Mutivariable Control of a Metrology Laboratory: Humidity and Temperature Regulation

Jorge M. Jaimes-Ponce, Jesús U. Liceaga-Castro, I. I. Siller-Alcalá. and Roberto A. Alcántara-Ramírez.

Abstract— in this paper the design and implementation of control system for a metrology laboratory is presented. The variables to be controlled are the temperature and humidity inside the laboratory. The control system was designed bearing in mind that it must render a low cost solution, simple to design and manufacture and not also easy to operate but to repair and maintain. The control system must comply with the requirements of a metrology laboratory dedicated to the calibration and certification of industrial scales. The control system was designed using standard industrial components for both hardware and software. In this sense, the control system is based on the microcontroller PIC16F877A, the humidity and temperature sensor HMW61/71 and the well-known classical PID controllers. The PID controllers result in a decentralized multivariable controller based on the multivariable control system framework known as Individual Channel Design (ICD).

***Keywords*—**Humidity and temperature control, PID control

I. Introduction

METROLOGY laboratories dedicated to the calibrations and certification of industrial and commercial scales require to operate under certain conditions regarding the humidity, temperature, air flow, airborne particles, etc. However, the most important variables are the humidity and the temperature. That is, this kind of laboratories must operate at 20°C±2% with a relative humidity of 50%±2%. Therefore, the control system focuses only in the regulation of the humidity and temperature within the laboratory. The control system reported in this paper is part of an industrial project which is subject to confidentiality in all the information concerning laboratory real time responses. Therefore, actual data of the laboratory cannot be published. Nonetheless, a general description of the designed control system together with important technical information is thoroughly described.

Similar problems are presented in the humidity and temperature control of green-houses, [1,2,3], where different control strategies are applied, ranging from neural networks to predictive controllers. However, these approaches require rather complicate control techniques that must be avoided as required by the customer specifications.

The regulation of the environment –temperature and humidity- inside a laboratory represents a multiple input multiple output (MIMO) control problem. Therefore, the strategy of analysis and design for linear MIMO control systems known as Individual Channel Design (ICD) [4] was used to design an appropriate control law capable of meeting the requirements of a metrology laboratory.

The control law to regulate de humidity and temperature was implemented using the microcontroller PIC16F877A [5] from which one input port is used to connect a keyboard and one output port to connect a liquid crystal display (LCD). Also, six A/D input channels were used to sense in three different positions the humidity and temperature -three channels for each variable-. One of the most important characteristics of the control system is the sensing of the humidity and temperature in three different locations of the laboratory, so a better measurement of these variables can be obtain by the average of the three measurements, Figure 1. Moreover, the system is capable of detecting the number of sensors that are actually connected allowing the control system to keep operating even in the case of a failure of any sensor.

J. M. Jaimes-Ponce is with the Electronic Department of the UAM-Azcapotzalco, Av. San Pablo 180 C.P. 02200, México (e-mail: jjp@correo.azc.uam.mx).

J. U. Liceaga-Castro is with the Electronic Department of the UAM-Azcapotzalco, Av. San Pablo 180 C.P. 02200, México (phone: 52-55-53189041 ; e-mail: julc@correo.azc.uam.mx).

I. I. Siller-Alcalá is with the Electronic Department of the UAM-Azcapotzalco, Av. San Pablo 180 C.P. 02200, México (e-mail: sai@correo.azc.uam.mx).

E. Arévalo-Zamudio is with the Electronic Department of the UAM-Azcapotzalco, Av. San Pablo 180 C.P. 02200, México (e-mail: enarza@hotmail.com).

