African Journal of Agricultural Research Vol. 6(11), pp. 2544-2557, 4 June, 2011
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJAR10.1042
ISSN 1991-637X ©2011 Academic Journals

Full Length Research Paper

Fuzzy irrigation greenhouse control system based on a field programmable gate array

Domingo Gómez-Melendez[1], Alvaro López-Lambraño[2]*,Gilberto Herrera- Ruiz[2], Carlos Fuentes[2], Enrique Rico-Garcia[2], Carlos Olvera-Olvera[3], Daniel Alaniz-Lumbrerasc[3], T eobaldis Mercado Fernández[4] and Sven Verlinden[5]

[1]Universidad Politécnica de Querétaro, Carretera Estatal 420 S/N, El Rosario, C.P. 76240, El Marqués, Querétaro, México.
[2]División de Investigación y Posgrado, Facultad de Ingeniería, Universidad Autónoma de Querétaro, Centro Universitario, Cerro de las Campanas s/n, C.P. 76010, Querétaro, Qro, México.
[3]Universidad Autónoma de Zacatecas, Jardín Juárez 147 Centro Histórico, C.P. 98000 Zacatecas, México.
[4]Colegio de Postgraduados, Km 36.5 Carretera México-Texcoco, C.P. 56230, Montecillo, Texcoco, Estado de México, México.
[5]Division of Plant and Soil Sciences, West Virginia University, Morgantown, WV 26506, USA.

Accepted 16 May, 2011

Fuzzy logic provides a methodology to represent, manipulate, and implement heuristic knowledge to control a system. In this work, the development of a fuzzy irrigation control system based on a field programmable gate array (FPGA) to control greenhouse fertigation was presented. Factors involved in crop nutrition were discussed first. Next, the description of the fuzzy control system was presented, followed by the analysis and design of the fuzzy controller, and its implementation, a FPGA-integrated circuit. The FPGA system is not only flexible (it can be easily reconfigured and reused for different designs) but it also provides rapid prototyping and offers the capability to perform multiple operations at the same time, producing positive economic returns. The design, compilation, and simulation of the system were developed in Active-hardware description language (HDL) using the hardware description language, very high-speed integrated circuit hardware description language (VHDL). Results from simulation and experiments showed the simplicity of the design, the viability of its implementation, and the low cost that the use of a fuzzy logic controller and FPGA system represents.

Key words: Fuzzy logic controller, irrigation system, field programmable gate array (FPGA).

INTRODUCTION

When addressing food production in greenhouse environment, there are two main systems which determine quality and productivity in the business operation, namely the climate control system and the irrigation control system. The later is of vital importance due to the fact that the nourishing of the crop depends on it. In this system, it is imperative to measure and control the pH, as well as the amount of fertilizer in the nutrient solution, and to minimize the amount of the nutrient solution applied to the plant. Obviously, the amount of water and nutrients required depends on the needs of the plant which in turn is influenced by the climate and stage of development of the plant. There are number of approaches based on closed loop control using different feedback sensors that have been developed for irrigation purposes. Luthra et al. (1997) developed a system based on soil water tension measured by a modified manometer type tensiometer, in order to control the irrigation process. Similarly, Gieling et al. (2000) automatically controlled the amount of water flow to a crop by

---

*Corresponding author. E-mail: altoti@gmail.com Tel: +52 442 194 6654.

Abbreviations: CMOS, Complementary metal oxide silicon; FPGA, field programmable gate array; **SoC,** single integrated circuit; **EC,** electrical conductivity; **DCFS,** dosage of the concentrated solution of fertilizers; **MUX,** multiplexer; **MAC,** multiplier accumulator.

compensating for the fluctuations in evapo-transpiration by means of sensor feedback. A pulse modulated pump kept the flow at a constant set-point through a feedback control action on the repetition rate and a feed forward control action on the pulse width; the water consumption by the plant was treated as a disturbance.

In both cases, the control on the amount of nutrients was not considered. Bahat et al. (1999) presented an alternative for an irrigation controller based on fuzzy-logic methodology. The authors controlled the open/closure times of a valve using feedback information provided by different sensors (soil moisture level, temperature, etc.) and diverse pre-programmed set points. This way, it was possible to control the moisture levels of the soil. In this study, however, only the volume of water was controlled without any control over nutrient levels.

In all these cases, real-time remote monitoring of the feedback variables is an important factor if these solutions are to be implemented in practice. Mendoza-Jasso et al. (2005) developed such a system. The use of their equipment allowed data transmission and storage in a computer in real-time. The system allowed for the sensing of large fields, collecting data from any kind of sensor that could then be transmitted by radiofrequency to a computer with a system capable of monitoring the environmental or physiological status of a crop. This work was not specifically oriented to irrigation control, but it can be seen as an effective tool to implement any feedback approach. In the studies described above, the authors measured and controlled different variables in order to control the amount of water and irrigation timing, but they did not specifically control the pH and the amount of dissolved fertilizer, both important factors to guarantee optimal nutrition of plants and therefore yields. However, in 1989, Papadopoulos et al. presented a device that allows a control system to meet the diverse and changing nutrient requirements of a number of crops from one standardized concentrated fertilizer solution.

