UNIVERSITÉ FRANCHE COMTÉ

MASTER IN CONTROL FOR GREEN MECHATRONICS

AUTOMATIQUE ET ROBOTIQUE

Year one

Pratical work

Digital Control

Nahashon Osinde

2021-2022 year

26 octobre 2021

General presentation of the TP

The Digital control labs take place in room 106 B and consist of 5 four-hour sessions corresponding to the following 3 labs :

— T.P. 1 : Sampled system ;

— T.P. 2 : Modeling and control of a water level regulation model ;

— T.P. 3 : Digital control of a thermal system using a DSP card ;

The students will be divided into 4 pairs. The rotations of TP are shown in the table of FIG. 2. S_i corresponds to session i, B_i in the binomial i.

	B_1	B_2	B_3	B_4
S_1	TP 1	TP 1	TP 1	TP 1
S_2	TP 2	TP 2	TP 3	TP 3
S_3	TP 3	TP 3	TP 2	TP 2
S_4	TP 4	TP 4	TP 5	TP 5
S_5	TP 5	TP 5	TP 4	TP 4

FIGURE 2 – Table of TP rotations

Preparation should be done before each TP session [1]. The report of each TP should be sent two weeks after the TP to nahashon.osinde@femto-st.fr. The practical assessment will consist of a preparation assessment and continuous assessment during the session and an assessment on the practical report.

1. This does not mean that you have to know how to do everything in the "preparation" sections of the practical workout) but that you should at least try to do everything.

Chapitre 1

Sampled systems

1.1 Discretization

Consider the system described by its following continuous transfer function :

$$G(p) = \frac{2p+1}{p^2+2p+1} \tag{1.1}$$

Question 1.1.1 *Discretize this transfer function with a sampling period Ts = 0.1s using the* ***c2d*** *instruction. Let G_d be the discrete transfer function obtained.*

Question 1.1.2 *Visualize on the same figure the index responses of G and G_d using the* ***step*** *instruction.*

1.2 Discrete transfer function

Consider the system described by the following continuous transfer function :

$$H_d(z) = \frac{0.047z + 0.046}{z^2 - 181z + 0.9} \tag{1.2}$$

Question 1.2.1 *Use the* ***tf*** *instruction to write H_d, Rewrite H_d using the* ***zpk*** *instruction.*

Question 1.2.2 *Visualize the poles and zeros of H_d using the* ***pzmap*** *instruction.*

Question 1.2.3 *Find the poles of H_d with the* ***pole*** *instruction.*

1.3 Stability study

Let the system be described by the following sampled transfer function $Ts = 0.1\ s$:

$$H(z) = \frac{1}{(z-0.4)(z-0.8)} \tag{1.3}$$

Definition 1 (Stability of the sampled system)
A sampled linear system is stable if all the poles of its sampled transfer function are inside the unit circle of the z-plane.

Question 1.3.1 *What can you say about the stability of $H(z)$?*

Question 1.3.2 *We want to integrate $H(z)$ in a closed loop with unit return FIGURE .1.1. Calculate the new transfer function as a function of K.*

Question 1.3.3 *For $K = 1$, find using the feedback instruction, the result obtained in 2.*
Let $G(z)$ be the resulting transfer function.

Question 1.3.4 *Locate the poles of G(z) using the* ***rlocus*** *instruction.*

- *Determine the value of K that corresponds to the limit of stability of our system.*
- *Using the* ***step*** *function. Give the answer of $G(z)$.*

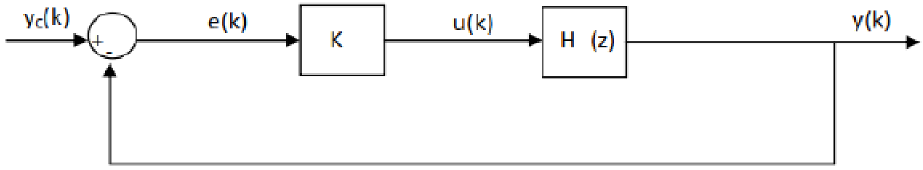

FIGURE 1.1 – Functional diagram of the closed loop system.

