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# Model-free and time-constant prediction for closed-loop systems with time delay

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ABSTRACT

This study presents a model-free method of signal prediction dedicated to closed-loop systems affected by time delay. The proposed prediction method leads to better prediction results than the Smith Predictor for relatively small delays. Moreover, the solution is dedicated to complex systems, which are susceptible to differences between the system and its model. The theoretical analysis, experiments, and comparisons performed in this study confirmed these features. This paper presents simplifications that were conducted to obtain the Prediction Block directly from the Smith Predictor control scheme. The Prediction Block, under specific conditions, allows for signal prediction with a constant time value. The Prediction Block was compared with an ideal anticipatory object. Furthermore, the Smith Predictor control scheme was compared with the proposed method. In this case, the transport-delay value in the closed-loop system is the only information required for proper prediction. An adapted Nyquist criterion that can prove the asymptotic stability of the control scheme was proposed. The theoretical part of the paper was supported by experiments performed on an experimental test stand with a hydraulic manipulator. In the experiments, the Prediction Block improved the position tracking of the system. The prediction control scheme has already demonstrated widespread potential for applications in multiple control approaches and experiments. The solution is dedicated to complex systems that are susceptible to differences between the system and its model.

## 1. Introduction

Currently, problems of closed-loop systems affected by time-delay phenomena are addressed by many scientific papers. The Smith Predictor is one of the most popular approaches for minimising the constant transport delay in closed-loop systems and was proposed in 1957 by Smith (1957). After this publication, the approach focused on the elimination of the time-delay component from the control scheme was strongly improved and developed.

From recent literature, it is possible to find solutions related to the internal model control approach and its developments. An internal partitioned model control method for nonlinear systems that is described by the just-in-time learning technique was proposed by Kalmukale, Chiu, and Wang (2007). The control scheme consists of a conventional internal model controller that is augmented by an assistant loop to include nonlinearities in the system. In the study, simulation results showed that the control strategy tracked the reference trajectory more effectively than the conventional internal model-based control scheme (Kalmukale et al., 2007). In 2007, Yi-Da Chen et al. modified the Smith Predictor for linear systems with time delays by adding a disturbance reduction part. The new approach consisted of a proportional–integral (PI) controller incorporated with a disturbance reduction part of the control. Thus, the control unit could successfully reduce the step and cyclic disturbances in the system (Chen, Tung, & Fuh, 2007). In 2009, R.S. Sánchez-Peña et al. continued analysis and extended the Smith Predictor structure to multiple-input and multiple-output (MIMO) systems with unknown delay. The new approach was applied to models that could be factorised by rational models in a series connection with delay diagonal matrices (Sánchez-Pena, Bolea, & Puig, 2009). Furthermore, V. Feliu-Batlle introduced a new design method for fractional integral controllers merged with Smith Predictors. This change resulted in robust operation despite high-frequency model changes. These controllers are characterised by a lower sensitivity than basic PI/PI–derivative (PID) controllers owing to the high-frequency noise and disturbance (Feliu-Batlle, Pérez, García, & Rodriguez, 2009). In 2012, M.R. Mataušek and A.I. Ribić presented a modified Smith Predictor control scheme that was classified as a compensator for the dead time in integrating

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processes. In the paper, the authors showed that the control scheme consisted of a PID controller connected to a second-order filter that could be defined by the dead time and its parameters. The control-scheme implementation led to a performance increase and a robustness tradeoff and even guaranteed fast set-point step responses for stable, integrating, and unstable processes, which were affected by the dead time (Mataušek & Ribić, 2012). However, the key proposed modification to the entire Smith Predictor was presented by Chen, Zouaoui, and Chen (2013). In the paper, a control-scheme design to handle process control characterised by uncertainties induced by disturbance loads, model errors, and time-varying parameters was proposed. The new control scheme implemented the backpropagation neural network. In this case, the predictive control replaced the Smith predictor and was initially trained offline. According to the results obtained from simulations, the neural network was characterised by robustness according to disturbances and model errors (Chen et al., 2013). Then, in 2014, T.L.M. Santos et al. presented a paper addressing a filtered Smith predictor with a unified implementation structure for MIMO processes with dead time. The authors showed via simulation that the proposed approach could be applied to control unstable processes in the open-loop control scheme that is affected by multiple dead times. This was achieved by considering a model without any input/output or internal coupling delays (Santos, Flesch, & Normey-Rico, 2014). In 2016, a related paper was published by C. Rodríguez et al. In this case, the filtered single-input and single-output Smith Predictor was dedicated to processes with measurable disturbance. The controller provided a framework that was focused on industrial processes (Rodríguez, Normey-Rico, Guzmán, & Berenguel, 2016). In 2017, G.L. Raja and A. Ali presented a cascade controller in a parallel scheme equipped with the Smith Predictor dedicated to open-loop, unstable, and integrating process models with relatively large time delays. The proposed tuning strategy yielded to robustness and improved the closed-loop performance. Moreover, the new control scheme stabilised unstable process models (Raja & Ali, 2017).