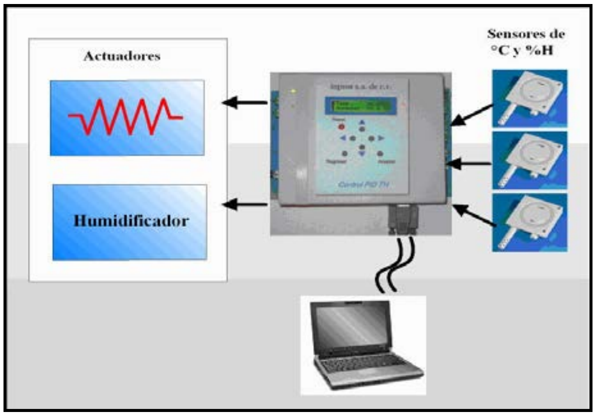

Fig. 1 Humidity and temperature Control System

To operate the electric heater and the ultrasonic humidifier it was necessary to design and construct 120 VCA power drivers. Another requirement from the client was that the system must keep a record of 4 measurements per hour during a period of 10 hours of operation for both the humidity and the temperature. This is important for quality control procedures. This information is stored in the microcontroller's *eeprom* and after that it is sent to a PC by a serial port.

Additional basic functions are performed using basic keys such as *arrows –up, down, right, left-*, *stop*, *reset*, and *enter*, as show in Figure 2.

Finally, the control law is based on the well proved classical PID controller.

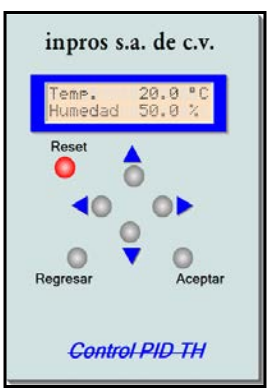

Fig. 2 Control system mask

Another alternative is to use commercial systems based on microcontrollers like Arduino. Arduino is a very economic microcontroller for which already exist many LabVIEW applications allowing the substitution of the data acquisition hardware.

A final option is the use of the National Instruments software, from which the modulus for USB data acquisition are the cheapest and sufficient enough for many applications.

The paper is organized as follows: In the next Section a general description of the control system, together with controller design approach is presented. Also, a description of the sensors, actuators are presented. In Section III, the description of the hardware –microcontroller, A/C, C/A convertors and RS232 serial data transmission- are shown. In Section IV the software programming is exposed. Finally, in Section V, some conclusions are given.

II. General Description

The most important characteristics of the control system are:

a) A PID controller for each variable
b) It has 3 temperature sensors with output signals between 4 to 20 *mA*
c) It has 3 humidity sensors with output signals between 4 to 20 *mA*
d) Separate selection of Set Points for each variable
e) A $120V_{ac}$ electric heater
f) A $120V_{ac}$ ultrasonic humidifier
g) Data storage with the possibility of data transmission to a PC via a serial port.

A. PID Controller Design and Implementation

The humidity and temperature control is in fact a 2 input 2 output multivariable control problem where the inputs are given by the voltages fed to the actuators, and the outputs are the temperature and humidity. Also, as it was shown in [6] this kind of systems are highly coupled. That is, when the heater is on it affects not only the temperature but the humidity because it also tends to dry the air; on the other hand, when the humidifier is on, together with the humidity, the temperature will be affected because of the cold atomized water fed to laboratory chamber.

Similar to the case reported in [6] the model system was obtained using real time step responses of the system around the desired operating point resulting in a 2x2, stable, minimum phase and low coupled multiple input multiple output (MIMO) system; In should be noted that contrary to the system reported in [6], where the humidifier works by introducing hot water vapor, our humidifier works by introducing cold atomized water, nonetheless, both systems have the same structure. Also, the time responses of our system are considerably faster than those of [6] so a GPC [7] control structure is not required.

In order to design a controller capable of satisfying the requirements defined above, the framework of analysis and design for linear MIMO control systems known as ICD [4] was used. ICD makes used of the well-known and proved tolls of classical control theory but applied to multivariable control systems. It is also based in the decomposition, without loss of information, of the multivariable system into single input single outputs individual channels.

