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# A simple Simulink® model of a conductivity system for exploring the performance of a Smith's predictor

# Un modelo simple de Simulink® de un sistema de conductividad para explorar el desempeño de un predictor de Smith

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**Abstract**

*In this work, a simple Simulink® model of a conductivity control system, based on a Smith's predictor, is presented. This model has three main didactic outcomes. First, it allows to show to the students how a computational tool can be used to solve problems that would require a fair amount of work if they were solved analytically. Second, it allows to present an example of advanced controller: the Smith's predictor. Finally, using this model, students can "play" with the system in order to study the effect of the different system and controller parameters on the performance of the controlled system.*

*En este trabajo se presenta un modelo sencillo de Simulink® de un sistema de control de conductividad, basado en un predictor de Smith. Este modelo tiene tres objetivos didácticos principales. En primer lugar, permite mostrar a los estudiantes cómo se puede usar una herramienta computacional para resolver problemas que requerirían una cantidad considerable de trabajo si se resolvieran analíticamente. En segundo lugar, permite presentar un ejemplo de controlador avanzado: el predictor de Smith. En último lugar, empleando este modelo los estudiantes pueden "jugar" con el sistema para estudiar el efecto de los diferentes parámetros del sistema y del controlador sobre el desempeño del sistema controlado.*

Keywords: Computer simulation, Conductivity control, PID controller, Process control, Simulink®, Smith Predictor
Palabras clave: Control de conductividad, Control de procesos, Controlador PID, Predictor de Smith, Simulación computacional, Simulink®

# 1. Introduction

Process dynamics and process control are important topics of today's chemical engineering undergraduate curricula (Edgar et al., 2006). In general, a purely theoretical approach is selected to teach these subjects. This approach involves high levels of abstract mathematical concepts, and very little hands-on work (Astrom and Ostberg, 1986). Its major drawback is the fact that students do not get a practical view of the different explained concepts. In many cases, this results in demotivated students that do not see any practical utility to the subject, and therefore, that will not extract from the course any relevant knowledge for their future career (Ambrose et al., 2010). Laboratory projects are a possible solution to this issue (Johansson et al., 1999). However, laboratory practices require a substantial amount of resources, and can only be implemented with fairly small groups of students. This makes the implementation of laboratory projects very difficult in nowadays Spanish Universities, in which the number of students in each class is increasing, and the amount of resources is decreasing (Hernández-Armenteros and Pérez-García, 2018). Computer practices are a great alternative (Salmerón-Manzano and Manzano-Agugliaro, 2018), since computer rooms are ubiquitous in today's Spanish university network (Hernández-Armenteros and Pérez-García, 2018).

In this work, a simple Simulink® model of a conductivity control system is presented in order to illustrate the concept of Smith's predictors. Two types of controllers were considered in the model: a conventional PI controller and a PI controller coupled with a Smith's predictor. The Simulink® model allows to obtain the simulated time-evolution of the output variable for a set-point change (i.e. servo mode) and/or a perturbation (i.e. regulation mode). The time-evolution curve of the output variable can then be used to obtain parameters that quantify the performance of the controlled system; such as the off-set, the response time, the settlement time and the over-shooting, amongst others. The students can easily visualize the great enhancement (with respect to a traditional PID controller) on the control performance when an ideal Smith's predictor is implemented. Moreover, the students can readily study the effect of the error in the estimation of the parameters of the system (i.e. non-ideal Smith's predictor) on the control performance indicators by simply repeating the simulation for different values of the predictor's parameters.

# 2. The conductivity system

The conductivity system consists of a constant volume chemical continuous stirred tank reactor fed with a constant flow rate stream of water, and a variable flow rate stream of hydrochloric acid. The controlled variable is the conductivity of the solution inside the reactor ($\kappa$), while the manipulated variable is the acid flow rate ($Q_a$). Figure 1 shows a sketch of the aforementioned system. The system was shown theoretically to behave as a first order system with time delay, and its dynamic parameters were obtained experimentally using an analogue experimental setup (Giner-Sanz et al., 2018). Table 1 sums up the dynamical parameters of the conductivity system in given operation conditions (since the system is a non-linear system). As it can be observed, the conductivity system presents a rather high time delay ($b$); and therefore it is a perfect example to illustrate the application of Smith's predictor, also known as time delay corrector.