The system activated a series of dosimetric pumps at varying frequencies for the preprogrammed application of the desired concentrations of all essential nutrients. The system adjusted automatically the supply of water and individual nutrients to the crops according to preset values and feedback sensors. Similarly, Kell et al. (1999) presented another computer-based system for controlling irrigation, fertilization, and climate in greenhouses; several sensors provided feedback information by means of input cards that allowed the system to manage the irrigation and fertilizer stations through pumps and solenoid valves. Nevertheless, in both cases, the solution quality control lacks closed-loop pH control. The fuzzy logic approach will be essential in any irrigation system that seeks to control amount of water, nutrients, and pH because such a system can easily deal with the non-linear conditions that crop production present. Other approaches are too difficult to use in order to effectively control pH levels. Moreover, by controlling the pH levels and the amount of dissolved fertilizer, it is possible to guarantee more safety for the crop during crop production. The fuzzy logic method, being part of artificial intelligence techniques, has been used to solve a number of different kinds of control problems (Lee, 1990; Leilei, 2007; Yang, 2006).

Fuzzy logic provides a methodology to represent, manipulate and implement heuristic knowledge to control a system. In addition, fuzzy control is robust and very economical (Passino, 1998). A fuzzy controller can be implemented in different technological platforms such as personal computers, microprocessors, microcontrollers, digital signal processors, digital memory devices, by using the semi-custom design with complementary metal oxide silicon (CMOS) standard cells, based on the standard complementary metal oxide silicon CMOS process in non-linear analogue current-mode circuits (Castañeda-Miranda et al., 2006). The implementation of a fuzzy controller in a field programmable gate array (FPGA) is attractive and presents a good option for irrigation technology development due to the fact that this platform is the most cost effective of all systems that can be envisioned to tightly control fertigation of crops. Moreover with an FPGA, we obtain complete engineering solutions on a single integrated circuit (SoC) allowing the system to be easily reconfigured and reused for different designs and applications. This characteristic provides rapid prototyping and the capability to perform multiple operations at the same time, producing a positive economic return, in other words, the relationship performance-price is very favorable for these kinds of devices. These devices have been used in many real life applications (Vega-Rodriguez et al., 2004) and a great number of contributions of FPGAs applications have been made in different fields (Ali et al., 2004; Romero-Troncoso et al., 2004; Castañeda et al., 2006).

IRRIGATION CONTROL SYSTEM

This irrigation control system is made up of two modules. One module named climate module is used to determine when and how much nutrient solution should be applied to the crop. The second defined as the nutrition module is in charge of pH control, nutrient solution dosage, and monitoring of the electrical conductivity (EC) (Figure 1). The climate module is based on a personal computer platform and the control algorithms were developed in C language. The inputs are climate variables and user parameters. The user parameters are time, cumulative solar radiation and volume of nutrient solution. These parameters are specific for each crop and decided on by the user because the system can control several greenhouses.

The outputs of this module are the amount and timing of each nutrient solution application. These outputs are calculated by the module in two ways. One in manual mode, where the user inputs in the PC how much and when to irrigate, and the second one in automatic mode, based on the climate conditions (temperature, humidity, solar radiation, air speed) and parameters specified by the user (cumulative radiation and time amount of irrigation). The nutrition module controls the nutrient solution quality by measuring pH, EC, nutrients *in situ* and adjusting these factors, namely:

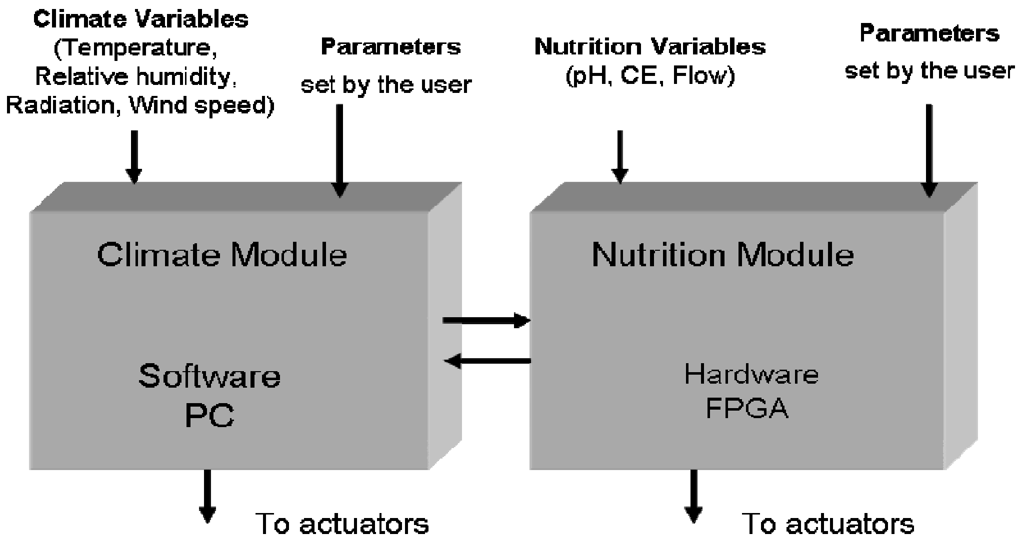

Figure 1. Irrigation control system.