Consider a 2x2 MIMO system defined by matrix transfer function $G(s)$:

$$G(s)=\begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{1}$$

Where $g_{i,j}(s),\ i=1,2,\ j=1,2$ are individual transfer functions.

Assume a diagonal (decentralized) controller $K(s)$

$$K(s)=\begin{bmatrix} k_{11}(s) & 0 \\ 0 & k_{22}(s) \end{bmatrix} \tag{2}$$

Resulting in the MIMO control system depicted in Figure 3 where, $R(s)=\left[r_1(s) \quad r_2(s)\right]^T$ is the vector reference and $Y(s)=\left[y_1(s) \quad y_2(s)\right]^T$ is the output vector.

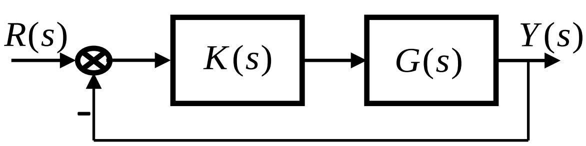

Fig. 3 Multivariable control system

An equivalent control system of Figure 3 is shown in Figure 4.

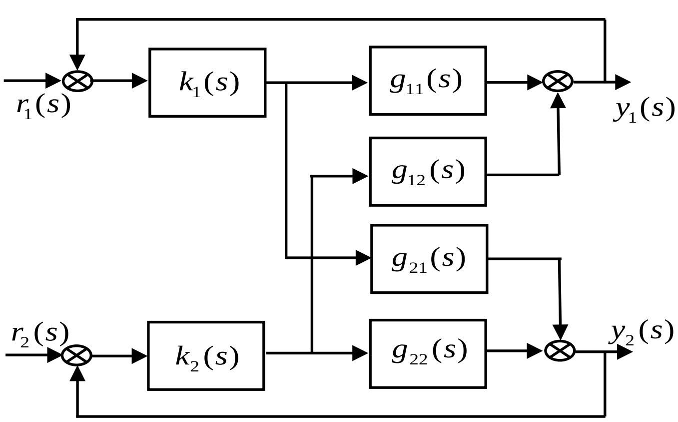

Fig. 4 Equivalent multivariable control system

The control system of Figure 4 can be decomposed, without any assumption or loss of information, into the single channels $C_j(s)$ as described in Figure 5, with $j=1,2$ and $i=1,2$

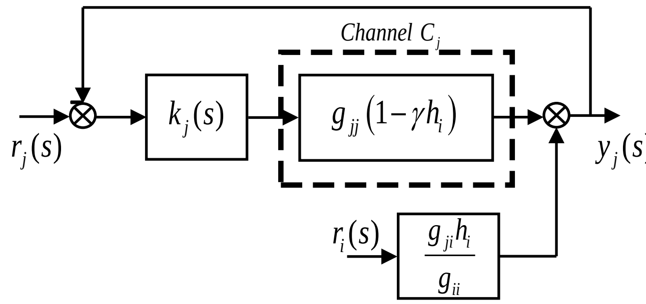

Fig. 5 Single Channels definition

Where:

$$C_j(s) \triangleq g_{jj}\left(1-\gamma h_i\right) \tag{3}$$

$$h_j(s)=\frac{k_j g_{jj}}{1+k_j g_{jj}} \tag{4}$$

$$\gamma(s)=\frac{g_{12}g_{21}}{g_{11}g_{22}} \tag{5}$$

From equations (3)-(5) it is clear that:

- The system is weakly coupled if the magnitude $\left\|\gamma(j\omega)\right\|,\ \omega\in(-\infty,\infty)$, known as the Multivariable Structure Function MSF, is small.
- Input $r_i(s)$ can be treated as a perturbation, passing through the filter $\frac{g_{ji}h_i}{g_{ii}}$, affecting output $y_j(s)$.

