Section 3, we introduce an extension with lead-lag weighting and a toy example. Section 4 presents the laboratory device, while Section 5 discusses the experimental results.

2. PROBLEM STATEMENT & PRELIMINARIES

We aim to design a a supervisory controller, that shapes the response of an existing closed-loop performance. The

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⋆ The authors gratefully acknowledge the contribution of the Scientific Grant Agency of the Slovak Republic under the grants VEGA 1/0490/23, the Slovak Research and Development Agency under the project APVV-21-0019 and APVV-20-0261. This paper is also funded by the European Union's Horizon Europe under grant no. 101079342 (Fostering Opportunities Towards Slovak Excellence in Advanced Control for Smart Industries).

main targets, that the supervisory controller must fulfil, are summarized as follows:

- T1 Preserve the architecture of the existing control strategy.
- T2 Provide non-invasive changes in the setpoints, respecting constraints, and tuning of existing control strategy.
- T3 The synthesis of the supervisory controller should not rely on the model of the nominal control system.
- T4 The tuning possibilities of the supervisory control must be simple and easy to use for operators of industrial plants.

Let us consider the user defined setpoint as the variable $r(t)$, while the shaped input to the nominal controller, i.e., the modified setpoint is denoted as $w(t)$. The variables within the existing closed-loop are given by $u(t)$, $x(t)$, and $y(t)$, which represents manipulated variable, state vector and measured (controlled) variables, respectively. The particular arrangement is visualized on the block diagram in Fig. 1.

2.1 Preliminaries

The rationale behind the universal tuner is inspired by the work of (Fikar et al., 2023), which offers the possibility to design a single gain factor K_w, which multiplies the user-defined reference $r(t)$ and controlled output $y(t)$. Specifically, for a single-input-single-output control problem, the shaped reference for the inner rigid control scheme is calculated via

$$w(t) = K_\mathrm{w} r(t) + (1 - K_\mathrm{w}) y(t), \tag{1}$$

where the parameter K_w represents the universal tuning parameter. By this extension of the control scheme, we allow the operator to weight the effect of the reference with respect to the controlled output. Therefore, choosing $K_\mathrm{w} = 1$ will provide nominal closed-loop performance, while increasing the gain $K_\mathrm{w} > 1$ will fasten the system response. On the other hand, by choosing $K_\mathrm{w} < 1$, we decrease the effect of the user-defined reference, hence we prolong the time constant of the baseline control performance. More detailed derivation with the static gain K_w can be found in (Fikar et al., 2023).

2.2 Nominal Controller

Nowadays, a standard practice in industrial applications is to apply advanced process controllers, such as model predictive control (MPC). In industrial applications, we are often limited by several hardware components; therefore, the explicit model predictive control (eMPC) is often considered, such no numerical optimization is required during the operation of the control strategy, as recently published by Ghezzi et al. (2023).

Consider the following formulation of the MPC

$$
\begin{aligned}
\min_{u_0,\ldots,u_{N-1}} \quad & \sum_{k=0}^{N-1} ||y_k - y_\mathrm{ref}||^2_{Q_\mathrm{y}} + \sum_{k=0}^{N-1} ||\Delta u_k||^2_{Q_\mathrm{du}} && \text{(2a)}\\
\text{s.t.} \quad & x_{k+1} = Ax_k + Bu_k, \quad k \in \mathbb{N}_0^{N-1}, && \text{(2b)}\\
& y_k = Cx_k + Du_k, \quad k \in \mathbb{N}_0^{N-1}, && \text{(2c)}\\
& \Delta u_k = u_k - u_{k-1}, \quad k \in \mathbb{N}_0^{N-1}, && \text{(2d)}\\
& \Delta u_k = 0, \quad k \in \mathbb{N}_{N_\mathrm{c}+1}^{N}, && \text{(2e)}\\
& x_0 = x(t), u_{-1} = u(t - T_\mathrm{s}), y_\mathrm{ref} = r(t), && \text{(2f)}
\end{aligned}
$$