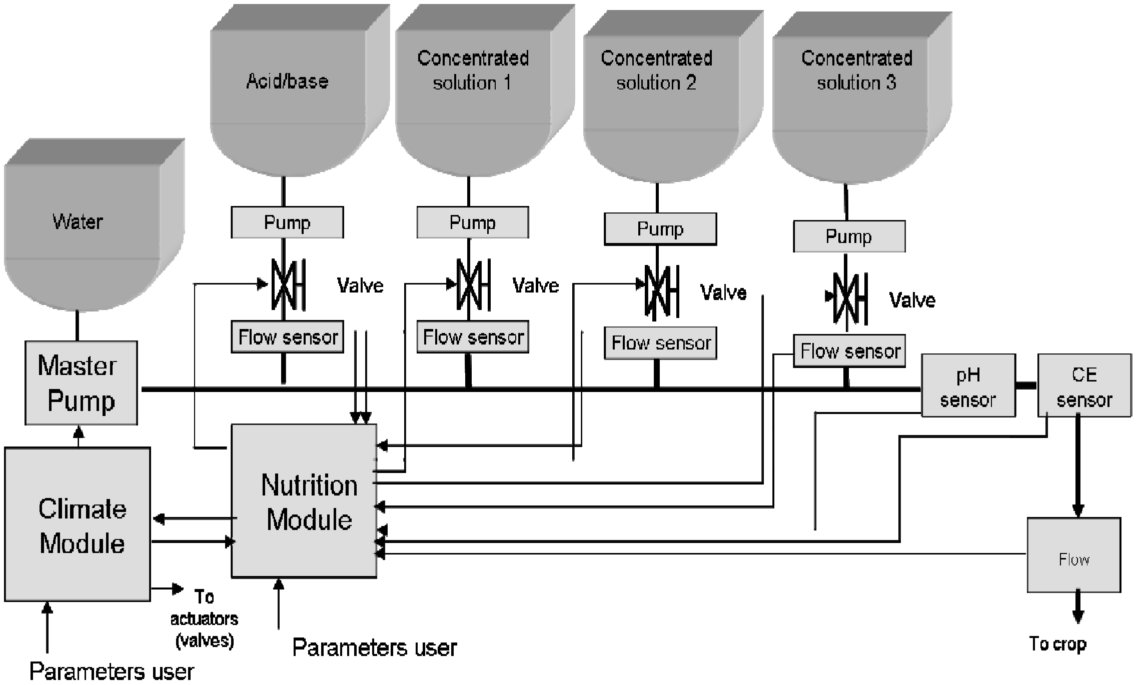

Figure 2. Required equipment for irrigation system implementation.

1. pH: Measures the acidity of the nutrient solution, and is controlled by the injection of a concentrated acid/base solution into the nutrient solution.
2. Dosage of the concentrated solution of fertilizers (DCFS): Related to the amount of concentrated solution of fertilizers that will be added to the water. Each one of the nutrients is kept in a separate tank.
3. Monitoring of electrical conductivity (EC): Related to the amount of fertilizers dissolved into the nutrient solution.

The module is based on a closed-loop control system that employs fuzzy logic in order to control the multivariable irrigation system with non-linear conditions related to pH levels, the amount of dissolved fertilizer, and EC. The nutrition module is based on hardware and implemented mainly in a FPGA. This allows us to free the PC from this task and leave the computational power to other more demanding tasks.

The implementation in a FPGA allows a complete engineering solution on a single integrated circuit (SoC), which can be easily reconfigured and reused for different designs (Castañeda-Miranda et al., 2006). The equipment required to implement the nutrition module, as shown in Figure 2, includes several tanks of

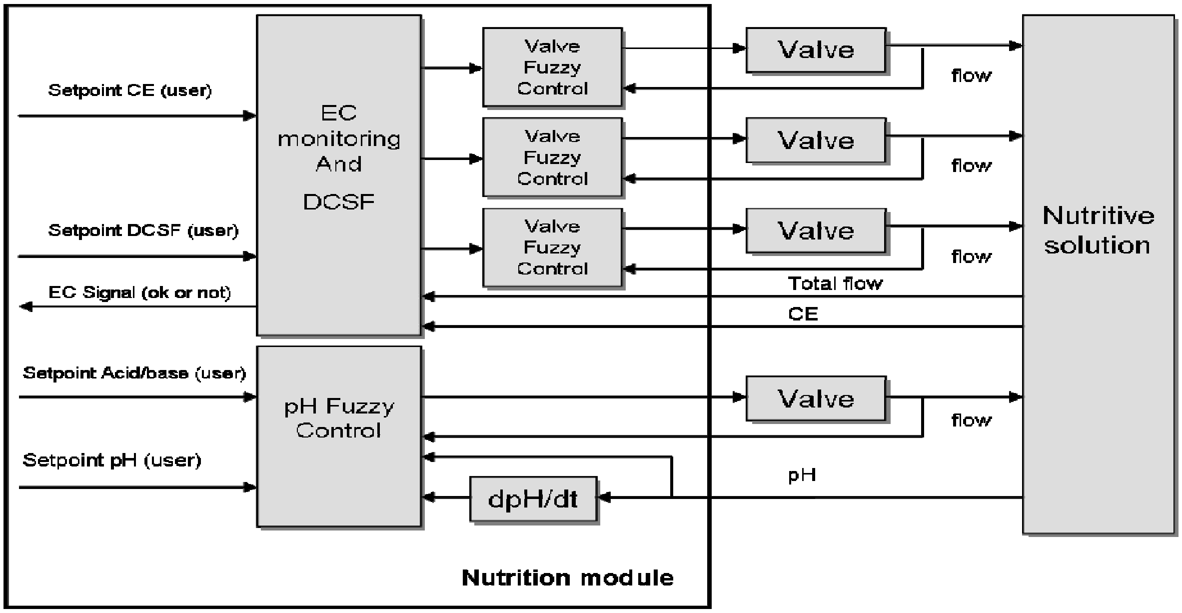

Figure 3. Block diagram of the nutrition module controller.

