Implementation of a Distributed Control Experimentation Platform

Mario A. Muñoz, Jesús A. López, Eduardo F. Caicedo,

Abstract— **In this work, we present the implementation of a planar temperature grid plant. This plant emulates the working of a control system that is designed to maintain a constant temperature over a surface. The behavior of the implemented plant presents characteristics difficult to describe in mathematical terms like disturbances, interferences, deviations, and temperature gradients. We describe the functional characteristics of the system and its application in the study of distributed control systems in an educational environment. To test the working of the plant we present the obtained results with two resource allocation strategies such as control algorithms.**

I. Introduction

THE development of faster and more sophisticated computing systems, including powerful embedded devices with data acquisition, plays an important role in the foundation of the new technologies of distributed control [1].

In this field, the decisions are not only made with the knowledge comprised in one sector, but based in the general needs of the industrial environment.

Although the industry is taking advantage of the capabilities offered by the development of distributed control systems (DCS) and industrial communication networks, the universities are facing the challenge of designing methods that allow engineering students in related areas to be prepared for the design, implementation and management of these systems. There are several approaches for the development of systems that include cooperative work for the search of a common goal by the implementation of DCS by a communication network. An approach worth studying is the development of laboratory equipment that allows the emulation of complex processes in which the use of DCS techniques can be applied [4].

The development of these low cost systems for educational purposes is necessary for the inclusion of new experiments that allow students to acquire a good knowledge in these areas of the control theory.

Besides, the needs faced by Latin American universities and other developing areas, where the economic resources must be allocated efficiently, make this an ideal approach for the development of curricula that give the students appropriate tools in their academic training [2]. This approach is inspired in the work performed by Passino and co-workers [3] where they explore the use of low-cost tools in educational laboratories for control systems and automation.

In this article, we present the functional aspects of a test platform based on the platform developed by Quijano, Gil, and Passino [4, 5]. This platform, which mimics a temperature grid plant, is composed of multiple sensors and actuators arranged in zones. As a first goal, we expect to increase the temperature to a maximum common value through an activation sequence of the actuators. The dynamic assignation and control is challenged by the zone interaction, environment temperature influence like air flow, and temperature gradients. Also we present a series of experiments performed with some dynamic assignation algorithms as a verification method of the workings of the system. Finally, we define the control rule and we show the corresponding results

II. Problem description

The planar temperature grid is a system that exhibits effects that are difficult to model. Therefore, it requires the use of particular control strategies. This type of system is mainly used in the semiconductor industry for the elaboration of crystals and the generation of photo resistive layers. This processes require to maintain a constant surface temperature as is shown in [6] and [7].

In [6] a device was designed with 49 individual zones. Each one is independently controlled by feedback control mechanism. A supervised control strategy was applied to coordinate the individual zones. The advantage of this system is a good uniformity in the surface and the ability to perform different experiments by the displacement of the substrate set point. The system was configured as concentric pattern of lamp–sensor pairs with a centralized PID controller.

In [7] the system was composed of a series of foil heaters in contact with the surface of a heat exchanger. An algorithm was presented using the heater to compensate the non-uniformities in the temperature of a semiconductor

M. A. Muñoz is an Electronics Engineering student at the Universidad del Valle, Cali, Colombia (andremun@gmx.net).

J. A. López is Ph D Candidate in the Escuela de Ingeniería Eléctrica y Electrónica, Universidad del Valle, Cali, Colombia, South America (jesuslop@univalle.edu.co).

E. F. Caicedo is with the Escuela de Ingeniería Eléctrica y Electrónica, Universidad del Valle, Cali, Colombia, South America (ecaicedo@univalle.edu.co).

wafer. The results presented are based in a high-energy expense.

While these articles show the use of these systems in industry, our system can emulate the existing interactions in most buildings where a temperature control is performed. Our system also allows the evaluation of task allocation strategies for energy efficiency [5]. With these characteristics in mind, a series of challenges in control theory can be developed as experiments in this platform.

1) Uniform temperature regulation in the entire surface with a maximum fixed value. The search for a fixed or dynamical temperature pattern can be proposed.

2) Temperature tracking in which a group of zones follows other zone average temperatures or a reference value.

3) Distributed control with different zone controllers and network communication with delays for the sensed information and control information.

Allocation or control algorithms of stochastic or heuristic nature can solve these challenges.

III. System Description

A. System Architecture

In the construction of our multizone temperature process was necessary the development of a two system: a process system (planar temperature grid) and a data acquisition system. In the implemented design these systems are independent, it allow different architecture configuration for the realization of several experiments.