As mention before the system is weakly coupled so controllers $k_1(s)$ and $k_2(s)$ can be designed based only on $g_{11}(s)$ and $g_{22}(s)$, respectively; That is, despite the multivariable nature of the system it can be treated as set of two single input single output (SISO) processes. From Equation 3, if $\left\|\gamma(j\omega)\right\|$ is small, then:

$$C_j(s)=g_{jj}\left(1-\gamma h_i\right)\approx g_{jj}(s) \tag{6}$$

Despite the existence of a great variety of control laws the classical PID [5] controller is still one of the most effective controllers for industrial applications. Also, it is a controller which is quite easy to implement. In the case of the humidity a temperature control system two digital PID controllers were implemented. The discrete definition of the PID controller is shown in Equation 7

$$u(kT) = K_p \left[e(kT) + T_d \frac{e(kT) - e(kT-T)}{T} + \frac{T}{T_i} \sum_{k}^{n} e(kT) \right] \quad (7)$$

Where

T: Sampling Period
k: k-th sampling instant
e(kT): error
$e(kT)=q_d(kT)-q(kT)$
$q_d(kT)$=*Process output or controlled variable*
q(kT)=Set point or reference signal
K_p=*Proportional gain*
T_d=*Derivative gain*
T_i=*Integral gain*
u(kT)= Controller output or control variable

The energy supplied to the actuators –electric heater and ultrasonic humidifier- is periodic and bursty. That is, every 10*sec* the actuators will be powered by $120V_{ac}$ during a period of time determined by the value of *u(kT)* which can be equal or less than 10*sec*

B. Sensors

The temperature and the humidity sensor is the HMW61/71 from VAISALA, Figure 6. The HMW61/71 sensor includes two sensors: One to sense the temperature with an output between 4 to 20 *mA* for a variation of temperature between -20°C to 80°C, and the second to sense the humidity with an output between 4 to 20 *mA* for a variation of a relative humidity of 0 to 100%.

The control system was constructed using three of this sensor, allocated in different positions inside the laboratory, to estimate the temperature and the humidity by the average of the measurements proportionated by the sensors. Moreover, the system can detect the number of sensors that are actually connected in order to adjust the average calculations. This is done by recalling that the minimum output signal value of the sensors is *4mA* so if the sensors currents outputs are passed through 250 Ω resistances a minimum voltages, different from zero, are produced; hence, if at zero voltage is detected at the microcontrollers input ports this data is eliminated from the averaging.

Fig. 6 Temperature and humidity sensor HMW61/71

B. Set Point

As any control system it is necessary to define a Set Point. In this case, through the system menu it is possible to define the temperature Set Point from 15°C to 25°C. This range was stablished according to the temperature requirements for scale calibrations. The ideal condition is 20°C±2% with a relative humidity (RH) of 50%±2%.

C. Actuators

The temperature actuator is a 350 Watts resistance sufficient enough to heat a laboratory of $55m^3$. The resistance is powered with $120V_{ac}$ via a triac. To drive the triac the microcontroller uses the optocoupler MOC3030. In the same way the humidifier is operated. It must be noted that the humidifier does not induce a temperature increment.

Additionally, due to the physical characteristics of the actuators the control system actuates only when the error signals –Equation 6- are positive. In the case of negative error signals –when the temperature and/or the RH are above its Set Point values- the control system switch off and a cooling air condition system automatically is turned on.

D. Data storage, Serial Transmission and Timer

An important client requisite for the system was that it must have the possibility to keep a record of the temperature and humidity. Hence, the system keeps 4 samples per hour during 10 hours –normal every day work load- per day with a total of 40 samples for each variable. This is controlled by a timer implemented in the same system. This information is important for quality control statistics. The data is recorded in the microcontroller *eeprom* and can be sent to a PC computer via serial port.