which is a well-known formulation ensuring offset-free control if combined with a suitable state observer. For more details, we direct the reader to the paper by Muske and Badgwell (2002) and references therein. Note, that N stands for the prediction horizon, tuning matrices Q_y, and Q_du are positive definite, and $\mathbb{N}_0^{N-1}$ represents integers in given interval. The solution to the problem (2) gives sequence of optimal control inputs $U^\star = [u_0^\intercal, \ldots, u_{N-1}^\intercal]^\intercal$. The problem in (2) is then solved parametrically with the MPT3.0 toolbox (Herceg et al., 2013) and yields control law in the form of a piecewise affine function (PWA) (Bemporad et al., 2002) expressed as:

$$\kappa(\theta) = \begin{cases} \alpha_1 \theta + \beta_1 & \text{if } \theta \in \mathcal{R}_1 \\ & \vdots \\ \alpha_{n_\mathrm{R}} \theta + \beta_{n_\mathrm{R}} & \text{if } \theta \in \mathcal{R}_{n_\mathrm{R}} \end{cases}. \tag{3}$$

Here, the variable θ represents the vector of parameters aggregated from (2f). Next, n_R denotes the total number of regions, while variables α_i and β_i define the specific control law with respect to a region $\mathcal{R}_i$. The regions are defined as polyhedral sets, namely

$$\mathcal{R}_i = \{\theta \mid \mathbf{\Gamma}_i \theta \le \gamma_i\} \quad i = 1, \ldots, n_\mathrm{R}, \tag{4}$$

where, matrices $\mathbf{\Gamma}_i, \gamma_i$ denote the half-space representation of individual regions.

Note that the form in (3) is used as the nominal controller (cf. Fig. 1), and its retuning or any change calls for extensive and time-consuming calculations. The arrangement, together with the universal tuner, poses a great advantage of combined optimal performance under constraints of the eMPC and with tunability coming from input universal input shaper.

3. LEAD-LAG SHAPER AND DEMONSTRATION EXAMPLE

The equation representing the tuner (1) is similar to extending the formulation of the PID controller to remedy derivation kicks, rapid changes in the setpoints etc. However, we propose a general and universal approach, where the nominal controller can be of any form, for example, the explicit model predictive control (see results from the case study in Section 5).

Simple implementation of a similar setpoint shaper was also presented by Dyrska et al. (2023b). In processes with nonlinear dynamics that are controlled by linear controllers, however, the setpoint shaping as presented in (1) or in (Dyrska et al., 2023b) often prove inefficient (as demonstrated in Section 5). We aim to further improve the overall closed-loop performance by introducing dynamically weighted input shaping with the help of the lead-lag transfer function. Suppose the lead dynamics is

