Development and validation of control systems with variable dead time for networked control systems

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Abstract: Dead times can manifest in various control systems, posing a challenge due to their limiting effect on the maximum allowable gain required for system stability. Consequently, researchers have developed various structure-based controllers to enhance control performance or mitigate the strong influences of the dead time component. Among these structures are the Smith Predictor, Generalized Predictive Controller (GPC), and fractional PID controllers. With the significant advancements in networking and communication technology, the application of networked control has gained importance. However, due to the diverse network characteristics, additional variable delays are challenging to avoid. Modern control engineering offers methods capable of significantly improving control performance, considering both theoretical and practical aspects.

Key-Words: Smith Predictor, GPC, Networked Control Systems

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1 Introduction

Many processes in the industry, as well as in other domains, exhibit dead times in their dynamic behavior. Dead times primarily consist of delays in information, energy transport, or communication networks [1], [2]. They can also be caused by processing time or the accumulation of time delays across a series of interconnected dynamic systems. In processes with dead time, a change in the process setpoint affects the controlled variable only after the process's dead time. Additionally, disturbances become noticeable only after some time, and it also takes time for the controller to respond to these changes. Therefore, the analysis and design of controllers for systems with dead time are challenging [2], [3].

Time delay poses a significant challenge in process control and regulation as it can lead to undesirable oscillatory behavior or even instability within the system. Stability analysis and robust control of time delay systems are therefore of both theoretical and practical significance [4]. Although these are typically associated with disturbances in Closed-loop control systems, some methods intentionally integrate delays into control laws to achieve stable behavior or improve control quality [5].

Processes with significant dead times are challenging to control using standard controllers. By employing a predictor structure, the performance of the closed-loop system can be improved. These predictor-based controllers, known as dead time compensators, find applications across various technical domains, primarily in the process industry [6], [7], but also in other areas such as robotics [8] and internet congestion control [9]. These controller structures were introduced to enhance the performance of classical controllers (such as PI or PID controllers) in systems with dead time.

The outline of the remaining paper is as follows: Section 2 describes the PID controller, followed by the Smith predictor in Section 3 and the GPC controller in Section 4. Section 5 presents their applications, and finally, Section 6 provides the conclusion.

2 PID, PI Controllers

Many processes are regulated using classical controllers such as Proportional Integral (PI) and Proportional Integral Derivative (PID). However, when the process exhibits dead time, tuning the controller parameters becomes challenging. Consequently, extensive efforts have been made to explore and derive better tuning rules for controller parameters of processes with dead time [10], [11].

The ideal controller is defined as follows [12]:

$$C(s) = K_c(1 + \frac{1}{T_i s}) \tag{1}$$

where K_c is the proportional gain and T_i is the time constant and s the Laplace operator. The Process is assumed as:

$$P(s) = e^{-s\tau_m}(\frac{K_m}{1 + T_m s}) \tag{2}$$

This classical controller can be designed using various methods, including the following rules [10] as shown in Table 1:

Table 1: Tunings rules for PI controller [10], [11]

Rule	K_c	T_i	**Comment**
Ziegler Nichols (1992)	$\frac{0,9T_m}{K_m\tau_m}$	$0,33\tau_m$	$\frac{\tau_m}{T_m} \leq 1$
Aström Hägglund (1995)	$\frac{0,63T_m}{K_m\tau_m}$	$0,2\tau_m$	
Chien, et al. (1952)	$\frac{0,6T_m}{K_m\tau_m}$	$4\tau_m$	$\frac{\tau_m}{T_m} \leq 1$
St. Clair (1997)	$\frac{0,333T_m}{K_m\tau_m}$	T_m	$\frac{T_m}{\tau_m} \leq 3$

The closed loop system of a process $P(s) = G(s)e^{-Ls}$ controlled by a PID controller can be defined as follows:

$$\begin{aligned} \frac{Y(s)}{R(s)} &= \frac{C(s)P(s)}{1 + C(s)P(s)} \\ &= \frac{C(s)G(s)e^{-Ls}}{1 + C(s)G(s)e^{-Ls}} \end{aligned} \tag{3}$$