concentrated acid/base and fertilizer solutions operated by pumps and proportional valves with flow meters measuring the amount of solution extracted from each tank, and a master pump to inject water into a mixing pipe. The amount of nutrient solution coming out of the mixing pipe is in turn measured with another flow meter, and its pH and EC are measured by means of feedback sensors. In order to control the DCSF, the operator sets the controller to the amount of concentrated solution of fertilizers that will be added to the water. The control of the amount of concentrated solution to be added is performed using feedback data provided by the flow sensors. The desired pH of the solution is also selected by the user and is controlled using the feedback of the mixing pipe pH and flow sensors. According to the measurements provided by the sensors and the preprogrammed parameters, the controller activates the valves to control the pH and the DCSF.

The EC is also monitored in the mixing pipe and whenever the value crosses outside of the desired ranges, the nutrition module generates a signal which can be used as an alarm signal or as an input to a control alarm module. The input parameters used by the nutrition module are pH, acid/base, DCSF, and EC parameters (set points), and feedback variables (data gathered by the sensors). Parameters set by the user are: Set point for pH, (0 to 14); set point for acid or base, acid (1), base (0); set point for DCSF, (0 to 100%); set point for EC, (0 to10 mS/cm). If the EC exceeds a preset value in this range, an alarm signal is generated and user action is requested. These parameters are compared with the following feedback variables: Flow coming out from each tank, flow of nutrient solution coming out from the mixing pipe, pH of the nutrient solution, EC of the nutrient solution. The output variables computed by the fuzzy controller are used to perform control actions, namely, opening or closing of the valves of acid/base concentrated solution and/or tanks containing concentrated fertilizer solutions, with each tank operated (controlled) by an independent valve.

Nutrition module controller

Figure 3 describes the block diagram controller of nutrition module; the controller is operated by different interrelated sub-modules as thus explained.

pH fuzzy control

This sub-module deals with two different kinds of information, namely, user set points and feedback sensors (pH, variation of pH over time and flow of concentrated acid/base). The set point values, set by the user, are compared continuously with the feedback data in order to guarantee that the crop is grown under optimum conditions. The user must set the pH and the amount of acid/base to be injected. Thus, the feedback variables are: (1) Flow of acid/base concentrated solution; this represents the flow of solution from the acid/base tank. (2) pH of the nutrient solution; this represents the negative logarithm of the hydrogen ion concentration in the solution. (3) Variation in the pH of the nutrient solution; this represents the variation of the negative logarithm of the hydrogen ion concentration in the nutrient solution over time.

The output from this stage is the flow for the acid/base valve. This represents the amount of concentrated acid/base solution that needs to be added to the nutrient solution (Figure 3). The fuzzy input variables of the controller are: 1) Variation pH: this represents the variation of the current pH of the nutrient solution over time. 2) pH error: this represents the difference between the set point pH and the actual pH of the nutrient solution. 3) Acid/base: this represents the solution to be added, whether it is acid or base.

The controller fuzzy output variable is named required flow. This is the required flow from the concentrated acid/base solution container to be added to the nutrient solution in order to control the pH (Figure 5). The reason these variables where selected was because of the non-linear behavior of the pH in the nutrient solution when acids or bases are added to the solution. Figure 4 shows pH values of a 10 L tank with the addition of a sulfuric acid solution of 1, 2 and 3%. Figure 4 clearly demonstrated that the pH of a nutrient solution can show tremendous variation when the same volume of different concentrations of an acid/base solution are added to a nutrient solution. Developing a deterministic model for this process can be quite complex and expensive. However, a fuzzy controller can provide an efficient solution to this problem. Taking into