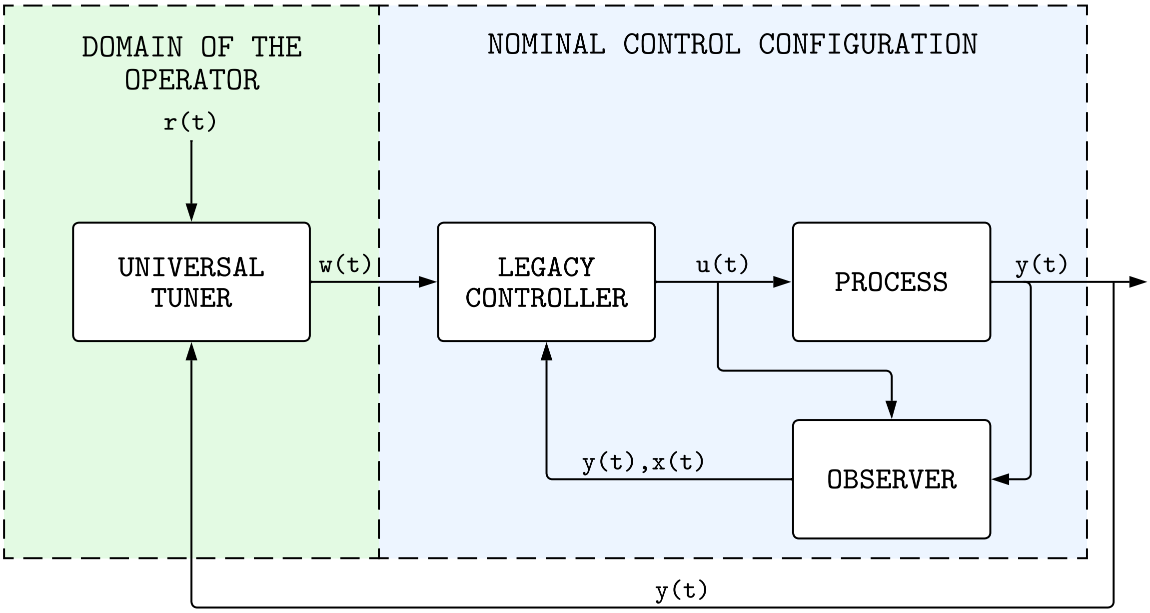


Fig. 1. Block diagram of the universal tuner and baseline nominal control configuration.

approximately equal to the dominant time constant T of the rigid closed-loop process. In that case, it allows us to decrease further the rise time response of the closed-loop dynamics of the rigid system. Such a lead-lag (LL) term is given by

$$G_{\mathrm{T}}(s) = \frac{Ts+1}{\frac{T}{K_{\mathrm{w}}}s+1}, \tag{5}$$

which replaces the term K_{w} within the equation for universal tuner in the Eq. (1). We acknowledge that by considering T as the time constant of the closed-loop system, we partially violate the target (T3), but a crude information on the process dynamics is known to the operator and the desired closed-loop dynamics can be specified.

To give the reader a better understanding regarding the effects of the LL term, consider a demonstration example where the controlled process is given by $G(s) = \frac{1}{2s+1}$ and the controller is an explicit control law, as described in Section 2.2. The nominal controller featured 401 regions, $N = 20$, and unit weighing factors.

As indicated above, the introduction of the LL term as part of the input shaper allows us to decrease the rise time of closed-loop response, as shown in Fig. 2(a). The added benefit compared to the simplified universal tuner, where only the input shaper in the form of (1) is also the reduction of the overshoot. Such effect is caused by introducing a zero, canceling out the dominant dynamics of the closed-loop system. Unfortunately, considering the LL term has the opposite effect if considering $K_{\mathrm{w}} < 1$, then the original form of the input shaper is more suitable; see the example in Fig. 2(b). Practical implementation, therefore, calls for bump-less transfer and switching between several variations of the universal tuner, but that is standard practice Zaccarian and Teel (2005).

Primary responsibility of the nominal controller is to maintain the stability of the process, so the effect of the universal tuner on actual closed-loop stability is not considered in this work. However, the stability of the closed-loop system with the universal tuner can be analyzed using robust control frameworks.