Generally, processes with small dead time can be regulated using classical PI and PID controllers, and suitable tuning of the controller parameters can achieve a reasonable compromise between robustness and performance [10]. However, as depicted in Figure 1, processes with significant dead times are challenging to control with PI and PID controllers, and determining the optimal control parameters is difficult. Consequently, the performance of the control loop remains limited. The effect of disturbances on the controlled variable becomes noticeable only after a certain time, hence it also takes time for the response of the manipulated variable to reflect in the controlled variable [3].

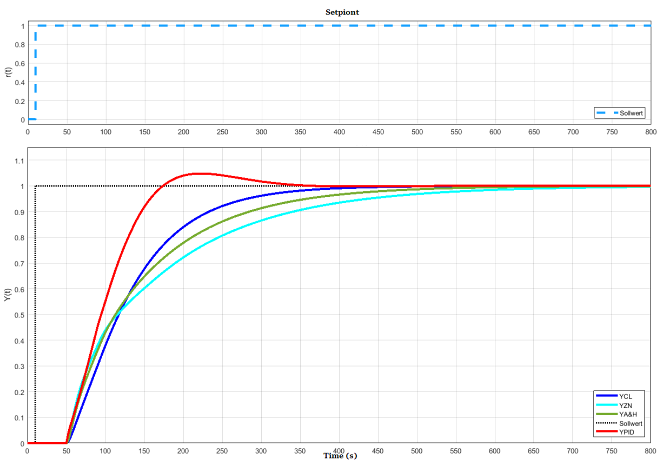

Fig. 1: PI Controller

3 Smith Predictor

Predictor-based control structures have been utilized in many control applications. The performance of the closed loop system can be enhanced by employing a predictor structure in two main cases [13]:

- when the process exhibits significant dead time.
- when the future setpoint is known.

In the first case, the main objective of the predictor is to eliminate the effects of dead time on the control loop. In the second case, the predictive controller enables prediction of the control process. In both scenarios, the predictive strategy involves a process model integrated into the controller's structure.

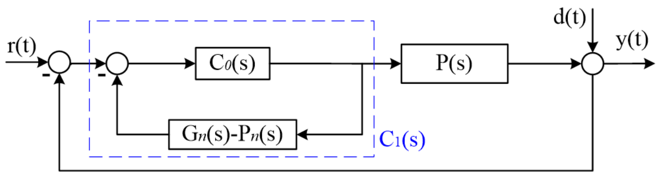

Fig. 2: Smith Predictor

Figure 2 illustrates the complete controller $C_1(s)$. The controller $C_0(s)$ is typically a PI or PID controller. The predictor includes a transfer function model without dead time $G_n(s)$, along with a dead time model $e^{-L_n}s$. Consequently, the complete process model is expressed as $P_n(s) = G_n(s)e^{-L_n s}$ [2].

$$\begin{aligned} C_1(s) &= \frac{C_0(s)}{1 + C_0(s)[G_n(s) - P_n(s)]} \\ &= \frac{C_0(s)}{1 + C_0(s)G_n(s)(1 - e^{-L_n s})} \end{aligned} \tag{4}$$

When $P_n(s) = P(s)$ and $L = L_n$, the transfer function of the closed loop system can be expressed as:

$$\begin{aligned} \frac{Y(s)}{R(s)} &= \frac{C_1(s)P(s)}{1 + C_1(s)P(s)} \\ &= \frac{C_1(s)G(s)e^{-Ls}}{1 + C_1(s)G(s)e^{-Ls}} \\ &= \frac{\frac{C_0(s)}{1 + C_0(s)G_n(s)(1 - e^{-L_n s})}G(s)e^{-Ls}}{1 + \frac{C_0(s)}{1 + C_0(s)G_n(s)(1 - e^{-L_n s})}G(s)e^{-Ls}} \\ &= \frac{C_0(s)G(s)}{1 + C_0(s)G(s)}e^{-Ls} \end{aligned} \tag{5}$$

Compared to the PID or PI control loop (Equation 3), the characteristic equation depends on the dead time, with the phase margin of the system reduced by the additional phase of the dead time.