1.4 Influence of the sampling period on the stability

We consider the following transfer function :

$$H(p) = \frac{10}{0.1p + 1} \tag{1.4}$$

Let H_1 and H_2 be the sampled transfer functions resulting from H respectively with respect to the sampling periods, $Ts_1 = 0,1\ s$ and $Ts_2 = 0,01\ s$.
Let H_{BF_1} and H_{BF_2} be the closed-loop transfer functions resulting from the integration respectively of H_1 and H_2 in closed loop with unit return.

Question 1.4.1 *Study the stability of transfer functions H_{BF_1} and H_{BF_2}.*

Question 1.4.2 *Conclude on the stability of the looped sampling system by comparing the sampling period to the time constant of the continuous time system.*

1.5 Using SIMULINK

Consider a sampled system of the following open-loop transfer function :

$$G(z) = \frac{0.23}{z^2 - 1.37z + 0.42} \tag{1.5}$$

Question 1.5.1 *Study the stability of transfer functions H_{BF_1} and H_{BF_2}.*

Question 1.5.2 *Using only SIMULINK :*
- *Locate the poles of the closed loop transfer function of the system considering a unit feedback.*
- *Give the open loop response of $G(z)$ for a step input. What is the static error value ?*
- *Give the closed loop response of $G(z)$ for a step input and for a gain $K =$ 1.1 . What is the value of the static error overflow ?*

1.6 Position error

Consider the following transfer function :

$$G(z) = \frac{0.9z}{z - 0.9} \tag{1.6}$$

Question 1.6.1 *Graphically determine the position error of the closed loop system by considering a unit return (the system is requested at a unit level).*

Chapitre 2

Modelling and control of a water level regulation system

2.1 Goals

Very often, process control involves level regulations. They can be controlled using standard closed loop controls using PID correctors. However, the components used in these processes often have complex, non-linear behaviors, which can lead to difficult PID tuning and disappointing performance. The aim of this practical work is to study, on an educational model, the real behaviors of these components, their non-linearities and the alternatives to the classic PIDs for their closed-loop control. More specifically, the objectives of this lab will be as follows :
- identify the non-linearities of a dynamic system (type of non-linearities, etc.) ;
- understand and trace the I/O characteristics of a system ;
- (re)condition the signals/systems MISO $\rightarrow$ SISO ;
- control a non-linear system with low dynamics ;
- linearize a nonlinear system.

2.2 Preparation (to be done before the practical work)

2.2.1 Presentation of the model

The model used in this practical work corresponds to an automated system for filling and checking the water level in tanks. This consists of three tanks of different geometries, each of which can be emptied by means of a manual valve and a valve electrically controllable using a digital system (PC + input/output card). A pump, also controllable by the PC, controls the supply to the upper tank, FIGURE .2.1

Question 2.2.1 *Explain the operation of a proportional solenoid valve and give, if possible, its constitutive law, i.e. the relationship between the flow rate obtained at the outlet of the valve and its two input quantities $\Delta p(t)$ and $s(t)$. $\Delta p(t)$ is the pressure difference across the valve terminals and $s(t)$ its opening section. Its opening section $s(t)$ is a function of the valve control voltage $u(t)$, so that $s(t) = s(u(t))$.*

Question 2.2.2 *Give the relationship between the water level in a tank as a function of its filling (or emptying) rate* [1]. *Give also the relation between the height of water in this tank and the pressure at the bottom* [2].

Question 2.2.3 *What is a PID corrector and what does each of these letters mean ? Briefly recall how it works.*

2.3 Experiments (to be done during the TP session)

The model is controlled by a PCI I/O card connected to a PC. The latter is programmable and controllable by means of `Matlab Simulink`. The conversion and compilation of the block diagram is drawn under

1. This relation is linked to a law of conservation of mass.
2. This relationship is linked to Pascal's principle.

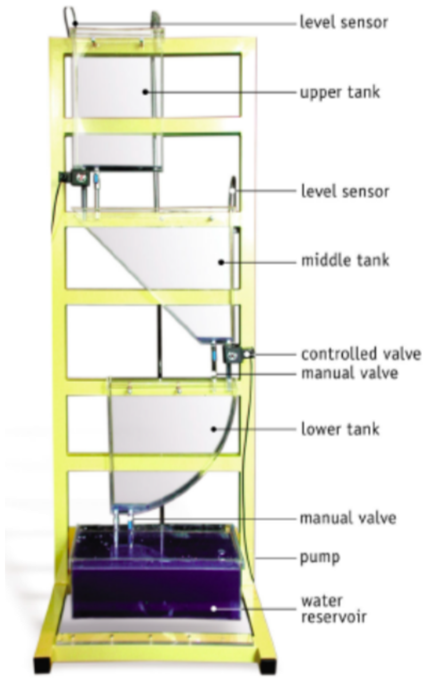

FIGURE 2.1 – Description de la maquette comportant du TP.