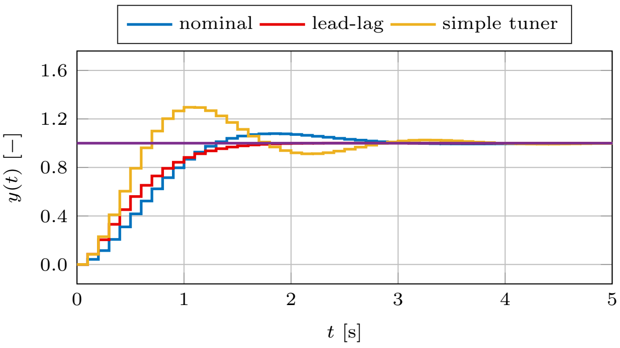
4. SETUP OF LABORATORY EXPERIMENT

4.1 Heat Exchanger

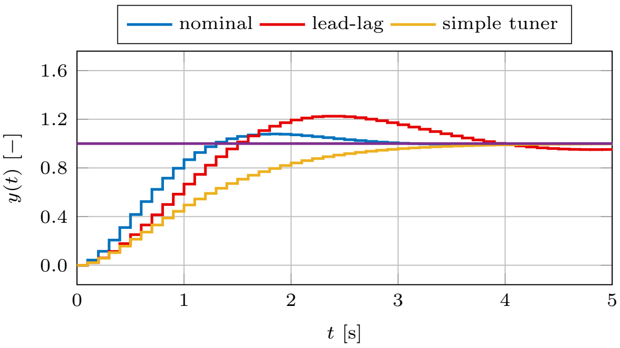
The laboratory device used in this experimental study is a liquid-liquid plate heat exchanger manufactured by Armfield. The heat exchanger is part of a larger laboratory pasteurization unit, as depicted in Figure 3.

In our experiments, we are using the heat exchanger to maintain a suitable temperature of outlet liquid T_3 by modifying the flow through the heat pump. The manipulated variable is constrained within $0\,\%$ to $100\,\%$. To ensure suitable operation of the heat exchanger, tighter limits are considered in the particular experiments, namely $25\,\%$ to $60\,\%$. Such a setting not only provides long-term continuous operation of the device but also shows the control performance with the universal tuner in place. The feed liquid is directed to the heat exchanger from the Feed tanks. The temperature of the feed liquid, i.e., the one that needs to be heated up, is within $20\,^\circ\mathrm{C}$ to $28\,^\circ\mathrm{C}$. We consider a constant feed which is ensured by a feed peristaltic pump, set to $50\,\%$. The heating medium comes from a retention tank with an electric heating rod, which ensures the constant temperature of $70\,^\circ\mathrm{C}$ of the heating medium. All experiments, including system identification, are performed with a sampling instant of $T_{\mathrm{s}} = 2\,\mathrm{s}$.

To design a nominal controller, we investigate previous work related to the design of control strategies with this



(a) Accelerating the response with $K_\mathrm{w} = 2.0$.



(b) Decelerating the response with $K_\mathrm{w} = 0.5$.

Fig. 2. Effect of the lead-lag term on the closed-loop performance of the rigid control system with the universal tuner. The blue solid line represents nominal performance, the yellow curve corresponds to the simplified input shaper (Eq. (1)), while the red line depicts the shaper with lead-lag.

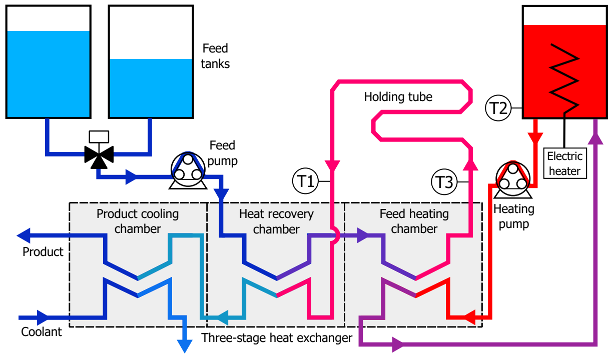


Fig. 3. Schematic representation of the heat exchanger device. Here, the controlled variable is represented by the temperature T_3, while the disturbance variable is the temperature of the inlet feed stream. The manipulated variable is the speed of the peristaltic pulses in the heating pump.

particular device, and we follow the work by Dyrska et al. (2023a), and obtain a model in the form of a transfer function

$$G(s) = \frac{K}{Ts + 1} \tag{6}$$

where $K = 0.435$ and $T = 50$. Note that the actual control design was done in discrete time domain (Galčíková et al., 2022). It's important to note that the simplicity of that specific model of the controlled process is not of particular interest regarding this research. The focus is on the concept and on the applicability of the universal tuner laid out in the next section.