3.1 Filtered Smith Predictor

Various approximation methods are employed in process modeling, which may entail simplifying higher order dynamics or approximating nonlinear dynamics with linearized equations [14]. Since the model merely represents an approximation of the real process, thorough analysis of modeling errors is indispensable to develop a reliable controller. To enhance the control quality of the Smith Predictor, filters are often employed, as depicted in Figure 3 [15]. A filtered Smith Predictor is an extended version of the conventional predictor circuit aimed at optimizing control quality in control loops. Various filtering techniques are integrated to reduce disturbances and enable more accurate prediction of process variables. Typically, low pass filters, band pass filters, or Kalman filters are used, depending on the specific system requirements and the nature of disturbances. These filters help eliminate noise, minimize signal distortions, and increase the robustness of the control loop [16].

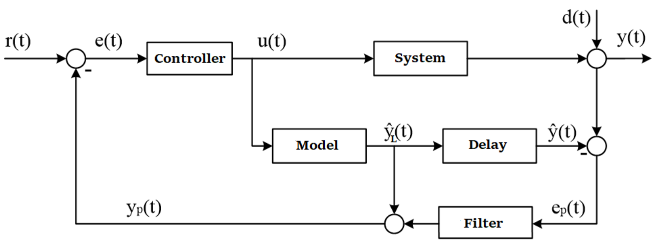

Fig. 3: Block diagram of the filtered Smith Predictor (FSP)

Dead time errors pose a significant challenge to the stability of the Smith Predictor. Thorough analysis of the block diagram of the Smith Predictor in Figure 3 illustrates that when considering dead time errors, periodic differences between actual and predicted outputs are fed back to the controller. These errors can jeopardize the stability of the closed-loop system [2], [17]. A practical solution to this problem is implementing a low-pass filter. The filter should be designed to effectively suppress oscillations in the system output [18].

Table 2: Smith Predictor and filtered Smith Predictor controllers

	SP	FSP	SP 10% error	FSP 10% error	SP 15% error	FSP 15% error
IAE	49.8	49.79	55.5	53.7	66.1	56

The results from Table 2 suggest a general conclusion that using a filtered Smith Predictor provides significantly better results in terms of setpoint tracking and sensitivity to modeling errors. However, it is noted that this does not necessarily lead to optimization of disturbance rejection and control time.

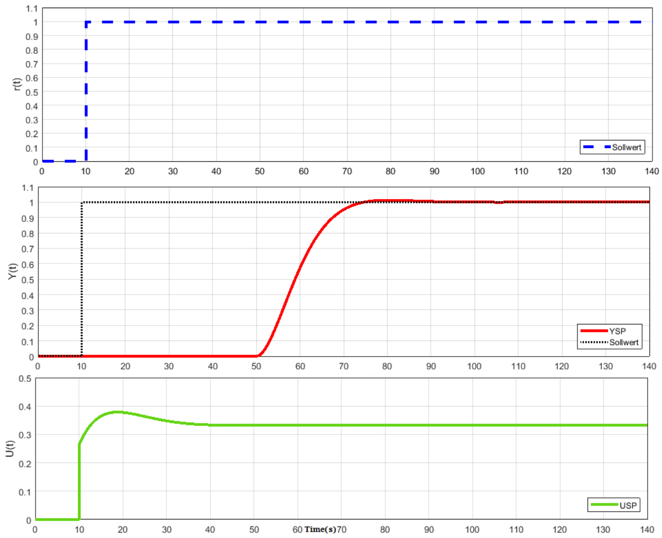

Fig. 4: Smith Predictor Simulation

Figure 4 illustrates that by continuously adjusting the manipulated variables and accurately predicting future system states, the Smith Predictor enhances control quality and ensures effective system control. Thus, the Smith Predictor proves to be an efficient dead time compensator for processes with long dead times. The control algorithm of a Smith Predictor typically involves a PI or PID controller, which is also prediction based. A comparison between the performance of the classical controller and the Smith Predictor for processes with long dead times shows that the Smith Predictor achieves the best results. The Smith structure eliminates the influence of dead time on the setpoint response, allowing for a balanced compromise between robustness and performance through appropriate controller tuning.