In all cases, the Smith Predictor is supported by a model of the system affected by the transport delay. Unfortunately, this feature leads to a problem of complex system modelling and achieving high levels of similarity between the object and the model that describes it (Kaya, 2003). Thus, an alternative solution exists, which was proposed by R.E. Kalman in 1960 and later called the Kalman filter. The filter was proposed to overcome the problems of random signal prediction and linear filtration, and it has been used as one of the advanced control methods for coping with modern engineering problems. To these examples, the state estimations that were implemented in the fusion Kalman filter for systems with an irregular rate and delayed measurements can be added (Fatehi & Huang, 2017). Furthermore, a basic nonlinear model could be easily implemented in the Kalman filter to perform the effective real-time state estimation of glucose, ethanol, and the cell dry weight (Krämer & King, 2017). In all cases, however, the approach requires knowledge about the measured signal noise distribution and its parameters. Moreover, for proper operation, the Kalman filter requires a process model and its statistical description (Kalman, 1960).

To deal with aforementioned problems, a sliding-mode control method dedicated to closed-loop control was proposed (Utkin, 1993). The sliding-mode control approach is based on discontinuous control laws and has become a very effective control scheme for coping with problems of robust stabilisation. However, the combination of the transport delay with discontinuous control laws makes the system more complex. Thus, it may lead to an unstable behaviour when the delay is not taken into account (Gouaisbaut, Dambrine, & Richard, 2002). Moreover, this approach requires a very accurate model of the process to control. Despite these disadvantages, the sliding-mode control approach is widely used in modern engineering problems, such as the interval sliding-mode observer design method for uncertain systems (Oubabas, Djennoune, & Bettayeb, 2018) or the Luenberger-sliding mode observer-based fuzzy double loop integral sliding-mode controller for electronic throttle valve control (Yang, Liu, Kim, & Cui, 2018).

This study suggests a model-free method of signal prediction dedicated to a low-frequency spectrum in closed-loop systems. The proposed solution does not require information about the model of the process without the transport delay, its distribution (this is why it is called model-free), or the distribution of noise in the signal or its statistical parameters. It is based only on the model of the transport delay. The proposed prediction method leads to better prediction results than the Smith Predictor for relatively small delays. In this case, the transport-delay value in the closed-loop system is the only information that is required. Nevertheless, the transport delay must be considered as a constant or at least described by a very low standard deviation during system operation.

The prediction control scheme has demonstrated widespread potential for applications in multiple control approaches and experiments. The solution is dedicated to complex systems that are susceptible to differences between the system and its model (Okulski & Ławryńczuk, 2018; Oprzędkiewicz & Dziedzic, 2018). This feature allowed it to be used in teleoperation, such as (i) inverse model-supported systems and their identification (Saków, Parus, Pajor, & Miądlicki, 2017); (ii) prediction in communication channels of unilateral teleoperation system-controlled motion scanners (Sakow, Parus, Pajor, & Miadlicki, 2017); (iii) inverse modelling comparison via a lead–lag approach (Saków & Miądlicki, 2018); (iv) to simplify the model structure in inverse model-supported systems (Sakow, Marchelek, Parus, Pajor, & Miadlicki, 2018); (v) to minimise the time-delay effect in the bilateral teleoperation system with force-feedback (Rybarczyk, Owczarek, & Myszkowski, 2018); or (vi) in systems or processes that require compensation of the transport-delay component (Marchelek & Tomków, 1998; Tomków & Marchelek, 1995). However, the Prediction Block (as it was called previously) comes directly from the Smith Predictor control scheme.

This paper is arranged as follows. Section 1 provides an introduction to the problem and our contribution; Section 2 describes modifications to the Smith Predictor control scheme that were performed to obtain the proposed method; in Section 3, the frequency analysis is compared between the Prediction Block and the anticipatory object, and a comparison of the Prediction Block-based control unit with the Smith Predictor is performed; Section 4 describes the simulation of step-response analysis; in Section 5, a stability analysis of the proposed control scheme is presented; Section 6 consists of the experimental report; and the paper ends with conclusions in Section 7.

## 2. Modifying Smith Predictor closed-loop control scheme

In this section, the Smith Predictor simplifications are performed under specific conditions. Fig. 1a presents one of two basic approaches for a graphical representation of the Smith Predictor control scheme. The scheme was used to obtain the Prediction Block from the structure of the Smith Predictor.

The system contains a controller C(s), an object G(s), a transport delay $e^{-Ts}$, and models of either object and the delay placed in the feedback loop. However, the simplifications required two changes in the control scheme. First, the transport delay affecting the object was moved from the main signal route to the feedback loop. This approach allows analysis of how the control scheme affects the non-delayed output signal when it is present. Second, the transfer function of the transport delay was equalised to unity. This removed the delay from the control scheme, as shown in Fig. 1b, creating a situation where the system was forced to predict its output without the presence of the delay.

Owing to the modified control scheme from Fig. 1, there is a possibility to describe the feedback control signal f(s) with respect to a known control signal u(s). Thus, the feedback signal f(s) is described as follows:

$$\mathrm{f}(s) = \left[\mathrm{G}(s) - \tilde{\mathrm{G}}(s)\, e^{-\tilde{T}s} + \tilde{\mathrm{G}}(s)\right] \mathrm{u}(s)\,, \tag{1}$$

where s is the Laplace operator. Furthermore, if the model is considered as equal to the object $\tilde{\mathrm{G}}(s) = \mathrm{G}(s)$, Eq. (1) can be simplified as

$$\mathrm{f}(s) = \mathrm{G}(s)\left[2 - e^{-\tilde{T}s}\right] \mathrm{u}(s)\,. \tag{2}$$