4.2 Nominal Controller

The baseline controller employed in our experiment follows the design given in Section 2.2, Eq. (2). Here, we consider $N = 100$, $Q_\mathrm{y} = \frac{1}{80}$, $Q_\mathrm{u} = \frac{1}{30}$, with constraints on state variables and inputs as given by

$$x \in [20, 60]^\circ\mathrm{C}, \quad u \in [25, 60]\%. \tag{7}$$

Furthermore, to ensure full reference tracking we employ a state observer in the form of Luenberger observer casted as extended state space model in discrete time

$$e_k = y_k - [C \;\; 1]\, \tilde{x}_k, \tag{8a}$$

$$\tilde{x}_{k+1} = \begin{bmatrix} A & 0 \\ 0 & 1 \end{bmatrix} \tilde{x}_k + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k + L e_k, \tag{8b}$$

where $\tilde{x}$ is estimated vector of states including artificial disturbance. The poles of $(A - LC)$ calculated according to pole placement method, with poles taken as twice as fast as the original controlled system. The MPC then contains 4 number of initial parameters, which was solved parametrically via the MPT3.0 toolbox to obtain a PWA control law defined over 15 036 regions.

5. EXPERIMENTAL RESULTS

Two sets of experiments are presented in this case study. First, we consider a traditional approach to the input shaper, as reported in Section 2.1. The second case study involves the verification of the proposed lead-lag weighing, as described in Section 3.

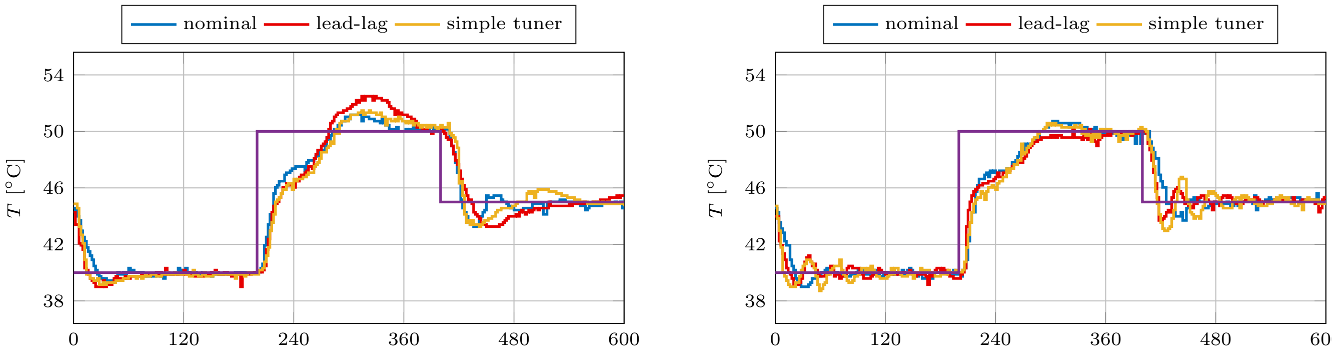
Each reported experiment was measured on a time window $T_\mathrm{f} = 600\,\mathrm{s}$, with baseline steady-state of the controlled variable, $T_3^\mathrm{s} = 45\,^\circ\mathrm{C}$. Operator-defined reference r was changed every 200 s. The sequence of reference changes was set to $[40, 50, 45]^\circ\mathrm{C}$. Note that the last user-defined setpoint is equal to the original steady-state value. Therefore, the experiments are structured such that both simple and LL variants of the universal tuner are investigated in both cases of reference step change, positive and negative.

Experimental results are shown in the Fig. 4, where we report 3 sets of figures. The primary effect of the universal tuner can be seen in the Figs. 4(c) and 4(d), where the shaped reference $w(t)$ is either softened, for $K_\mathrm{w} < 1$, or amplified for $K_\mathrm{w} > 1$.