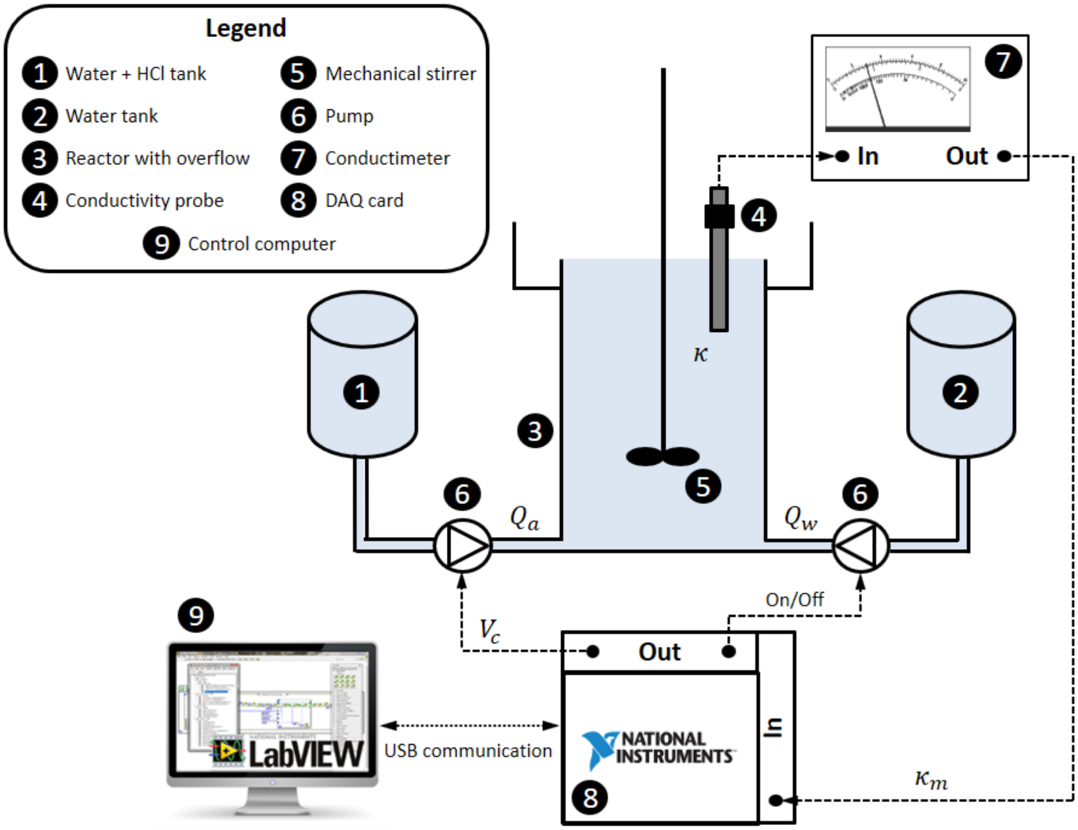


Figure 1: Conductivity system

| Parameter | Value |
|---|---|
| $K$ | $0.2\ mS \cdot cm^{-1} \cdot hr \cdot L^{-1}$ |
| $\tau$ | $1.6\ min$ |
| $b$ | $5\ min$ |

Table 1: Dynamic parameters of the conductivity system

## 3. The Simulink® model

Figures 2 and 3 display the implemented Simulink® model for the case of a traditional PI controller (Figure 2), and the case of a PI controller coupled with a Smith's predictor (Figure 3). Both of them model the conductivity system as a first order transfer function with time delay; the conductimeter as an ideal instrument (i.e. infinitively fast and accurate); and the pump as a pure gain element (i.e. negligible dynamics) with saturation (i.e. the flow rate delivered by the pump has physical limits).