4 Generalized Model Predictor Control

Single Input Single Output (SISO) process models can be described using Equation 6 with backward shift for the process output.

$$\begin{aligned} y(k) &= P(z^{-1})u(k-1) \\ &= z^{-d}\frac{B(z^{-1})}{A(z^{-1})}u(k-1) \end{aligned} \tag{6}$$

where u(k) and y(k) represent the control signal and the model output, respectively, d is the time delay, and [11].

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + \ldots + a_{n_a} z^{-n_a} \\ B(z^{-1}) &= b_0 + b_1 z^{-1} + \ldots + b_{n_b} z^{-n_b} \end{aligned} \quad (7)$$

The selection of the model process used to represent deviations is crucial. A widely used model is the Controlled Auto Regressive and Integrated Moving Average (CARIMA) model. With the CARIMA model (Equation 7), Generalized Predictive Control (GPC) provides a deviation free response as it considers both variable and constant future setpoints. However, recursion of the Diophantine equation is required for prediction [19]. Proper selection of the prediction and control horizon as well as weighting leads to optimal performance [20].

The difference between the measured and calculated model output is defined as [21]:

$$\delta(k) = \frac{C(z^{-1})}{D(z^{-1})} e(k) \quad (8)$$

where the polynomial $D(z^{-1})$ 1contains the integrator, e(k) represents white noise with zero mean, and the polynomial $C(z^{-1})$ is typically considered as one [22], [23]:

$$\begin{aligned} \hat{y}(k) &= y(k) + \delta(k) \\ &= z^{-d} \frac{B(z^{-1})}{A(z^{-1})} u(k-1) + \delta(k) \\ &= z^{-d} \frac{B(z^{-1})}{A(z^{-1})} u(k-1) + \frac{C(z^{-1})}{D(z^{-1})} e(k) \end{aligned} \quad (9)$$

With

$$\begin{aligned} C(z^{-1}) &= 1 + c_1 z^{-1} + \ldots + c_{n_c} z^{-n_c} = 1 \\ D(z^{-1}) &= \Delta A(z^{-1}) \\ \Delta &= 1 - z^{-1} \end{aligned} \quad (10)$$

The disturbance signal e(k) can be either a deterministic or a stochastic signal, but due to the Δ operator, its mean is assumed to be zero [24]. This leads to:

$$\begin{aligned} \hat{y}(k) &= z^{-d} \frac{B(z^{-1})}{A(z^{-1})} u(k-1) + \\ & \quad \frac{C(z^{-1})}{\Delta A(z^{-1})} e(k) \\ \Delta A(z^{-1}) \hat{y}(k) &= z^{-d} B(z^{-1}) \Delta u(k-1) + \\ & \quad C(z^{-1}) e(k) \end{aligned} \quad (11)$$

Generalized Predictive Control (GPC) employs a matrix approach, minimizing the cost function in Equation 12. It is crucial to note that the prediction horizon should be at least as large as the system's dead time to adequately consider delays. Often, it is even chosen larger to provide additional safety and compensate for potential model errors [25].

$$\begin{aligned} min \quad J &= \sum_{j=H_1}^{H_2} [\hat{y}(k+j|k) - r(k+j)]^2 + \\ & \quad \sum_{j=1}^{H_c} \lambda_j \Delta u(k+j-1|k)]^2 \end{aligned} \quad (12)$$