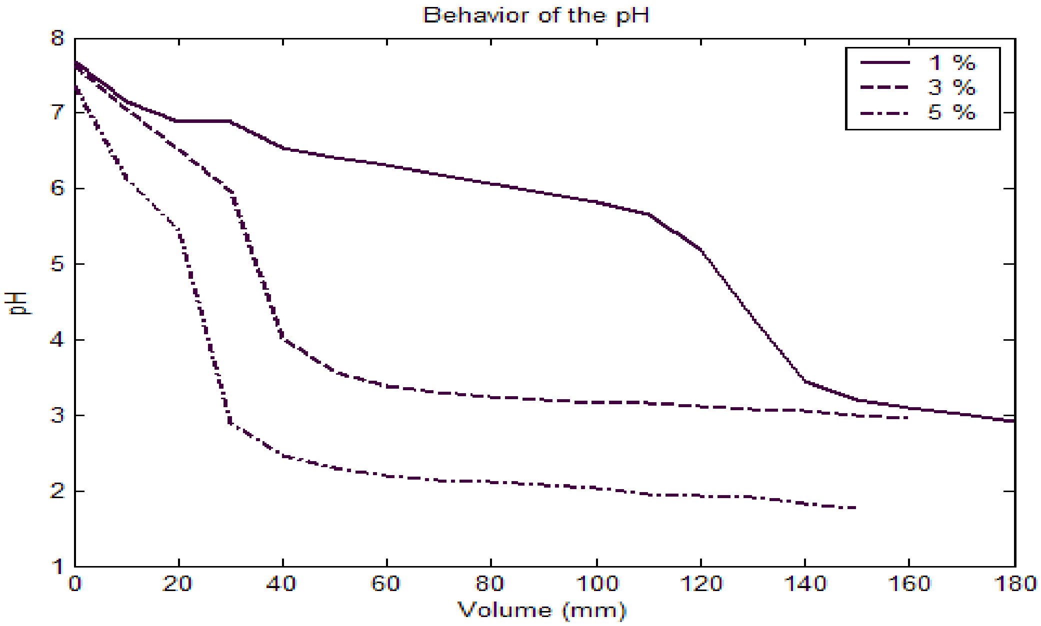

Figure 4. pH behavior at different concentration levels.

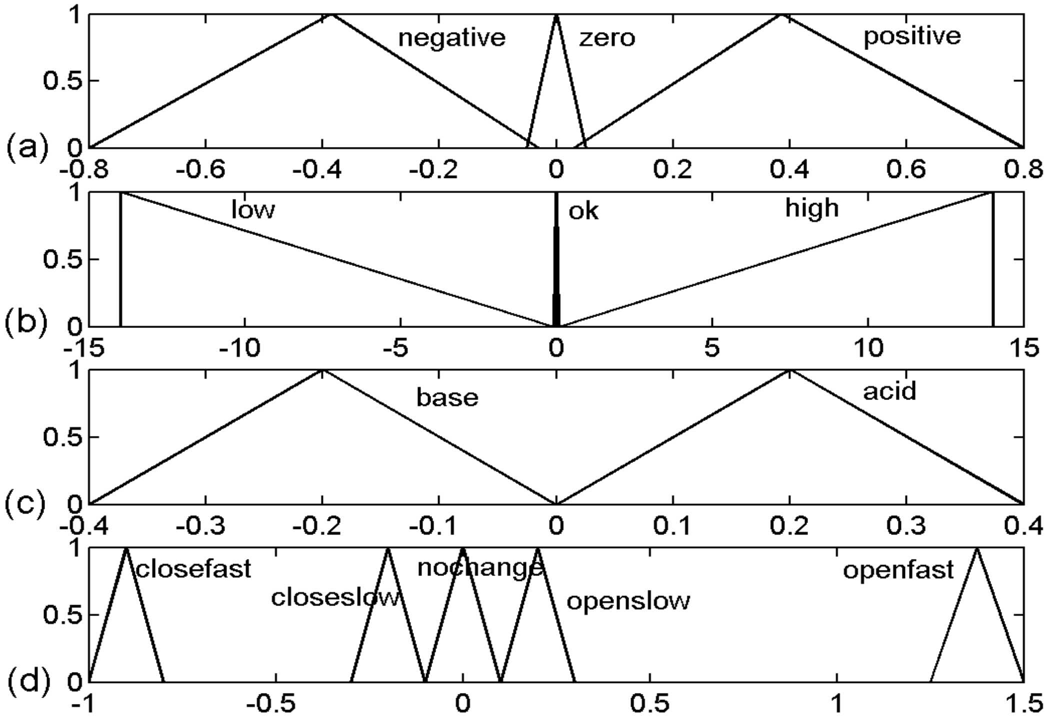

Figure 5. Membership functions for the pH fuzzy controller: (a) Variation pH, (b) pH error, (c) acid or base, (d) required flow.

consideration the non linear behavior of the pH values of nutrient solution, membership functions for the fuzzy controller were designed as shown in Figure 5. For example, the pH error variable lies in a range from -14 to 14 and, due to its behavior (Figure 4), three membership functions were chosen, namely, low, okay and high, and the ranges were set taking into consideration the non-linear behavior of this variable in the control context; similarly, in each case, the other membership functions were chosen according to the control problem nature.