`Simulink` in one program. This is done using the "*Real Time Workshop*" toolbox from `Matlab`. The real-time launch and control of the C program compiled for the PC processor is carried out using the "*Real Time Windows Target*" toolbox from `Matlab`.

2.3.1 System identification and characterization

As a first step and in order to familiarize yourself with the operation of the model, the experimental identification of the behavior of some components of the model will be carried out (solenoid valve, pump, tank, sensor). Only the upper (rectangular) tank will be studied initially.

Question 2.3.1 *For different set-point values for direct pump control and keeping the upper tank drain valves closed, note the change in the water level in the tank as a function of time. Check that this behavior matches the behavior you predicted in preparing for the lab. Deduce the flow entering the tank as a function of the pump control setpoint (control / pump flow rate relationship). Calibrate the level sensor according to the measurement on the computer and the height read on the tank.*

Question 2.3.2 *Propose and carry out an experimental test making it possible to determine the law of behavior of the controllable drain valve (flow rate / pressure difference relation according to its control instruction).*

Question 2.3.3 *Show that the filling/emptying control behavior of the upper tank has significant non-linearities (dead zones, saturations, filling/emptying heterogeneity). Draw on a graph this control characteristic.*

2.3.2 Implementation of level regulation

Question 2.3.4 *Suggest a solution to place a MISO*[3] *control from the tank to a SISO control (conditioning of the tank control input signal).*

Question 2.3.5 *Propose and implement a digital control system for closed loop control of the water level in the upper tank, according to the block diagram of FIGURE .2.2, for a level setpoint that you choose.*

3. Multi Inputs Single Output.

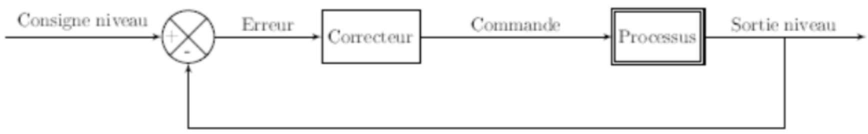

FIGURE 2.2 – Level regulation of the upper tank

Question 2.3.6 *For this type of process, check that a command by the PID corrector or by the discrete corrector (all or nothing) is not necessarily very practical or very relevant. Try to quantify the quality of your level regulation for the following properties :*

— *static error ;*
— *rise or fall time between two setpoints ;*
— *magnitude of any overruns ;*
— *5% response time ;*
— *correction of disturbances (carried out by opening the manual drain valve).*

Discuss the stability, precision, speed and damping of your control system and possible improvements.

Chapitre 3

Operation of a control card using a DSP. Application to the control of a heating model

3.1 Goals

The aim of this lab is to implement a digital control system using a DSP control card. The first part of this practical work will make it possible to discover this card, to highlight the advantages and the limits of digital processing and to develop human/machine communication interfaces. The second part of the practical work will allow the implementation of a digital control to control a heating model.

3.2 Getting started with the dSPACE card (2 hours)

The dSPACE card is an electronic control card comprising, among other things, a DSP processor and analogue/digital (ADC) and digital/analogue (DAC) converters. This is programmable using `Matlab Simulink`. Once programmed, it operates independently from the PC processor. A demonstration of how it works will be given to you by the TP teacher at the start of the session. The converter connection wires are accessible via a box connected to the rear panel of the PC. All the functions are accessible under `Simulink` (integrator, differentiator, filter, gain, adder...) can be used to achieve a control system like that of FIGURE. 3.1

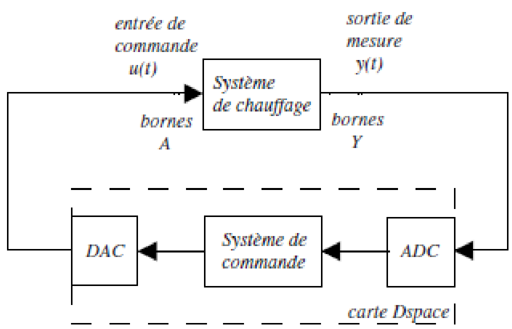

FIGURE 3.1 – Implementation of a digital control system.