From this, the analytical solution follows:

$$\Delta u = (G^T G + \lambda I)^{-1} G^T (r - f) \quad (13)$$

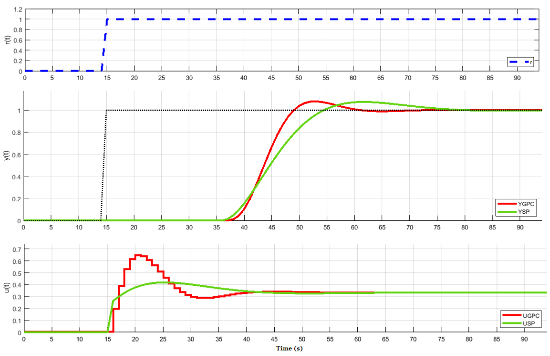

Fig. 5: Smith Predictor and GPC Simulation

The various control structures developed in this paper are now comprehensively simulated to compare and evaluate their performance. One of these control methods is the Smith Predictor, complementing the PI controller and achieving notable improvement. Additionally, a Generalized Predictive Control (GPC) has been implemented. Simulation results clearly demonstrate that GPC exhibits higher control quality, as shown both in Figure 5 and the results in Table 3. Furthermore, it responds more effectively to disturbances and setpoint changes, and compared to other control algorithms, it has the shortest settling time.

Table 3: Integral Absolute Error for GPC and Smith Predictor

	SP	GPC
IAE	43,71	49.79
IAE_s	64.6	53,78

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5 Networked Control Systems

The significant advancements in network technology and data communication have propelled the importance of networked and real time capable control and regulation applications. Among these applications are teleoperations, remote controlled mobile robots, and factory automation, all facilitated by interconnections between control systems via network resources [26]. This trend is further reinforced by the practical and systematic maintenance capabilities of network applications within the industry [27]. A notable modern industrial application is the networked control system (NCS), which enables a multitude of applications by seamlessly connecting all sensors, actuators, and controllers through networks [28].

Fig. 6: Representation of a networked control system with B&R controllers.

The communication system used is depicted in Figure 6. The PLCs are connected via access point modules, which act as bridges and routers, establishing the wireless network. The access point receives commands, forwards them to the respective PLC terminal, and then sends back the data.

5.1 Analysis and Implementation

The use of network technologies enables easy maintenance and scalability of the control system, but it also leads to issues such as delays, data losses, and packet collisions [29]. Another problem is that the NCS performance can become unstable due to the stochastic nature of network delay. Therefore, it is challenging to directly apply linear analysis of systems with delay and time. The network induced overall delay, both in the control system and in the drive, can significantly affect NCS performance [30]. The following Figure 7 illustrates the relationships and provides a visual representation of the problem.

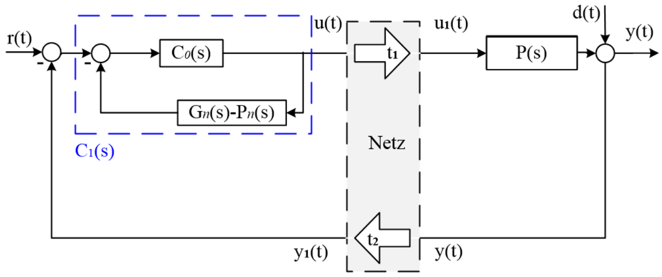

Fig. 7: Networked System

Now, the Smith Predictor and Generalized Predictive Controller (GPC) are implemented in Automation Studio™ and transferred to the controller, establishing communication between the server and client. Simulations are conducted in two steps or simulation conditions. The data is exported from Automation Studio and represented and evaluated in Matlab ®.