The membership functions were set following a try and error

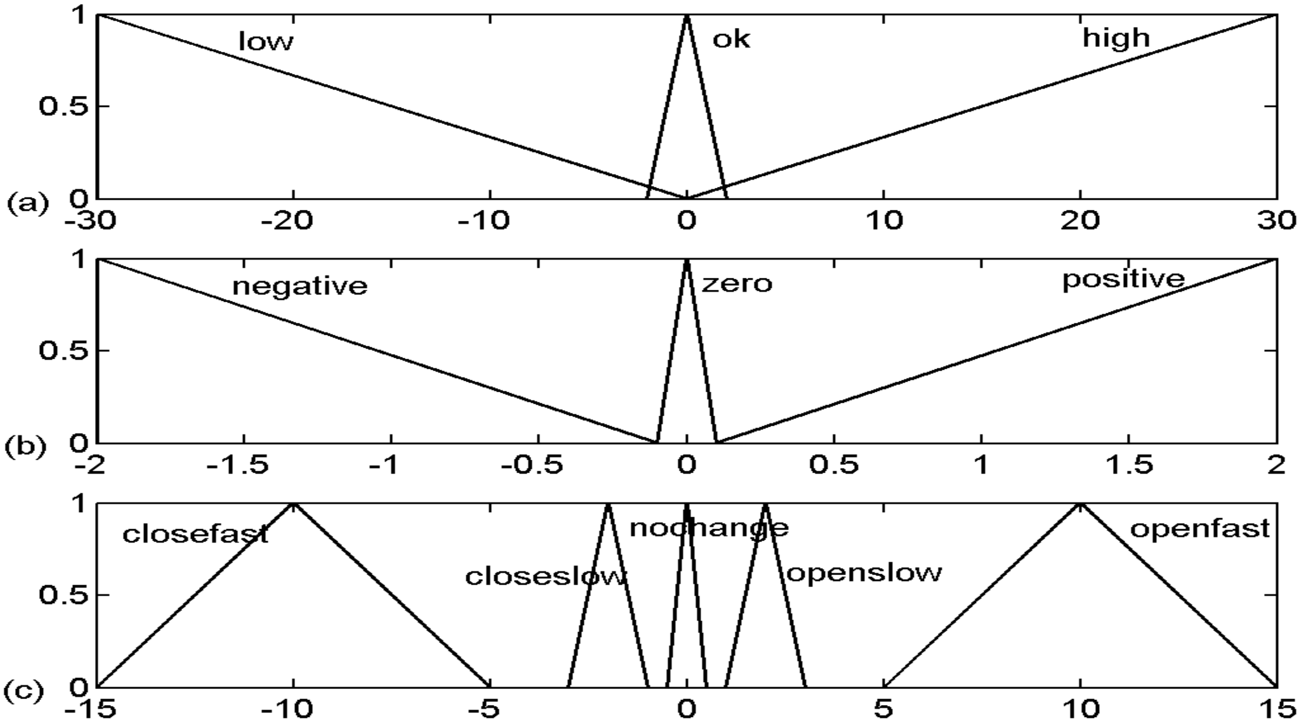

Figure 6. Membership functions for the valve fuzzy controller: (a) Error, (b) variation error, (c) valve.

strategy by making simulations in MATLAB until reaching optimum performance through careful tuning. The set of fuzzy rules to develop the control system for each variable has been obtained from an expert. In order to fine tune these rules, as well as the membership functions, we again used a try and error strategy, until the set of rules reached satisfactory performance in the simulations. Each linguistic input value is assigned to an action in the system.

The system consists of nine rules:

1. If pH error is okay then required flow is not changed.
2. If pH error is low and acid or base is acid, then required flow is opened fast.
3. If pH error is high and acid or base is acid, then required flow is closed fast.
4. If pH error is okay and variation pH is negative and acid or base is acid, then required flow is opened slowly.
5. If pH error is okay and variation pH is positive and acid or base is acid, then required flow is closed slowly.
6. If pH error is low and acid or base is base, then required flow is closed fast.
7. If pH error is high and acid or base is base, then required flow is opened fast.
8. If pH error is okay and variation pH is negative and acid or base is base, then required flow is closed slowly.
9. If pH error is okay and variation pH is positive and acid or base is base, then required flow is opened slowly.

EC monitoring and DCSF

This sub module deals with two different kinds of information, namely, user set points (EC, DCSF) and feedback variables. The feedback variables are: (1) Total flow of nutrient solution; this represents the total flow of nutrient solution to fertilize the crop. (2) Electrical conductivity: this represents the amount of fertilizer in the nutrient solutions. The outputs from this sub-module are the flow for each valve of the concentrated nutrient solutions. In other words, this represents the amount of concentrated nutrient solution against the total flow that needs to be added to the nutrient solution. The sub-module has an output for signal EC, used to indicate if the EC is out of the programmed range (Figure 3).

Valve fuzzy control

In this sub-module, the desired flow which comes from EC monitoring and the DCSF sub-module, was compared to the measured actual flow. Following this comparison, a decision can be made to control the amount of each concentrated solution that will be added to the nutrient solution. This sub-module is applied to every container of concentrated nutrient solution (Figure 3). The fuzzy input variable for the valve fuzzy controller is the error, that is, the difference between the desired flow and the current concentrated solution flow and variation error, that is, the variation of the error over time. The output fuzzy variable is the opening or closing of the valve; that is, the amount of flow the valve shall be allowed to pass through the pipe (Figure 6). For example, the input error variable has three membership functions; namely, low, okay, and high. Its ranges were chosen due to the simplicity of the injection system (valve and pump). Similarly, and in each case, the other membership functions were chosen by virtue of the nature of the control problem. The membership functions were determined following a try and error strategy. Simulations in MATLAB were carried out until we reached optimum (adequate) performance through a careful tuning of the system.