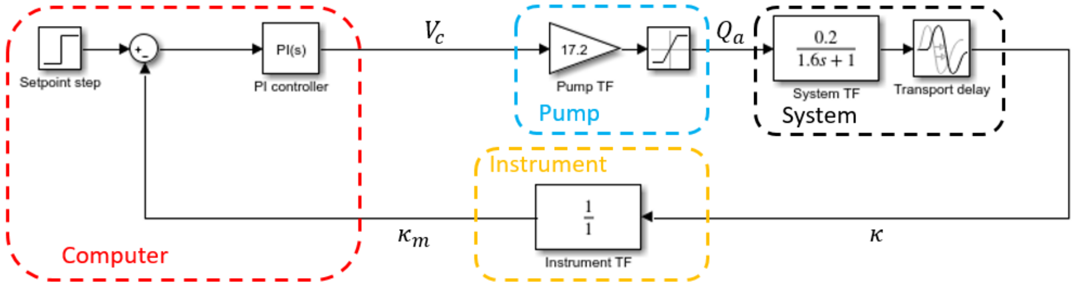


Figure 2: Simulink® model of the conductivity control system based on a PID controller

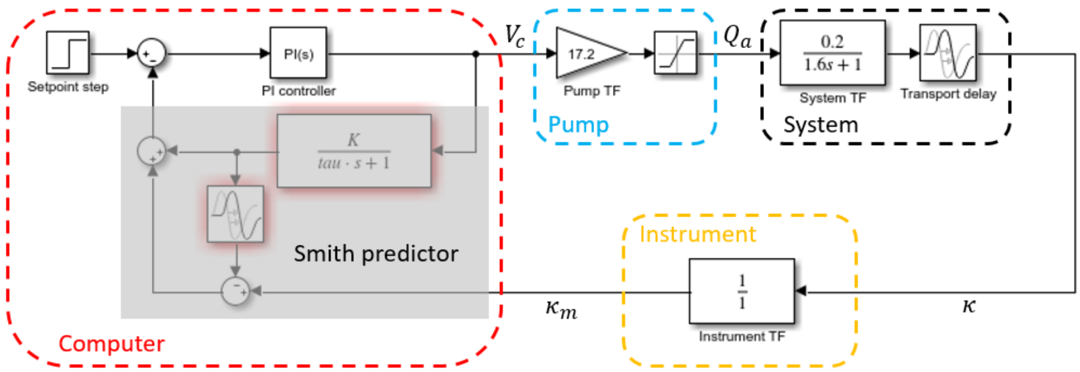


Figure 3: Simulink® model of the conductivity control system based on a PID controller coupled with a Smith's predictor

## 4. Results and discussion

All the results presented in this section were obtained considering a PI controller of gain $K_c = 0.1\ V \cdot cm \cdot mS^{-1}$ and integral time $\tau_1 = 0.2\ min$ ; and a unity step change in the set-point (i.e. servo mode).

On the one hand, Figure 4 compares the time evolution of the controlled variable (in deviation units) of the conductivity system controlled by a traditional PI controller and the conductivity system controlled by a traditional PI controller coupled with an ideal Smith's predictor (i.e. no error in the system's parameters). With this simulation students can visualize the effectiveness of Smith's predictor to correct the effect of large time delays: whereas the traditional PI system is unstable because of the relatively long time delay of the conductivity system; the system with the ideal Smith's predictor is stable. Moreover, this example can be used in order to make students aware of the difference between mathematical instability and physical one (i.e. real systems are always finite).

On the other hand, Figures 5 to 7 illustrate the effect of the error in the predictor's parameters on the time evolution of the controlled variable (in deviation units) of the conductivity system controlled by a traditional PI controller coupled to a non-ideal Smith's predictor. For each predictor's parameter $(K', \tau', b')$ "5 relative errors" were considered: -10 % $(e = 0.90)$, -5 % $(e = 0.95)$, 0 % $(e = 1.00)$,+5 % $(e = 1.05)$, and +10 % $(e = 1.10)$.