A single master architecture it is proposed. This architecture allows the development of the control strategy and the protocol management program inside a master PC. For the use of this architecture is necessary a RS232 – RS485 interface connected to a serial port as show in Fig 1.

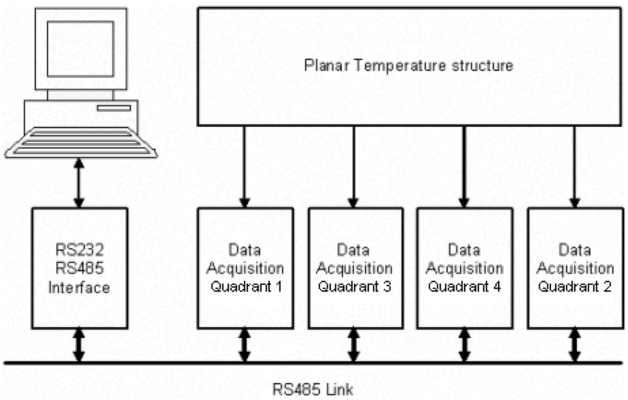

Fig. 1. System architecture for single master PC management.

B. Planar Temperature Grid

To emulate a multizone temperature control system an array of 25 temperature sensors and 16 actuators with a separation of 0.51 cm was constructed, as shown in Fig. 2. The grid was divided in 16 zones composed by an actuator and its four neighboring sensors. A group of 4 zones is called quadrant; which has its own data acquisition, control and serial communication system that is managed by a PC.

The used sensors in the process are LM35CAZ produced by National Semiconductor. These devices provide very similar characteristics between them and its response is very lineal with a resolution of 10 ºC/mV. As actuators a 12 V incandescent light bulbs were selected. As sockets for the sensors and actuators were used pieces of *header*. This avoid the damage or change of characteristics of the semiconductors due the heating produced by soldering. An additional advantage to use socket for the sensors and actuators is to facilitate the replacement of these devices.

To interfacing the microcontrolled acquisition system with the actuators a DS2003 integrated circuit was used. This device posses several Darlington pairs with TTL interface and a 300mA current support.

Because of the organization of the system there is the presence of temperature variation due wind currents, the obvious superposition of the zones and the presence of temperature gradients due the activation of the actuators.

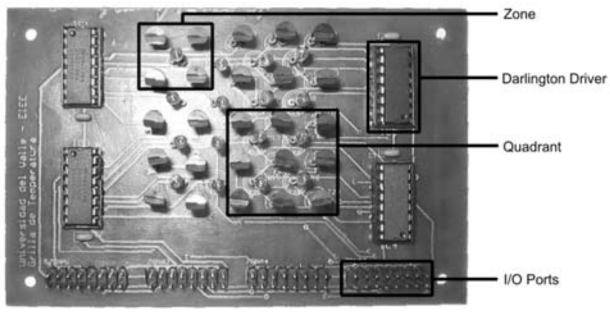

Fig. 2. Planar temperature structure

C. Data Acquisition System

The implemented data acquisition system it is based in a low cost Freescale MC68HC908MR8 microcontroller that provides the following characteristics:

1) An 8 bit central processing unit.

2) Internal bus frequency of 8 MHz

3) 8 Kbytes of program memory

4) 256 bytes of data memory

5) Digital – Analog conversion by a 12 bit six channel PWM generator (DAC).

6) 10 bit four channels Analog – Digital converser (ADC)

This device was selected because it has a Digital – Analog conversion based in hardware which is independent of the program used, allowing a selectable sample period limited only by the speed of the serial communication of 125 Kbps.

An 8 channel analog multiplexer connected to the channel 0 of the ADC was used to allow access to 8 of the 9 sensors that compose a quadrant. The ninth sensor was connected to the channel 1.

Because of the ADC range limitation from 0 to 5 volts, it is necessary the use of an amplification stage for the data suministrated by the sensors. It was used a TL072 operational amplifier that posses a low offset, low polarization current and high input impedance, set with a gain of 4 with a max tolerance of 7.5 % with a 5 % resistances. This gain allows a resolution of 0.25 ºC/bit.

To interconnect the four modules necessaries to a PC for managing, a bus architecture based in the RS485 half duplex protocol was used, by the utilization of the 75176B integrated circuit, which is connected in continuous reception and its transmission state is controlled by a microcontroller port. The full system shares the clock and reset signals, keeping the microcontrollers synchronized. The Fig. 3 shows the block diagram of the system, and the Fig. 4 shows the actual device.