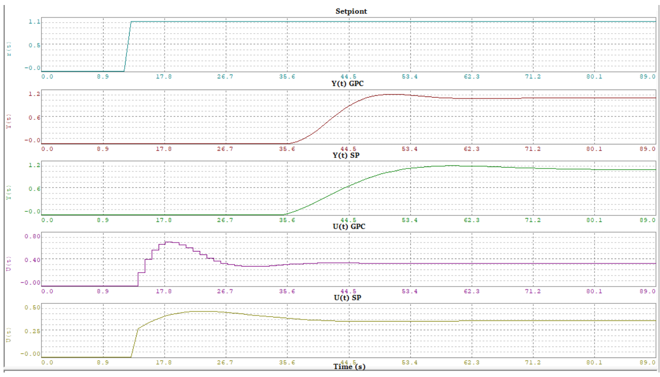

Fig. 8: Comparing Networked Systems

The analysis of Figure 8 illustrates that both the Smith Predictor and GPC control systems achieve the setpoint within a reasonable time and without overshooting. Even with disturbances introduced at the output, both controllers can fully compensate for and suppress deviations. However, it is observed that compared to the Smith Predictor, the GPC exhibits superior control quality, resulting in shorter control times, lower IAE values, and more efficient disturbance suppression.
In the second simulation (Figure 9), disturbances are added to assess the system's time delay compensation. The goal is to evaluate the system's time delay compensation.

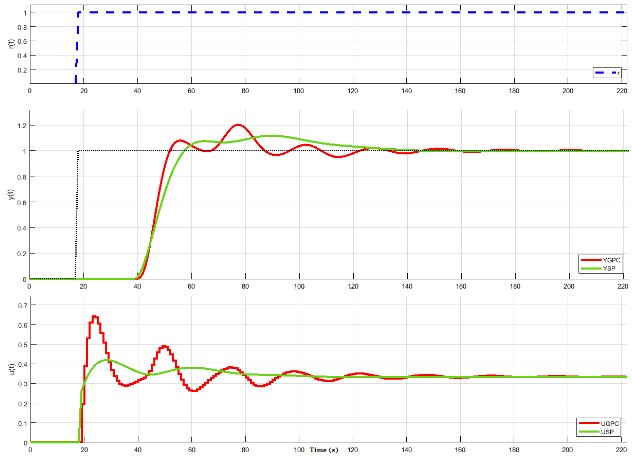

Fig. 9: Comparing Networked Systems with Delay

The uncertainty of the time delay in this case shows that the Smith Predictor exhibits stable behavior, which is not the case for the GPC. Variation in the time delay leads to system instability with the GPC, although it showed better control performance than the Smith Predictor in the case of constant time delay. This indicates that the GPC is sensitive to time delay uncertainties, and its robustness is clearly dependent on the time delay.

When communicating over networks, additional time delays can occur, significantly influencing the system's behavior. This is because the sender attempts to transmit a packet with constantly updated information after each cycle. The receiver, in turn, checks its input queue for newly received information after each cycle. If no new packet is received, the previous information is used. Thus, there is a deviation between the current and the used system information. Figure 10 depicts such a networked control system using the Smith Predictor.

5.2 Approach for Time Delay Compensation

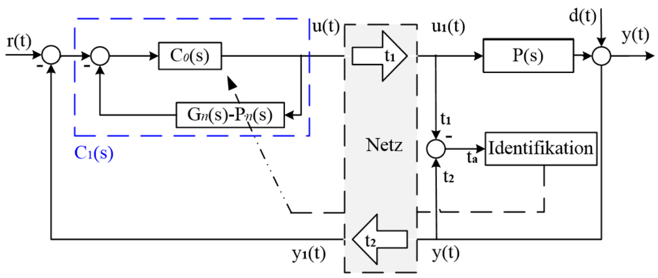

Fig. 10: Adaptive Smith Predictor

As a solution, time delay detection (online delay estimation) can be used with an adaptive Smith Predictor, where delays between the sender and the target system are identified through continuous monitoring. The gathered information can be utilized for adjustment and improvement of prediction.