III. Hardware

A. Microcontroller

In Figure 7, the microcontroller PIC16F876A is shown. This microcontroller has 8 A/D inputs, although only 6 are used. It also has several digital input/output ports, a keyboard and a liquid crystal display. Other important features of the PIC16F876A [8] are that it includes a modulus for serial communication and an *eeprom* memory. The purpose of using this internal nonvolatile memory is to reduce the need of external hardware resulting in a compact and dependable system.

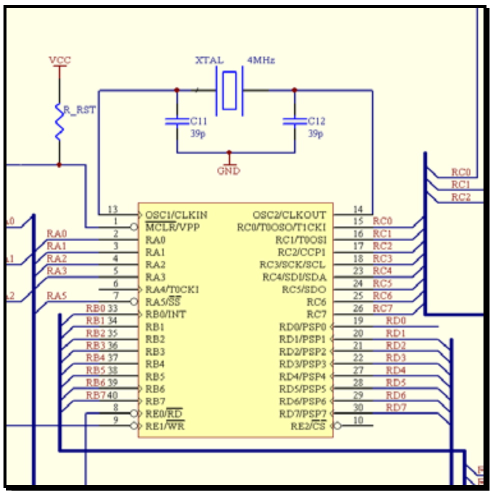

Fig. 7 Microcontroller PIC16F877A

B. Analog Inputs and A/D Conversion

To capture the sensors analog signals the input A/D ports are used, specifically the inputs AN0 to AN5, from the microcontroller ports A and E. However, it is necessary to transform the sensors current outputs into voltage signals. This is done by connecting the precision 250 Ω resistances RT1, RT2 and RT3, as shown in Figure 8. By a straight forward calculation it is clear that with the minimum current of 4 *mA*, the minimum voltage will be 1 *Volt.*

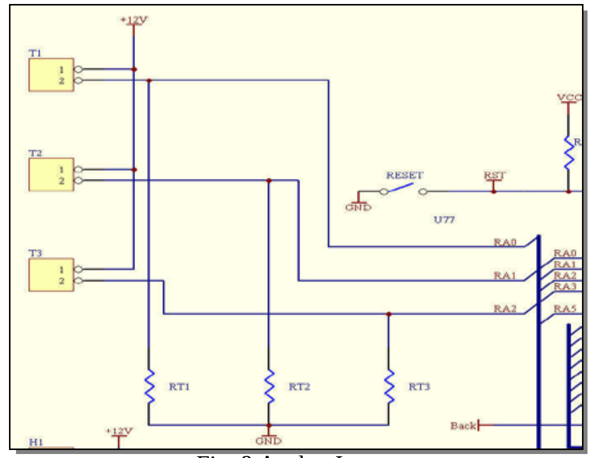

Fig. 8 Analog Inputs

C. Serial Data Transmission

The developed system has the necessary devices to connect to a PC. For the serial data transmission the microcontroller uses TTL signal –0*V* for the logic value "0" and 5*V* for the logic value "1"–. The PC uses the serial port RS232 [9] with 12*V* for the logic value "0" and -12*V* for the logic value "1". Therefore, to connect the microcontroller to the PC the MAX232 circuit with the connector DB9 is used, Figure 9. The transmission characteristics are: 9600 bauds, without parity, 8 data bits and 1 stop bit.

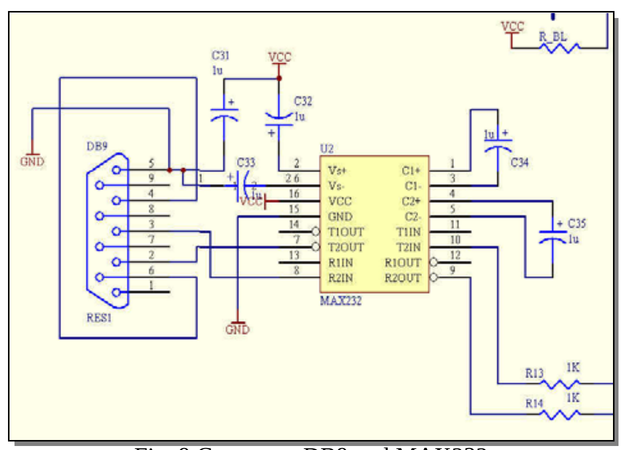

Fig. 9 Connector DB9 and MAX232

D. LCD and keyboard

Two significant elements of the system are the liquid crystal display (LCD) and the keyboard, Figures 10 and 11. Thanks to these elements it is possible to interact with the system; for instance, it is possible to select and visualize the set points for the temperature and the RH or to establish the serial communication with a PC.