3.3 Operation and programming of the dSPACE card

This part proposes to develop a digital system making it possible to send a signal $u(t)$ to the output from the DSP card via a DAC and to acquire an input signal $e(t)$ via an ADC.

Question 3.3.1 *Using `Simulink`, make an assembly making it possible to generate a sinusoidal signal $u(k)$ of amplitude 0.5 and frequency 1 Hz via a signal generator in `Simulink` then transform it into an external analog signal $u(t)$ by DAC1.*

Question 3.3.2 *Check the real-time operation of this assembly for a sampling period* $h = 1ms$. *View the analog signal* $u(t)$ *using an oscilloscope. What type of digital to analog converter does the dSPACE card use ? What is its gain ?*

Question 3.3.3 *Gradually increase the sampling period* h $(1,\ 5,\ 10,\ 50$ *then* $100\ ms)$ *and observe the evolution of the analog signal* $u(t)$. *What can you say ?*

3.4 Real-time visualization and control

In the version of the driver used by the DSP card, `Matlab` and `Simulink` are only used to program it in order to avoid having to program directly in C language. In this configuration, `Simulink` does not operate in real time at the same time as the DSP card and once programming has been carried out and the program has started, `Simulink` no longer has access to the DSP card. As a result, it can no longer view the signals in real time, nor modify program quantities.

3.4.1 Influence of the sampling period, phenomena of spectrum beating and aliasing

Question 3.4.1 *What is the Shannon and Nyquist frequency of the control system as a function of the sampling period h ? Set this sampling period to* $0,01$ *s. What then is the Shannon and Nyquist frequency and then what is the maximum allowable frequency for the input signal of the dSPACE card ?*

Question 3.4.2 *Remove the signal generator from `Simulink` and link directly in `Simulink` the output of ADC1 to the input of DAC1 as in exercise 3. Use an external GBF to apply a sinusoidal signal* $e(t)$ *of frequency 10 Hz to the input of the ADC. Vary the frequency of the input signal of the* $e(t)$ *card between 0 et 50 Hz and highlight the limits of the zero order blocker and the beating phenomena by observing the analog input signals with the oscilloscope* $e(t)$ *and output from the card* $u(t)$.

Question 3.4.3 *Use the external GBF again to apply a sine wave* $e(t)$ *of frequency 10 Hz at the entrance to the ADC. Gradually increase the frequency of the input signal until it exceeds 100 Hz and observe the evolution of the sampled signal* $e(k)$. *Describe in particular the signals sampled for frequencies below 50 Hz, for frequencies around 50 Hz, for frequencies between 50 and 100 Hz and finally for frequencies around 100 Hz. Explain the observed phenomena. Deduce the limits of digital acquisition and control systems in terms of frequency range.*

3.5 Control of a heating model using the dSPACE card (2 hours)

In this section, you will first of all choose the various adjustment parameters of the digital control system according to the characteristics of the process to be controlled (choice of the sampling period h and of the DAC and ADC converters) then you will carry out the digital control of a temperature regulation.

3.5.1 Description of the process

The thermal process used is a hair dryer mockup (FIGURE. 3.2).
This model is composed of a heating resistor in which flows a current supplied by a power amplifier *(power supply)*. The heated air is then propelled into the tube using a fan whose speed is adjustable by a potentiometer *(throttle control)*. Temperature control is achieved by applying a control voltage to the input of the power amplifier on the terminal A of the model. the switch located above terminal A on the right must be positioned down (towards terminal A) and the switch located above terminal A on the left must be positioned up (continuous control). The output of the process is the temperature measured at different places in the tube. A temperature sensor [1] allows a measurement to be made at three distinct points on the tube. The signal from this sensor is conditioned by means of a Wheatstone bridge, the output voltage

1. 1. This sensor is a thermistor : it is a semiconductor whose electrical resistance is a function of temperature. An electrical circuit *(a Wheatstone bridge)* converts this variation in resistance into a voltage. This thermistor is very small and very fragile, so it is imperative not to touch it and to handle the probe on which it is attached with great care.

of which is accessible on terminal Y of the model. The zero of this Wheatstone bridge can be adjusted by means of a screw located above the two dials. The operation of this heating system is shown below.