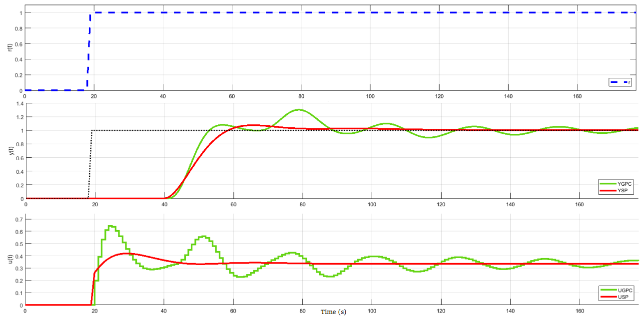

Fig. 11: Adaptive Smith Predictor in Matlab®

In a real network, network induced delays and packet losses depend on the current network load, which in turn is influenced by factors such as message size, data rate, transmission medium, and network cable length. This paper demonstrates that time delays in the communication of a networked control system impair performance and can lead to instability. An effective solution for highly delayed control systems is the adaptive Smith Predictor (Figure 11). This approach is based on the analysis of network information to enhance the performance and stability of the system. The adaptive Smith Predictor can utilize network information to adjust and optimize the prediction delay accordingly.

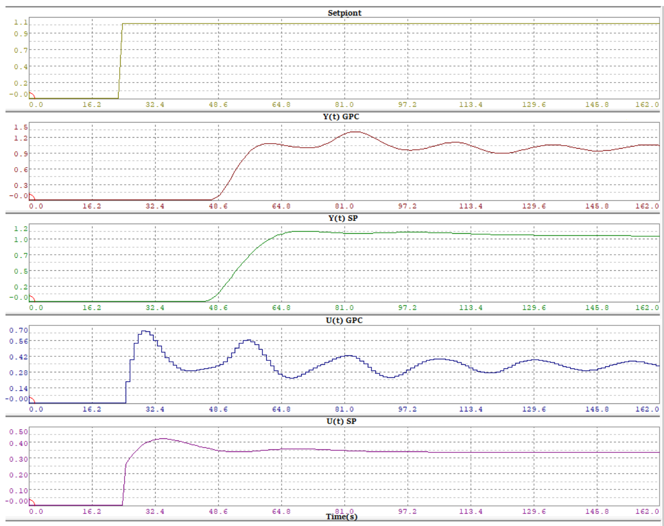

Fig. 12: Adaptive Smith Predictors for PLC Control

6 Conclusion

This paper concludes that control systems with dominant delays can only be controlled to a limited extent by simple feedback controllers. For high performance or large relative dead times, a predictive control strategy is required. For this purpose, a Smith Predictor and a GPC were developed. The Smith Predictor acts as an effective dead time compensator for processes with long dead times, providing excellent prediction and compensation capabilities. A comparison between classical controller and Smith Predictor demonstrates the superiority of the latter for long dead times. Furthermore, the GPC surpasses both the Smith Predictor and the classical controller in terms of control quality and disturbance rejection, owing to its precise output prediction and optimized control. The implementation of both approaches in networked PLC controllers, as depicted in Figure 12, shows that the Smith Predictor exhibits stable behavior with varying dead times. To enhance its stability and performance with highly varying delays, an adaptive Smith Predictor was developed, which evaluates network information and adjusts the prediction delay accordingly. Within this framework, the adaptive Smith Predictor yielded significant control quality.

References:

[1] CHAU, Pao C. Process control: a first course with MATLAB. Cambridge University Press, 2002.

[2] Julio Elias Normey Rico and Eduardo F Camacho. Control of dead time processes, volume 462. Springer, 2007.

[3] Julio E Normey Rico and Eduardo F Camacho. Dead time compensators: A survey. Control engineering practice, 16(4):407–428, 2008.

[4] Emilia Fridman. Introduction to time delay systems: Analysis and control. Springer, 2014.

[5] Thiago Alves Lima. Contributions to the control of input saturated systems: time delay and allocation function cases. 2021.

[6] Mihai Huzmezan, William A Gough, Guy A Dumont, and Sava Kovac. Time delay integrating systems: a challenge for process control industries. a practical solution. Control Engineering Practice, 10(10):1153–1161, 2002.

[7] Julio E Normey Rico, C Bordons, and Eduardo F Camacho. Improving the robustness of dead time compensating pi controllers. Control Engineering Practice, 5(6):801–810, 1997.