Implementation in FPGA

The designs are described in a hardware description language

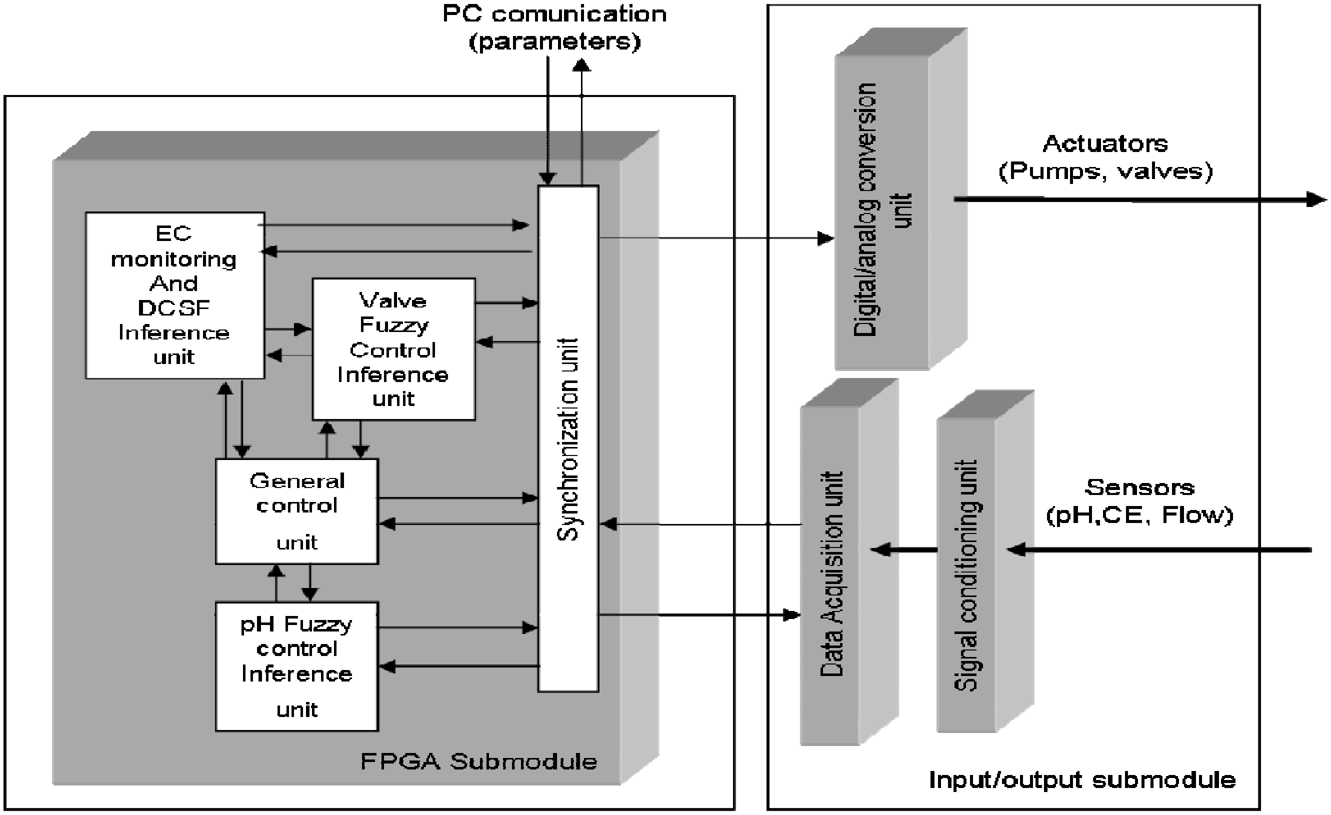

Figure 7. Nutrition module.

(HDL) and were confirmed through simulation. The implementation scheme of the nutrition module is shown in Figure 7. It consists of two sub modules. The input/output sub module receives the value of the sensors which measure the pH, EC, and flow from the irrigation system. This signal is then transmitted to the signal conditioning unit which eliminates noise from the signal. The data-acquisition unit is a 12 bit analogue-to-digital converter made by Burr-Brown (1998).

The FPGA sub module consists of the synchronization unit, pH fuzzy control inference unit, EC monitoring and DCSF inference unit, valve fuzzy control inference unit, and a general control unit. All digital structures were described using very high-speed integrated circuit hardware description language (VHDL). The FPGA sub module was implemented in a FPGA A54SX32A-TQ144 (Actel, 2001) with standard speed and 144 configurable inputs/outputs. The FPGA has 32000 gates and 1080 flip-flops with 150 MHz of internal frequency and an external frequency of 10 MHz. All simulations were made in an active HDL simulator. Logical synthesis was carried out using Synplify Pro 7_0 (Synplicity, 2001), and its FPGA implementation was made using software Designer v5_0 (Actel, 2001).

General control unit

The objectives of this unit are the synchronization and control of the different units on the FPGA sub module. The general control module is a state machine which communicates with the synchronization unit in order to coordinate the inputs and outputs to the module. The inputs are the user parameters, sensor signals, and the outputs are the signals that control the actuators. This coordination of inputs and outputs is done through the control block located in the synchronization unit. At the same time, the general control unit coordinates the information flow between the EC monitoring and DCSF inference unit, pH fuzzy control inference unit, and valve fuzzy control inference (Figure 7).

Synchronization unit

The synchronization unit provides an interface that enables the connection to an external computer, to the data acquisition unit, and to the digital/analog conversion unit (Figure 8). The synchronization unit consists of a control block which is in charge of the synchronization and control of the inputs to the module. It controls register 1 which has as its function to store information from read only memory (ROM) 1 making it possible to communicate with the PC. The control block also controls register 2 which stores external information such as set point pH, set point EC, % solution 1% solution 2% solution 3, acid/base acid (1) base (0), register 3 which stores information coming from the three control inference units (Figure 8), has crisp outputs which are directed to the digital/analog conversion unit. The control block also directs register 4 which captures information coming from ROM 2, the signal used for communication with the data acquisition unit. The control block also manages register 5 which stores status information of the sensors.