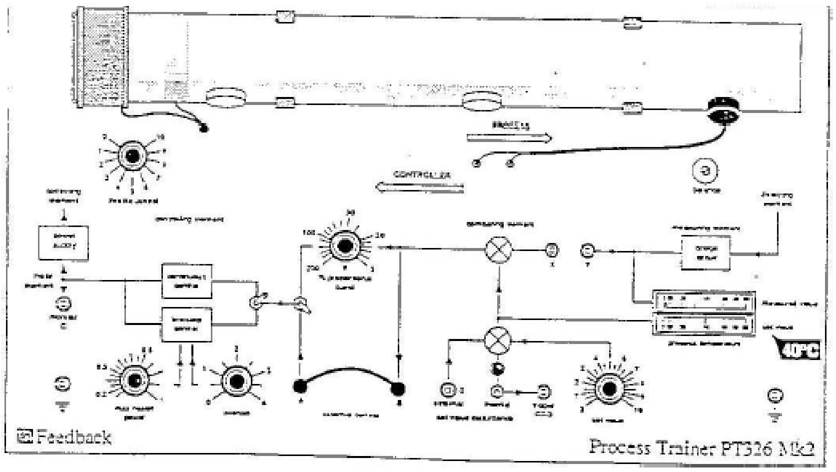

FIGURE 3.2 – Model of hair dryer.

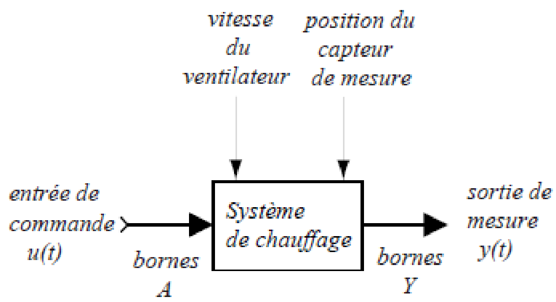

FIGURE 3.3 – Operation of the heating system.

3.5.2 Choice of dSPACE card parameters

In order to choose the digital control system, it is essential to have an estimate of the dynamics of the system to be controlled. For this, it is possible to identify at least approximately the transfer function of the process using a step response method as was done in the introductory labs. The following configuration will be done :

— sensor located in the middle of the tube (length of the resistance to the sensor $L = 140\ mm$) ;

— fan speed set to half (potentiometer in position $\alpha = 4$).

The dynamic behavior of a thermal system can generally be modeled by a Broïda model. The latter is composed of a delay T corresponding to the air propagation time in the conduits (due to transport phenomena in the tube), and a first-order system of time constant τ and gain K (due to the heat equation). If $U(s)$ and $Y(s)$ are the Laplace transforms of input $u(t)$ and output $y(t)$ of the analog process, then its transfer function can be approximated by :

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{1 + \tau.s} \times e^{-T.s} \tag{3.1}$$

Question 3.5.1 *Perform the step response test first using a GBF and an oscilloscope and then using the dSPACE board using a sufficiently small h chosen using the analog experimental results. Deduce the transfer function by experimentally identifying the three parameters K, τ and T .*

Question 3.5.2 *From this information, choose a suitable sampling period h for the dSPACE control card controlling the heating model and then deduce the bandwidth of the setpoint signals and the maximum dynamics of this control system.*

3.5.3 Development of a temperature control using a digital PID

The digital corrector used in this section will be *digitization* of the analog PID corrector with filter whose transfer function is as follows :

$$K(s) = K_p \times (1 + \frac{1}{T_i.s} + F(s) \times T_d.s) \tag{3.2}$$

The filter of the differentiator $F(s)$ is an element which makes it possible to make the causal corrector and therefore physically feasible. During digitization, if the implicit Euler approximation (rear) is used, there is necessarily a delay of one step in the command (strictly causal system) and the filter is no longer essential ; one can then take $F(s) = 1$. On the other hand, for a digitization using the explicit methods, the filter is essential to make the causal system and it is generally chosen of the first order, that is to say of the form

$$F(s) = \frac{1}{1 + \frac{T_d}{N}.s}$$

where the time constant $\tau_f = \frac{T_d}{N}$ is generally chosen with $3 \leq \mathrm{N} \leq 30$ (N = 10 by default). In addition to make the causal corrector, this filter allows to attenuate the signals of pulsations greater than $\omega_f = \frac{N}{T_d}$ which most often correspond to high frequency parasitic noises, this is why this filter is often used even with implicit approximation methods.