Table 1. Normalized comparison for $K_\mathrm{w} > 1$

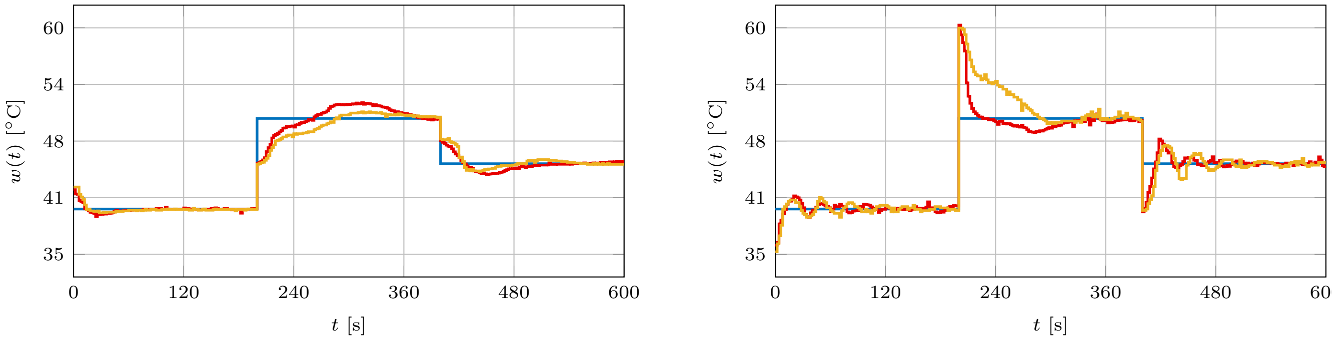
governor	J_ie	$J_{\Delta\mathrm{u}}$	J_u
nominal	1.000	1.000	1.000
lead-lag	0.950	1.481	1.002
simple tuner	1.078	1.855	1.015

Secondly, if we consider the $K_\mathrm{w} = 0.5$, as reported on Fig. 4(a), compared to the performance with $K_\mathrm{w} = 2$, as reported on Fig. 4(b), we observe dampening of the overshoots in case for higher choice of the $K_\mathrm{w} > 1$. Such an observation is aligned with results reported in Section 3. The choice of the tuning factors K_w stems from general



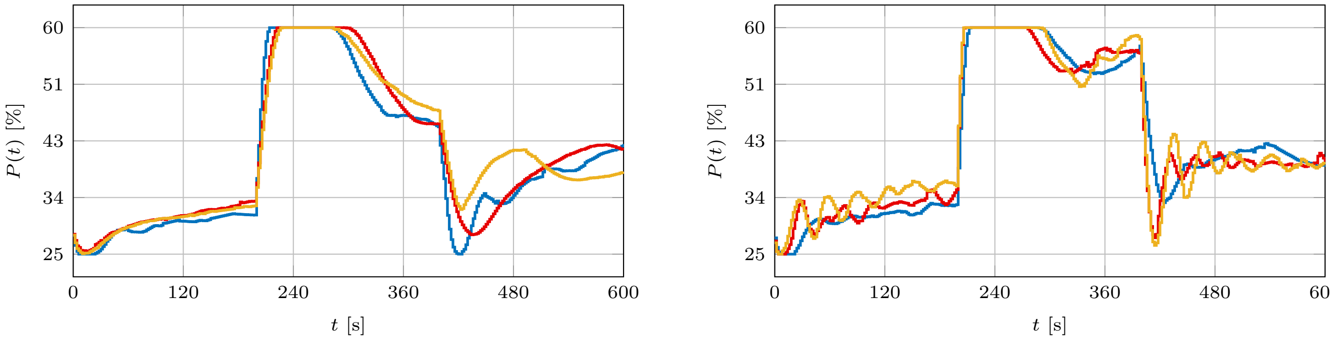
(a) Controlled variable.