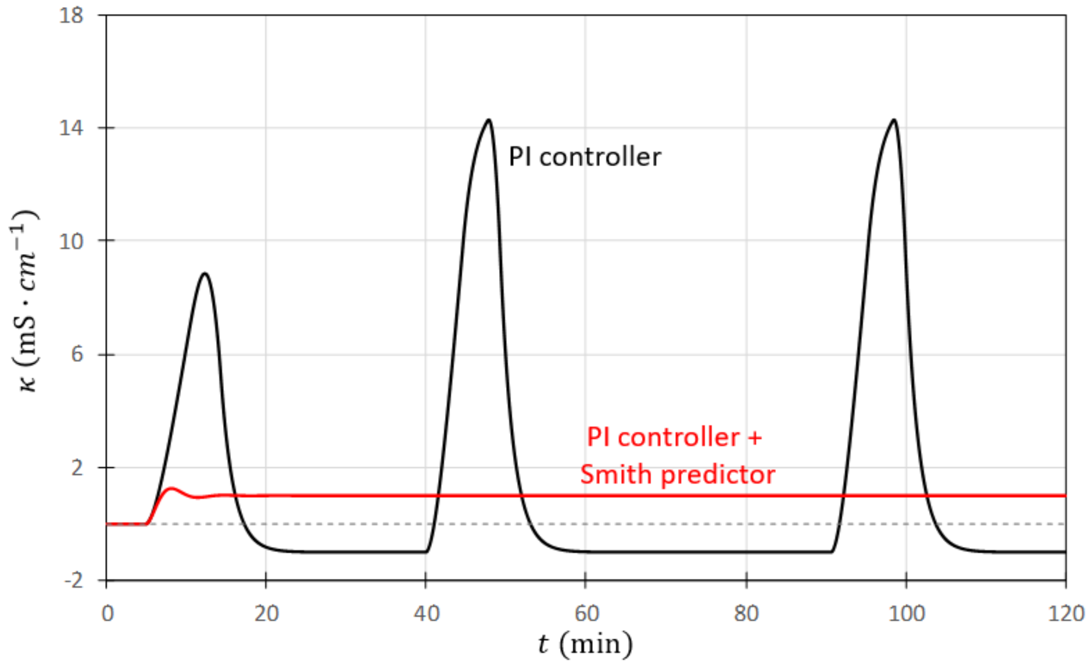


Figure 4: Comparison of the time evolution of the controlled variable (in deviation units) of a traditional PI controller versus a PI controller coupled with a Smith's predictor