Question 3.5.3 *Using the implicit Euler method (rear), digitize this analog $K(s)$ pcorrector to obtain a $K(z)$ transfer function digital PID corrector.*

Question 3.5.4 *From the identifications carried out previously and the performances of the dSPACE card (properties and choice of the sampling frequency), find possible settings of the analog PID corrector by the Ziegler-Nichols open loop method then digitize the corrector obtained to install it in the dSPACE control card. Test the completed command.*

Question 3.5.5 *What are the performances obtained in terms of response time at 5%, precision, damping and overall quality of the enslavement obtained ? Suggest other adjustment methods if the result is not satisfactory.*

3.5.4 Use of other correctors

PIDs reach their limits when processes cause significant phase delays. These phase delays appear for high order systems or for systems exhibiting significant pure delays, as is the case for chemical and/or thermal processes involving transport phenomena. As a pure delay cannot be compensated, in the sense that it can never be eliminated from the transfer function of the process and this whatever the method used, the phase shifts. The resulting large amounts of time reduce phase margins and can lead to unstable closed-loop systems when corrected by simple PIDs. The use of digital control systems then takes on all its importance because it allows the development of more *intelligent* correctors and therefore more *efficient* than simple PIDs. For the control of processes which are generally quite slow systems, the most interesting idea is to use a process model to develop new correctors. Among this class of new correctors are *Internal Model Control* and *Predictive Control*. In this lab, we will implement two forms of internal model control : first in its standard form and then in a form particularly well suited to systems with large pure delays (Smith predictor).

If you have time, you can place the temperature sensor in the extreme position of the tube and reduce the fan speed in order to amplify the delay phenomena. In this case, you will need to re-identify the transfer function of the process.

Internal Model Control

In this control, the regulator incorporates a simulation of the process $G(s)$ using a model estimate $\hat{G}(s)$ resulting from a previous phase of identification (hence the name of the control, internal model control), FIGURE .3.4). If the simulation is perfect, the difference $y(t) - \hat{y}(t)$ is a reconstruction of the disturbances $d(t)$ brought to the output and of the measurement noises. To reduce measurement noise and improve the robustness of the control, a low-pass filter $F(s) = \frac{1}{1+\tau_f.s}$ is usually added so as not to use the estimate of the disturbances $\hat{d}(t)$) (This filter is chosen in a similar way to the filter of the D term of PID). In the direct loop, we can place a simple proportional corrector $K_p = \frac{1}{\hat{G}(0)}$ which will develop a control $u(t) = Kp(y^*(t) - \hat{d}(t))$. However, to improve the tracking dynamics, some internal model control versions replace the simple proportional gain K_p by a more complex transfer function $K(s) = \frac{C(s)}{\hat{G}(s)}$, The filter C(s) makes it possible to make the transfer function K(s) causal and therefore feasible in practice. In the case of an exact model $\hat{G}(s)$, this control allows to obtain the final equality $y(t) = y^*(t)$ with a dynamic which depends on the causality filter $C(s)$.

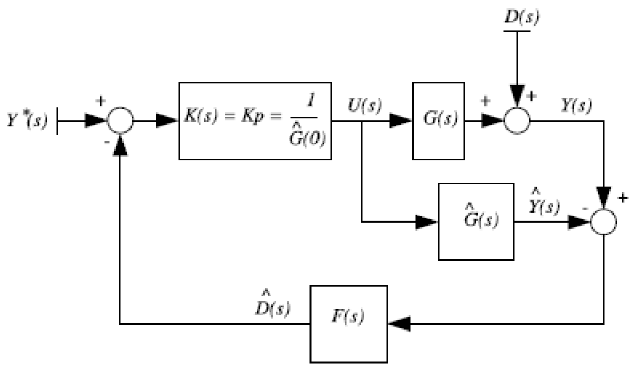

FIGURE 3.4 – Internal model control.