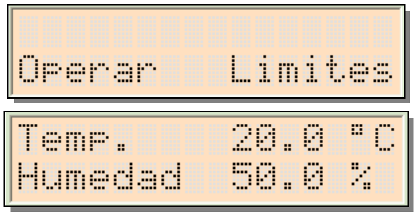

Fig. 10 Some LCD screens

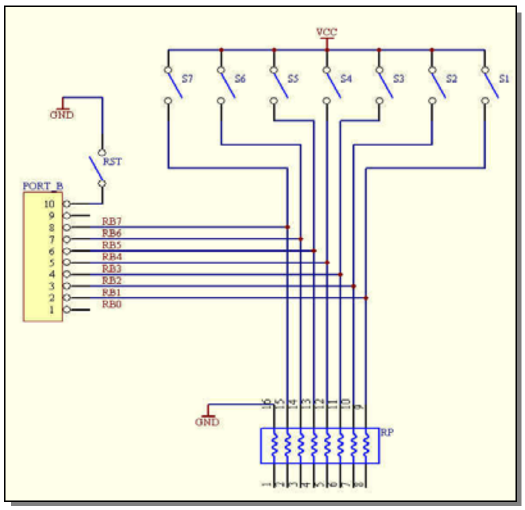

Fig. 11 Keyboard diagram

E. *Voltage Source*

The voltage source provides two voltages: the first is a TTL 5*V* source necessary to operate all the digital electronics, the PIC16F877A, the LCD, the optocouplers and the MAX232; the second is a 12*V* voltage source feeds the sensors, Figure 12.

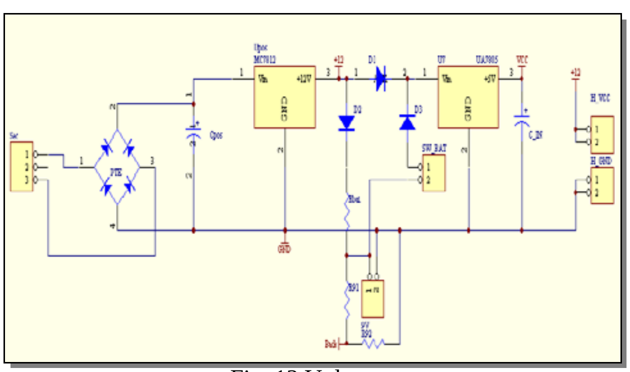

Fig. 12 Voltage source

IV. Software

The development of the programming is based on the BASIC language for microcontrollers. BASIC is an excellent language due to its simplicity and because it allows high level applications programming, that is, it includes several functions or toolboxes. For instance, an important part of the program is the sensors detection, necessary to the average calculation of the temperature or RH variables. The BASIC program for this calculation is shown next.

```
n = 0
Sum_Temp = 0
temp_res = Adc_Read(0)
if temp_res > 100 then
   Temp_0 = (temp_res - 204) * 12
   Temp_0 = Temp_0 / 10
   Sum_Temp = Sum_Temp + Temp_0
   n = n + 1
end if

temp_res = Adc_Read(1)
if temp_res > 100 then
   Temp_1 = (temp_res - 204) * 12
   Temp_1 = Temp_1 / 10
   Sum_Temp = Sum_Temp + Temp_1
   n = n + 1
end if

temp_res = Adc_Read(2)
if temp_res > 100 then
   Temp_2 = (temp_res - 204) * 12
   Temp_2 = Temp_2 / 10
   Sum_Temp = Sum_Temp + Temp_2
   n = n + 1
end if

if n > 0 then
     temp_res = Sum_Temp
     temp_res = (temp_res / n) - 200
else
     temp_res = 0
end if
```