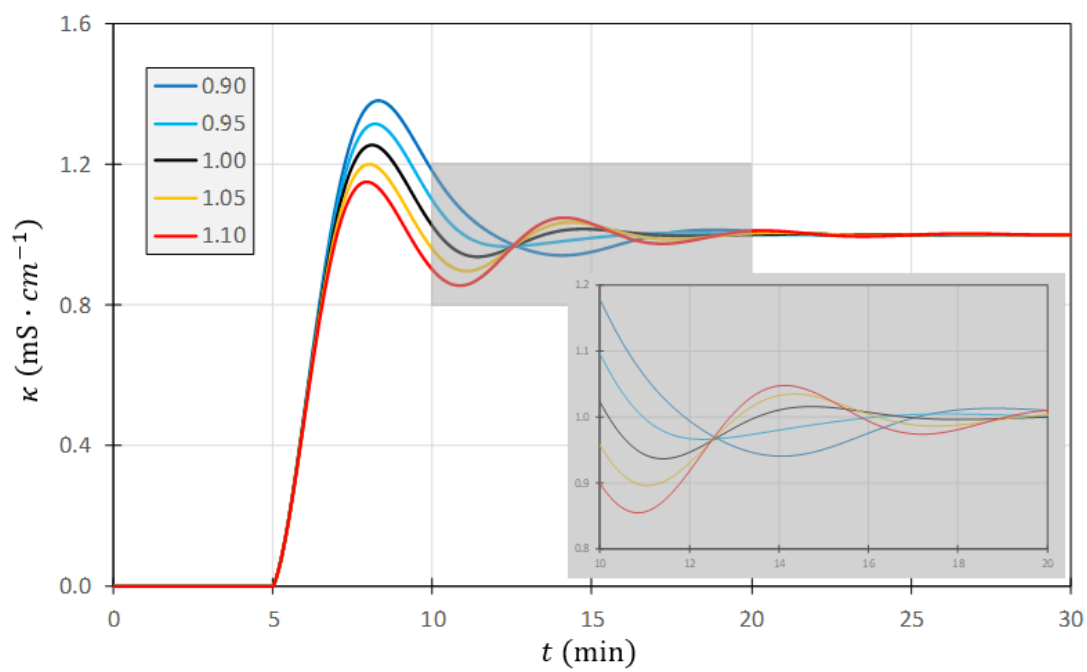


Figure 5: Effect of the error ($e$) in the gain of a non-ideal Smith's predictor ($K' = e \cdot K$) on the time evolution of the controlled variable (in deviation units)

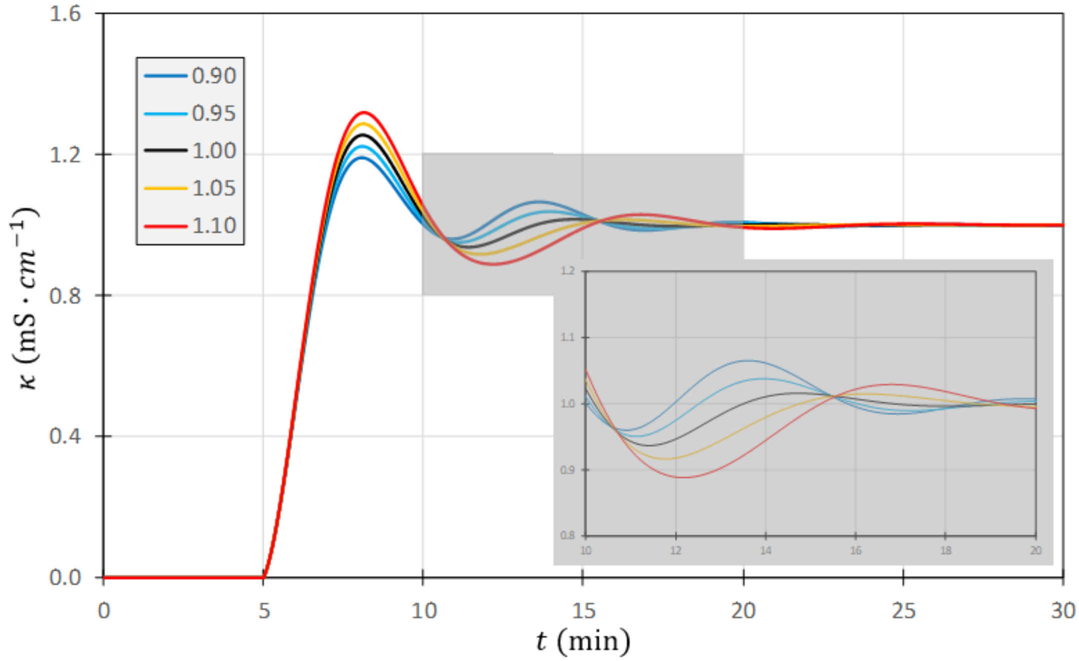


Figure 6: Effect of the error ($e$) in the time constant of a non-ideal Smith's predictor ($\tau' = e \cdot \tau$) on the time evolution of the controlled variable (in deviation units)