Question 3.5.6 *Using the process identification $\hat{G}(s)$ performed earlier, implement this command on the heating mockup using the dSPACE card.*

Smith's predictor (to get extra points!)

Smith's predictor is a form of internal model control specifically dedicated to elimination of pure delays. This predictor is based on a model of the process $G(s)$ whose estimate $\hat{G}(s)$ can be separated into a term without delay $\hat{G}_{rs}(s)$ and a term due to the pure delay T , $\hat{G}_r(s) = e^{-Ts}$.

$$\hat{G}(s) = \hat{G}_{rs}(s).\hat{G}_r(s) = \hat{G}_{rs}(s).e^{-Ts} \tag{3.3}$$

The purpose of the Smith predictor is to remove the delay in the feedback loop because this decreases the phase margin and makes the system unstable. For that, it would be necessary to be able to separate the pure delay e^{-Ts} from the rest of the transfer function $\tilde{G}(s) = G_{rs}(s)$ in the measurement chain, that is to say to try to obtain the configuration of FIGURE .3.5

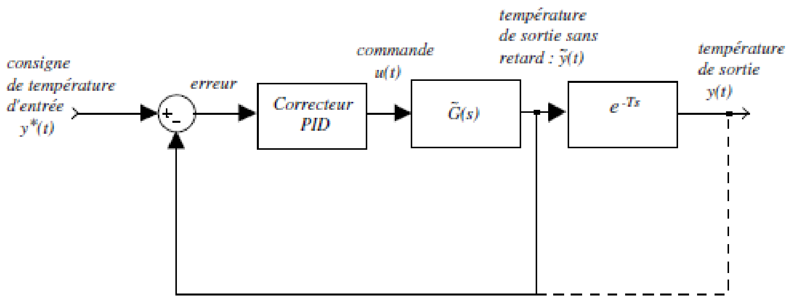

FIGURE 3.5 – Assembly making it possible to overcome the delay of the system in the feedback loop.

Unfortunately, it is not physically possible to separate the delay from the rest of the transfer function, but the ingenious assembly proposed by Smith makes it possible to obtain identical behavior. To use it, however, it is necessary to determine a model of the process where the delay will be known with precision. Unlike the assembly of FIGURE .3.5, the assembly of the Smith predictor is physically feasible. It is shown in FIGURE .3.6.

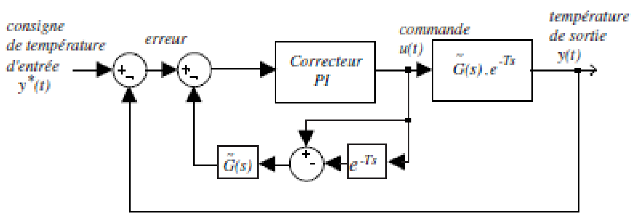

FIGURE 3.6 – Smith predictor : assembly making it possible to overcome the delay of the system in the feedback loop.

The numerical version of Smith's predictor is shown in FIGURE .3.7 for $\hat{H}(z) = \hat{H}_{sr}(z).z^{-d}$ the estimation of the discrete transfer function $H(z)$. If the delay is correctly identified and corrected by the Smith predictor, the D term of the PID corrector is no longer necessary and therefore we can be satisfied with a simple PI. The structure thus formed is then called a PIR or PI with delay compensation.

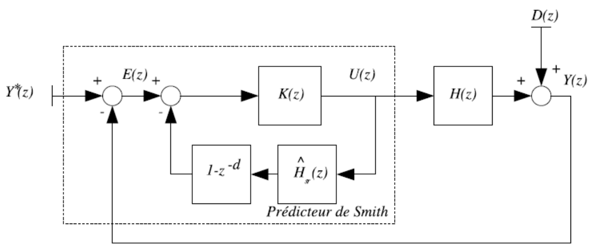

FIGURE 3.7 – Numerical Smith predictor.

Question 3.5.7 *Using the process identification, implement a digital PIR corrector (Smith predictor with a digital PI corrector for K (z)) to control the heater mockup. Compare the performance of this control to that of the digital PID corrector and to that of the standard internal model control.*