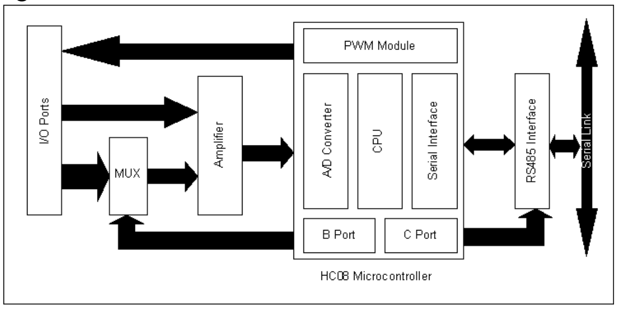

Fig. 3. Data acquisition system block diagram

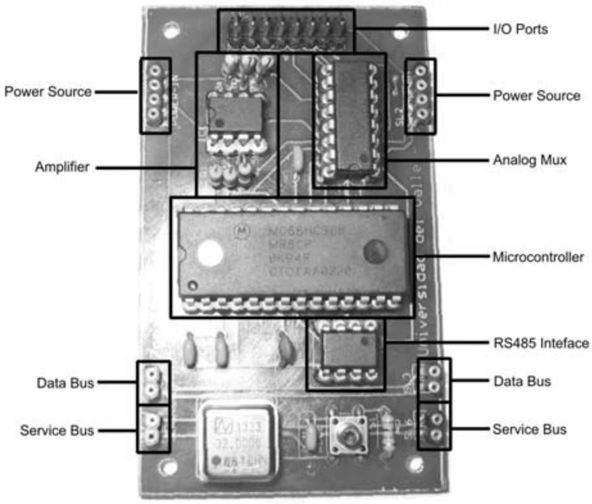

Fig. 4. Data acquisition system block diagram

D. Communication protocol

The use of a microcontrolled system allows the construction of a management algorithm with a communication protocol capable of the realization of all task required for the problem solution. A master slave protocol with variable package length was implemented, also was necessary the definition of four basic commands. The package contains these fields.

1) Head: This field indicates the beginning of a package. It is composed by two bytes with the number 7Eh.

2) Source Address: Indicates the source device that is sending the message. The address is a four bit number and allows devices from address 0 to E. The address F is used as a broadcast address so it can never be a source address.

3) Destination Address: Indicates the destination device of the message. The address follows the rules of the Source Address. The address F can be used as destination address.

4) Type: Indicates the type of message being sent. For a basic design, four types have been implemented:

- Data request: Type 0. Usually used as a broadcast message. Indicates to all the devices connected to initiate a routine that takes all the data from the sensors, and store them in memory. It does not have DATA field.
- Data send request: Type 1. Used as a unicast message, indicates one device to send all the data stored in memory to the master. It does not have DATA field
- Data transmission: Type 2. Response of a type 1 message. Sends all the contents of the sensor data stored in memory to the master. The DATA field is 18 bytes long in this case.
- PWM response: Type 4. It can be executed as a broadcast or unicast message. Allows the transmission of new values for the DAC. It has an 8 byte DATA field.

5) Length: Indicates the length in words of the data field. This field will allow the future expansion of the messages type.

6) Data: Includes the data sent based in the message type.

7) End: Represents the end of the message. It is composed by two bytes, one 7Eh, and the other FFh.

This protocol allows a non-blocking operation of the microcontrolled system and the transmission of any request at any time. Nevertheless, a sequence of requests is necessary for the completion of all tasks:

1) Transmission of a data request message in broadcast mode, allowing a sample take.

2) Transmission of a data send request for each device. This request is made in order and the master waits until gets a response from the device by a data transmission message, before making a new request.

3) Transmission of a PWM response to actualize the outputs of the devices.

When these tasks are finished, the system is ready to restart.

E. Other hardware architectures allowed

Besides the architecture proposed, this experimentation platform can be configured in other forms for the execution of different centralized and distributed control experiments. Some configurations are:

1) Independent system, where one of the microcontroller units acts as a master in which the control or management algorithm is implemented.

2) Multi-master system, where each of the microcontroller units is managed by a single PC. The communication between the quadrants would be by TCP/IP links. This configuration allows the implementation of different control strategies in each PC or the implementation of the control strategy in one single PC.

IV. Dynamic Task Allocation by Feedback Algorithms

The hardware platform implemented can be used in the study of several control or optimization strategies. One of them is the implementation of dynamic task allocation algorithms that are presented in [4, 5]. In this algorithms, an optimization objective is presented. With the use of a limited amount of actuators, a highest and uniform temperature must be reached, in all the structure, at the end of an experiment. For testing purposes the allocation algorithms were implemented using Mathworks' MATLAB [8].