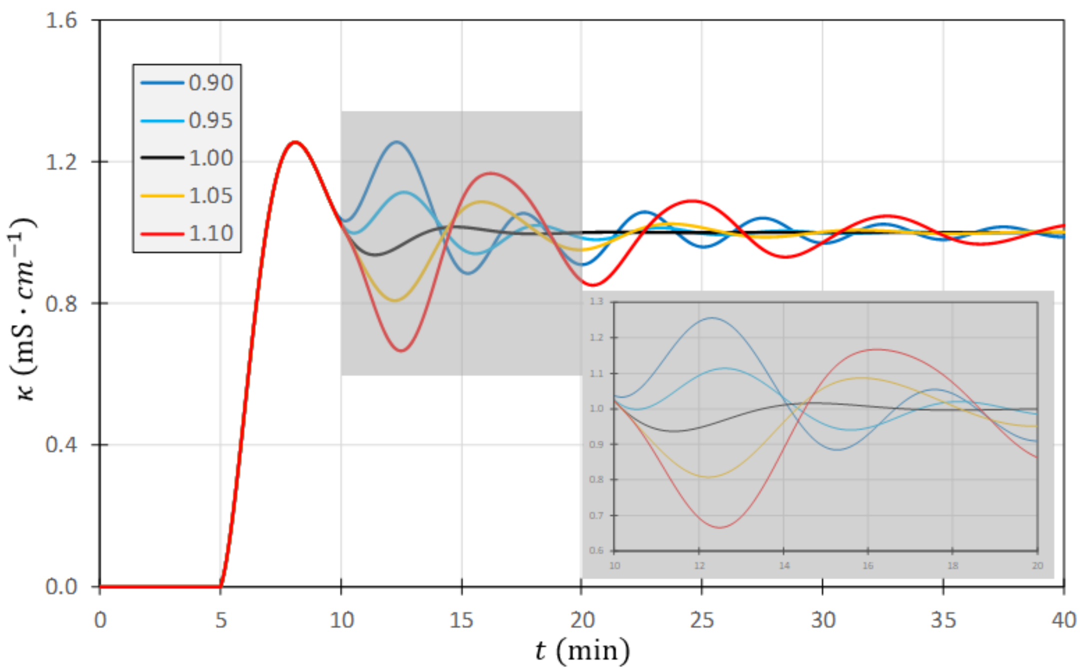


Figure 7: Effect of the error ($e$) in the time delay of a non-ideal Smith's predictor ($b' = e \cdot b$) on the time evolution of the controlled variable (in deviation units)

From these simulations, students can analyze the effect of a given relative error in each one of the predictor's parameters, on the control performance indicators of the response of the controlled variable. On the one side, students can observe in Figure 5 that errors in the gain do not affect the response time of the controlled system; but they heavily affect the overshooting of the system and slightly affect its settling time. On the other side, students can observe in Figure 6 that errors in the time constant do not affect the response time of the controlled system; and slightly affect both, the overshooting and the settling time of the system. Finally, students can observe in Figure 7 that errors in the time delay neither affect the the response time nor the overshooting of the controlled system; but they heavily effect its settling time.

By comparing the different figures, the students can visualize that the most critical parameter to estimate correctly to get a better performance Smith's predictor is the time delay of the system: errors in this parameter lead to greater degradation of the control performance. Moreover, students can observe that errors are not symmetric for any of the 3 parameters: it is not the same to overestimate by x % a given parameter, than to underestimate it by the same percentage. This can lead to suggestive in class discussions in which students should reflect (and even demonstrate mathematically) possible explanations to the aforementioned observations.

## 5. Conclusions

The proposed simple computational model has three main didactic outcomes. First, it allows to show to the students how a computational tool can be used to solve problems that would require a fair amount of work if they were done as shown in theory (i.e. by hand). Second, it allows the students to visualize and understand an example of advanced controller, the Smith's predictor. Finally, thanks to this model, students can 'play' with the system in order to study the effect of the different system and controller parameters on the performance of the controlled system. Using this tool, they can verify, and get a clear intuition, of the theoretical trends explained in the theory recitations, such as the effect of the estimation errors of the different system parameters (i.e. non-ideal Smith's predictor) on the response of the controlled system.

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## Supplementary materials

The simulator code files for use in MATLAB R2018a, are available in:
http://jmcalabu.blogs.upv.es/files/2020/01/simulinkMSELfiles.rar

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