In the same way, the PID programming is shown next.

```
Err_T = Qdt - Qt
Prop_T = Kpt * Err_T
Deriv_T = Tdt * Err_T
Sum_Err_T = Sum_Err_T + Err_T
Int_T = Tit * Sum_Err_T

Ut = Prop_T + Deriv_T + Int_T
```

Part of the microcontroller programming includes additional options, such as:

a) Set the time
b) Define the set points
c) Define the when to initiate the data storage

d) Initiate the serial communication

In Figure 13 LCD display of some the previous options are shown.

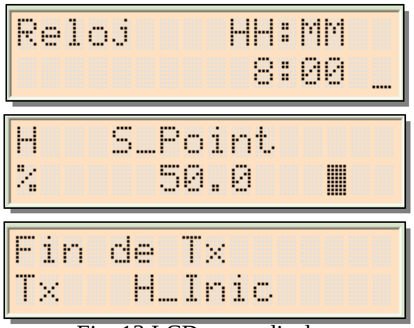

Fig. 13 LCD menu display

V. Conclusions

It was possible to design and construct a temperature and humidity control system for a metrology laboratory dedicate to the calibration and certification of scales. The control system fulfils the customer requirements: Low cost, easy to implement, operate and maintain, and constructed with standard industrial components. The control law based on the framework known as Individual Channel Design result in a multivariable decentralized PID controller. Also, the Multivariable Structure Function shows that the process is weakly coupled so the process can be treated as a set of two SISO systems. So far, the costumer reports that the system works as expected. Due to confidentiality issues it is not possible to present real time responses of the control system; nonetheless, in Figures 14-16 the hardware of the control system is shown.

Fig. 14 LCD and keyboard

Fig. 15 Microcontroller and power boards

Fig. 16 Controller board and sensor

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Jorge Miguel Jaimes Ponce was born in México City, México in 1959. Since 1990 he is a Professor in the Department of Electronics at the UAM-Azcapotzalco. He graduated from Department of Electronics of the same University with a MSc in Mechatronics Engineering in 2008 from the TESE, México. The main fields of his professional interest include Classical Control, Instrumentation, Digital Electronics, Power Electronics and Mechatronics.

Irma Irasema Siller Alcalá was born in Frontera, Coahuila, México in 1961. Currently, since 1990 is a Professor in the Department of Electronics at the Universidad Autónoma Metropolitana Unidad Azcapotzalco. She graduated from Faculty of Mathematics and Physical Sciences at UANL with a MSc in Automatic Control. She obtained her Ph.D. in Control from the University of Glasgow, U.K. Her research interest includes Classical Control, Non-linear Control and Predictive Controllers.

Jesús U. Liceaga-Castro was born in México, México. He received the B. Eng. Degree in electronic engineering from Universidad Iberoamericana Ciudad de México, México, in 1985; the M.Sc. degree in automatic control from the CINVESTAV-IPN, México, in 1988, and the Ph.D. degree from the University of Glasgow, U.K., in 1995. He was a full-time Professor and the Leader of the Electric Machine Control Research Group with the ITESM, México. He is currently a full-time research professor with the Department of Electronic at the UAM-Azcapotzalco, México

Roberto Alfonso Alcántara Ramírez was born in México City, México in 1963. Since 1990 is a Professor in the Department of Electronics at the UAM-zcapotzalco. He graduated from Department of Electronics of the same University with an MSc in Mechatronics Engineering in 2008 from theTESE, México. The main fields of his professional interest include Control Classic, Instrumentation, Digital Electronics, Power Electronics and Mechatronics.