A. Simple task allocation by minimum value

One of the simplest ways to allocate a resource in closed loop is by the determination of the minimum value in the surface and make the allocation to that zone. This algorithm proposed in [4] presents a centralized approach to the problem where a single computational agent takes a destination based in the global knowledge. Being the temperature in the i-esim zone as Ti, and the input to the actuator in that zone as u_i. The i-esim zone temperature is calculated by the average value from the four neighboring sensors that will be more affected by the actuator. This strategy allocates the resource defined by the on time of the actuator for each instant k based in the rule:

$$u_i(k) = \begin{cases} 1, & \text{if} \quad T_i(k) < T_j(k) \quad \text{for} \quad j \in \{1,2...16\} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

This strategy searches to increase the minor temperature in the surface, forcing the uniformity while the values are maximized. The assignation then emerges from this simple optimization strategy.

This algorithm was tested in a 30 minutes experiment with a second sampling time. The results are shown in the Fig. 5 and Fig. 6. The Fig. 5 shows that the actuators in the corners of the surfaces are more used than those in the middle of the surface. This task allocation allows the zones temperatures (Fig. 6) to establish at an average of 5.2275ºC with 0.3568ºC spread, at 609s settling time.

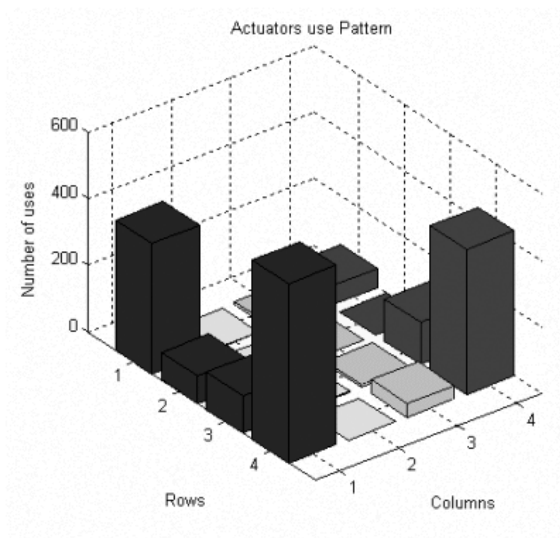

Fig. 5. Actuators use pattern for the simple task allocation algorithm

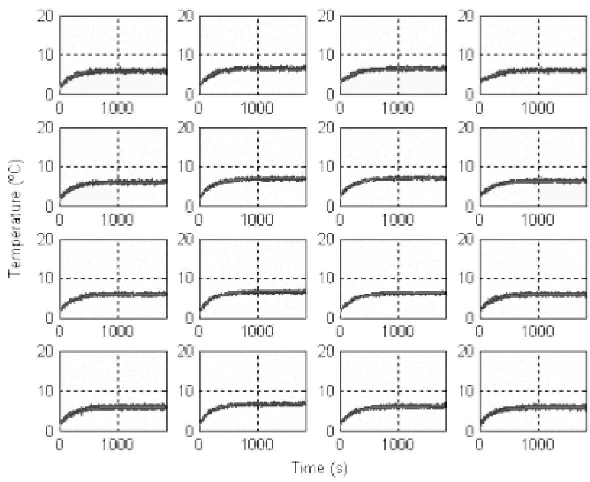

Fig. 6. Zones temperatures obtained by the simple task allocation algorithm

B. Distributed task allocation by minimum value

Other approximation developed in [4] is a distributed version of the simple method. In this case, a local computing agent for each zone is defined, and its decision would be taken based in the knowledge of the neighboring zones.

To define the control rule, its necessary the definition of the neighborhood $N(i)$ for a i zone, including itself. For every i.

$$T_i^{\min}(k) = \min\{T_j(k) : j \in N(i)\} \tag{2}$$

$$u_i(k) = \begin{cases} 1, & \text{if} \quad T_i(k) = T_i^{\min}(k) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

This strategy follows the concepts used in the last algorithm. The mayor difference is the possibility that one or more actuators can be on at one time. During a 30 minute experiment with 1 second sample time, the average number of actuators on at the time is 3.4856.

In the Fig. 7 the actuator use pattern shows again a mayor use of the corner actuators. The mayor difference in this pattern is the increase in the use of actuator (1,4). The result is that the zones achieve a mayor final average temperature (Fig. 8) of 12.4800ºC with a 0.5748 spread at 482 s settling time.