[8] Julio E Normey Rico, Juan Gomez Ortega, and Eduardo F Camacho. A smith predictorbased generalised predictive controller for mobile robot path tracking. Control Engineering Practice, 7(6):729–740, 1999.

[9] Saverio Mascolo. Modeling the internet congestion control using a smith controller with input shaping. Control engineering practice, 14(4):425–435, 2006.

[10] Aidan O'Dwyer. Pid compensation of time delayed processes: a survey. 2000.

[11] Magno Prudêncio de Almeida Filho. Contributions on model based controllers applied to dead time systems. 2020.

[12] Schwarz M.H., Börcsök J., 2017: Digital Controller Design Using A Reliable Code Generation Framework. 3rd Workshop & SymposiumSafety and Integrity Management of Operations in Harsh Environments, C-RISE3, October 18-20, 2017, St. John's, NL, Canada.

[13] Rawlings, J. B., Mayne, D. Q., & Diehl, M. (2017). Model predictive control: theory, computation, and design (Vol. 2). Madison, WI: Nob Hill Publishing.

[14] Seborg, D. E., Edgar, T. F., Mellichamp, D. A., & Doyle III, F. J. (2016). Process dynamics and control. John Wiley & Sons.

[15] Sun, X., Cai, Y., Wang, S., Xu, X., & Chen, L. (2019). Optimal control of intelligent vehicle longitudinal dynamics via hybrid model predictive control. Robotics and Autonomous Systems, 112, 190-200.

[16] Rossiter, J. Anthony. Model based predictive control: a practical approach. CRC press, 2017.

[17] Ogata, Katsuhiko. "Control systems analysis in state space." Modern Control Engineering. Pearson Education, Inc., 2010. 648-721.

[18] ROCA, Lidia, et al. Filtered Smith predictor with feedback linearization and constraints handling applied to a solar collector field. Solar Energy, 2011, 85. Jg., Nr. 5, S. 1056-1067.

[19] ZHANG, Wei; LIU, Bin; FANG, Kangling. A Fast GPC Algorithm with Output Penalty. In: 2008 First International Conference on Intelligent Networks and Intelligent Systems. IEEE, 2008. S. 425-428.

[20] KS Holkar and Laxman M Waghmare. An overview of model predictive control. International Journal of control and automation, 3(4):47–63, 2010.

[21] Sadhana Chidrawar and Balasaheb Patre. Generalized predictive control and neural generalized predictive control. Leonardo journal of sciences, 7(13):133–152, 2008.

[22] Eduardo F Camacho and C Bordons. Model predictive controllers. In Model Predictive control, pages 13–30. Springer, 2007.

[23] Eduardo F Camacho and Carlos Bordons Alba. Model predictive control. Springer science & business media, 2013.

[24] Robert R Bitmead, Michel Gevers, and Vincent Wertz. Adaptive optimal control the thinking man's gpc. 1990.

[25] Kuo, Benjamin C., and M. Farid Golnaraghi. Automatic control systems. Vol. 8. Englewood Cliffs, NJ: Prentice hall, 1995.

[26] Chien-Liang Lai and Pau-Lo Hsu. Design the remote control system with the time delay estimator and the adaptive smith predictor. IEEE Transactions on Industrial Informatics, 6(1):73–80, 2009.

[27] Feng-Li Lian, James R Moyne, and Dawn M Tilbury. Performance evaluation of control networks: Ethernet, controlnet, and devicenet. IEEE control systems magazine, 21(1):66–83, 2001.

[28] Jan Lunze. Regelungstechnik 2: Mehrgrößensysteme, Digitale Regelung. Springer- Verlag, 2014.

[29] KREDO II, Kurtis; MOHAPATRA, Prasant. Medium access control in wireless sensor networks. Computer networks, 2007, 51. Jg., Nr. 4, S. 961-994.

[30] Dan Zhang, Peng Shi, Qing-Guo Wang, and Li Yu. Analysis and synthesis of networked control systems: A survey of recent advances and challenges. ISA transactions, 66:376– 392, 2017.

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