(b) Controlled variable.



(c) Shaped reference.

(d) Shaped reference.



(e) Control authority.

(f) Control authority.

Fig. 4. Experimental comparison two scenarios. Left hand side shows comparison for $K_\mathrm{w} = 0.5$, while right hand side for $K_\mathrm{w} = 2.0$.

Table 2. Normalized comparison for $K_\mathrm{w} < 1$

governor	J_ie	$J_{\Delta\mathrm{u}}$	J_u
nominal	1.000	1.000	1.000
lead-lag	1.300	0.878	1.026
simple tuner	1.246	0.845	1.034

guidelines for tuning of the controllers, where the value of $K_\mathrm{w} = 1$ represents the nominal performance. Particular choice of greater and lower value of K_w is related to this particular case study.

Last, but important, the time profile of the controlled variable, second, the time profile associated with the shaped reference $w(t)$, and last, the authority of the nominal controller. First, observe that under all circumstances, the limitations on manipulated variables are rigorously kept (Figs. 4(e), and 4(f)). This is the benefit of the explicit model predictive control as the nominal controller. The effect on the rise time is rather limited in both variations of the universal tuner, which is caused by the saturation of the control action immediately once the shaped reference is applied. Hoverer, especially on Figs. 4(e), and 4(f) can be seen the position of the nominal performance concerning the the control authority of the nominal controller but with $K_\mathrm{w} \neq 1$. For $K_\mathrm{w} = 0.5$, the nominal performance precedes the other two, while in the case of $K_\mathrm{w} = 2$ the curve representing the nominal performance is passed by performances given by shaped $w(t)$.

To rigorously evaluate the quality of the control performance, we choose three individual quality criteria. First, the summation of the absolute error is evaluated, and denoted by J_ie, next an indication of the control effort, related to wearing of the actuator, denoted by $J_{\Delta\mathrm{u}}$, and a summation of absolute value of manipulated variable J_u, which corresponded to total energy requirements. Namely, we evaluate:

$$J_{\mathrm{ie}} = \sum_{k=0}^{T_\mathrm{f}} |r(k) - y(k)|, \tag{9a}$$

$$J_{\Delta\mathrm{u}} = \sum_{k=0}^{T_\mathrm{f}} |u(k) - u(k-1)|, \tag{9b}$$

$$J_{\mathrm{u}} = \sum_{k=0}^{T_\mathrm{f}} |u(k)|. \tag{9c}$$

The evaluation of the quality criteria is reported in the Table 1, and 2. If we apply the gain of the universal tuner as $K_\mathrm{w} < 1$, then we decrease the wearing of the actuator by approximatelly 15%, as reported by the parameter $J_{\Delta\mathrm{u}}$. On the other hand, the reduction by 5% of the J_ie factor for the $K_\mathrm{w} > 1$ proves that response of the closed-loop is accelerated, but only for the case of the LL term. Consider simple input shaper, the response is accelerated, but generates oscillation in the controlled variable.

6. CONCLUSION

This manuscript illustrates a systematic and straightforward approach to fine-tuning existing and rigid closed-loop systems. The proposed tuning algorithm enables both the acceleration and deceleration of the closed-loop system's response while preserving the fundamental characteristics of the original controller, particularly in terms of maintaining stability and meeting constraints. Furthermore, the universal tuning approach enhances the relatively simple input shaper algorithm by incorporating a lead-lag weighting technique, effectively eliminating oscillations stemming from forced changes in the closed-loop system's response.

The experiments conducted in this study demonstrate the capability to dynamically adjust the behavior of unmodifiable explicit model predictive control. This adjustment can serve to reduce rise time by increasing the universal tuner's gain or to minimize wear and tear on the actuator by reducing the tuner's gain.

REFERENCES

Bemporad, A., Morari, M., Dua, V., and Pistikopoulos, E.N. (2002). The explicit linear quadratic regulator for constrained systems. *Automatica*, 38(1), 3–20.