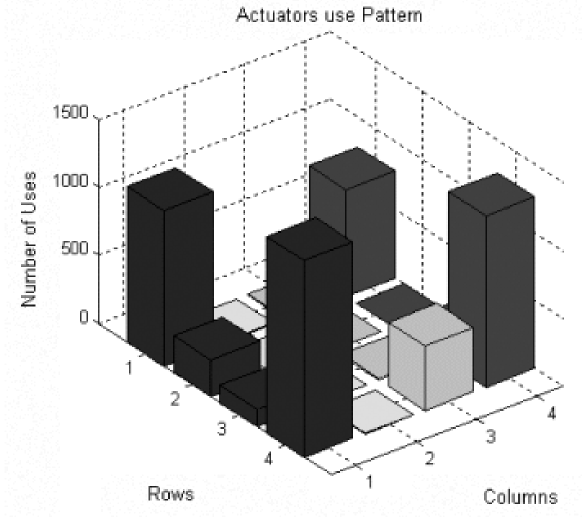

Fig. 7. Actuators use patter for the simple task allocation algorithm

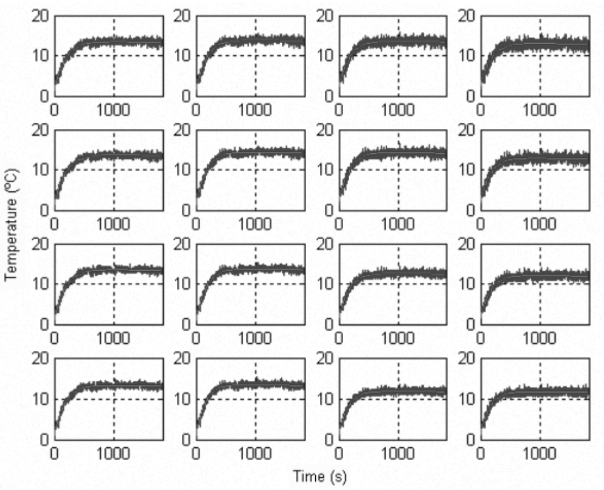

Fig. 8. Zones temperatures obtained by the simple task allocation algorithm

V. Conclusion

The implemented system is ideal for laboratory practices and investigation in advanced control schemes in low economic resources environments. Because of its low cost, easy reproduction, modularity, versatility, and communications characteristics, this system allows the study of distributed control systems.

The use of a microcontrolled system as the core of the data acquisition system allows the use of these modules as low cost, scalable data acquisition system in other environments.

The algorithms used in this experiment show the capabilities of the system and the development of other experiments with different approaches is in the way. Some projects that include this device and show its versatility are:

1) Development of task allocation algorithms based in biological cooperative agents [9].

2) Development of a feedback adaptive controllers based in biological cooperative agents.

3) Study and modeling of the dynamics experimented in the system.

4) Modification of the system dynamics by the addition of covers made from different materials.

VI. Acknowledgments

We thank Professor Kevin Passino for inspiring this work and his graduate students Nicanor Quijano, Jorge Finke, and Alvaro Gil for valuable discussions. Part of this work has been supported by COLCIENCIAS and UNIVERSIDAD DEL VALLE through a graduate research fellowship awarded to Jesús A. López.

References

[1] R. M. Murray, "Future directions in control, dynamics and systems: Overview, grand challenges and new courses," *Eur. J. Contr.*, vol. 9, no. 2, pp. 144–158, 2003.

[2] OSU International Educational Laboratory Development for Feedback Control Engineering and Automation. [Online]. Available: http://www.ece.osu.edu/~passino/labdevelopment.html

[3] OSU Control Systems Implementation Laboratory, *EE 758* [Online]. Available: http://www.ece.osu.edu/~passino/ee758.html

[4] N. Quijano, A. E. Gil, K. Passino "Experiments for dynamic resource allocation, scheduling and control" in *IEEE Control Systems magazine,* February 2005, pp. 63-79

[5] N. Quijano*, "Experiments and technologies for decentralized temperature control"* M.S. thesis, The Ohio State University, Columbus OH, 2002.

[6] C. D. Schaper, K. A. El-Awady, A. E. Tay, *"Spatially programmable temperature control and measurement for chemically amplified photoresist processing"* Procedures SPIE Vol. 3882, p. 74-79, Process, Equipment and Materials Control in Integrated Circuit Manufacturing V; A. J. Toprac, K. Dang; Eds. September 1999

[7] K El-Awady, C. D. Schaper, T. Kailath, *"Temperature cycling and control system for photosensitive materials processing"* 2003

[8] Mathworks [Online]. Available: http://www.mathworks.com/products/matlab/

[9] M. Muñoz, *"Asignación dinámica de recursos con técnicas bio inspiradas para un sistema de control de temperatura"* B.A. thesis, Universidad del Valle, Cali, Colombia, 2005.