Burlion, L., Schieni, R., and Kolmanovsky, I.V. (2022). A reference governor for linear systems with polynomial constraints. *Automatica*, 142, 110313. doi: https://doi.org/10.1016/j.automatica.2022.110313.

Cavanini, L., Ferracuti, F., and Monteriù, A. (2021). Optimal error governor for PID controllers. *Int. J. Sys. Sci.*, 52(12), 2480–2492.

Dyrska, R., Horváthová, M., Bakaráč, P., Mönnigmann, M., and Oravec, J. (2023a). Heat exchanger control using model predictive control with constraint removal. *Applied Thermal Engineering*, 227. doi: 10.1016/j.applthermaleng.2023.120366.

Dyrska, R., Müller, J., Fikar, M., and Mönnigmann, M. (2023b). Simple controller tuning for unmanned aerial vehicles using governors. In R. Paulen and M. Fikar (eds.), *Proceedings of the 2023 24th International Conference on Process Control*, 108–113. Slovak University of Technology in Bratislava, IEEE, Slovak University of Technology in Bratislava, Radlinského 9, 81237, Bratislava, Slovakia.

Fikar, M., Kiš, K., Klaučo, M., and Mönnigmann, M. (2023). Simple tuning of arbitrary controllers using governors. In *22nd IFAC World Congress, Tokyo, Japan*, 9109–9114.

Galčíková, L., Horváthová, M., Oravec, J., and Bakošová, M. (2022). Self-tunable approximated explicit model predictive control of a heat exchanger. *Chemical Engineering Transactions, 2022, Vol. 94*, (94), 1015–1020. doi:10.3303/CET2294169.

Ghezzi, A., Messerer, F., Balocco, J., Manzoni, V., and Diehl, M. (2023). An implicit and explicit dual model predictive control formulation for a steel recycling process. *European Journal of Control*, 74, 100841. doi: https://doi.org/10.1016/j.ejcon.2023.100841. 2023 European Control Conference Special Issue.

Herceg, M., Kvasnica, M., Jones, C., and Morari, M. (2013). Multi-Parametric Toolbox 3.0. In *Proc. of the European Control Conference*, 502–510. Zürich, Switzerland. `http://control.ee.ethz.ch/ mpt`.

Kalabić, U. and Kolmanovsky, I. (2014). Reference and command governors for systems with slowly time-varying references and time-dependent constraints. In *53rd IEEE Conference on Decision and Control*, 6701–6706. doi:10.1109/CDC.2014.7040441.

Klaučo, M. and Kvasnica, M. (2019). *MPC-Based Reference Governors*. Springer, 1 edition.

Liu, Y. and Ossareh, H.R. (2021). Preview reference governors: A constraint management technique for systems with preview information. *Systems & Control Letters*, 152, 104932. doi: https://doi.org/10.1016/j.sysconle.2021.104932.

Muske, K.R. and Badgwell, T.A. (2002). Disturbance modeling for offset-free linear model predictive control. *Journal of Process Control*, 12(5), 617–632. doi: 10.1016/S0959-1524(01)00051-8.

Oravec, J. and Klaučo, M. (2022). Real-time tunable approximated explicit MPC. *Automatica*, 142, 110315. doi:10.1016/j.automatica.2022.110315.

Pilbauer, D., Michiels, W., Bušek, J., Osta, D., and Vyhlídal, T. (2018). Control design and experimental validation for flexible multi-body systems pre-compensated by inverse shapers. *Systems & Control Letters*, 113, 93–100. doi: https://doi.org/10.1016/j.sysconle.2018.01.002.

Zaccarian, L. and Teel, A.R. (2005). The l2 (l2) bumpless transfer problem for linear plants: Its definition and solution. *Automatica*, 41(7), 1273–1280. doi: https://doi.org/10.1016/j.automatica.2005.02.003.