pH fuzzy control inference unit

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. In this unit, there are 5

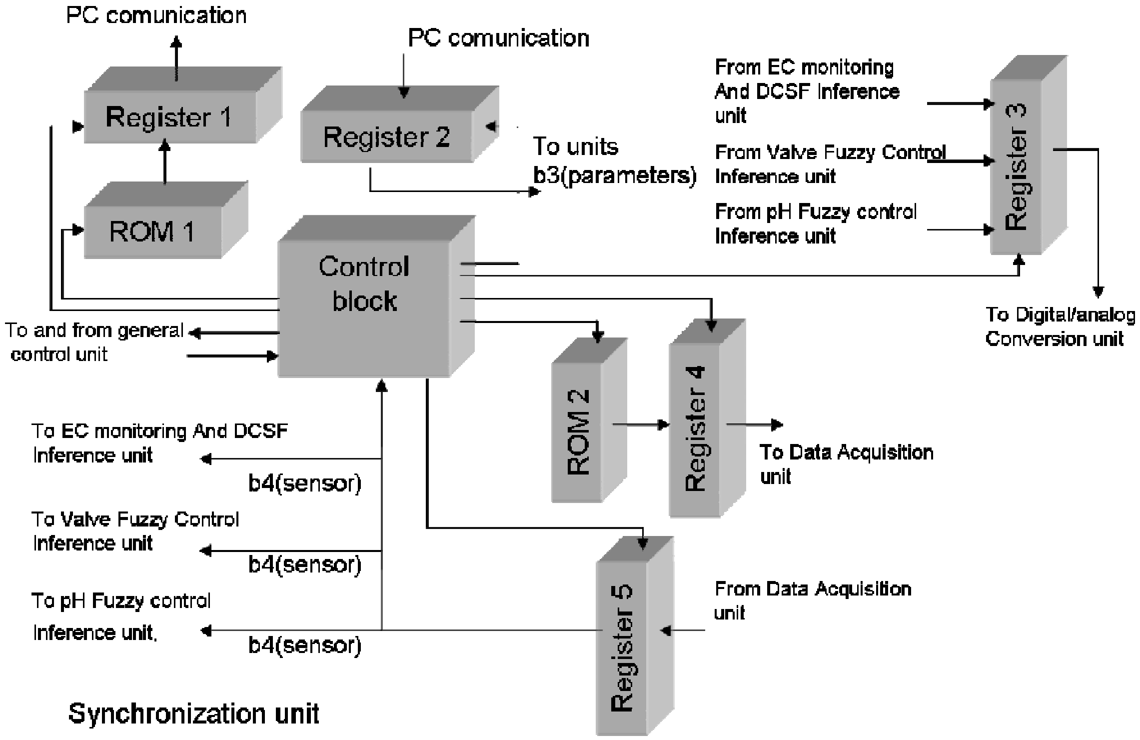

Figure 8. Synchronization units.

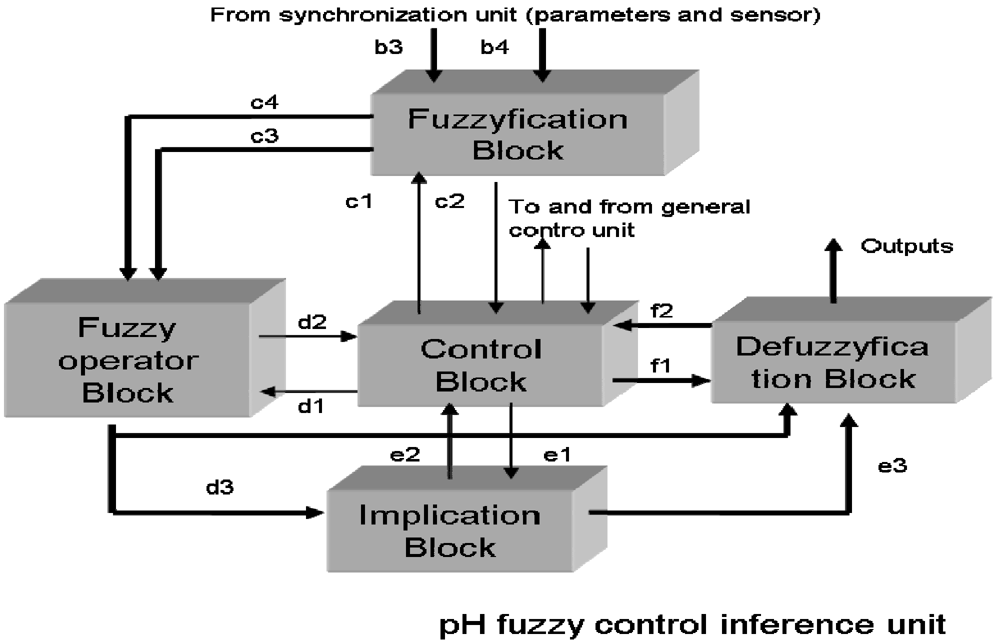

Figure 9. pH fuzzy control inference unit.

blocks which make up the inference process: the fuzzification block, the fuzzy operator block, the implication block, the defuzzification block, and the control block all explained later (Figure 9). The objective of the control block in the synchronization and control of the unit is to communicate with the other blocks through the signals c1, c2, d1, d2, e1, e2, f1, f2, and with the general control unit (Figure 9).

Fuzzyfication block: In this block we take inputs b3 and b4 (from the synchronization unit) and determine the degree to which they

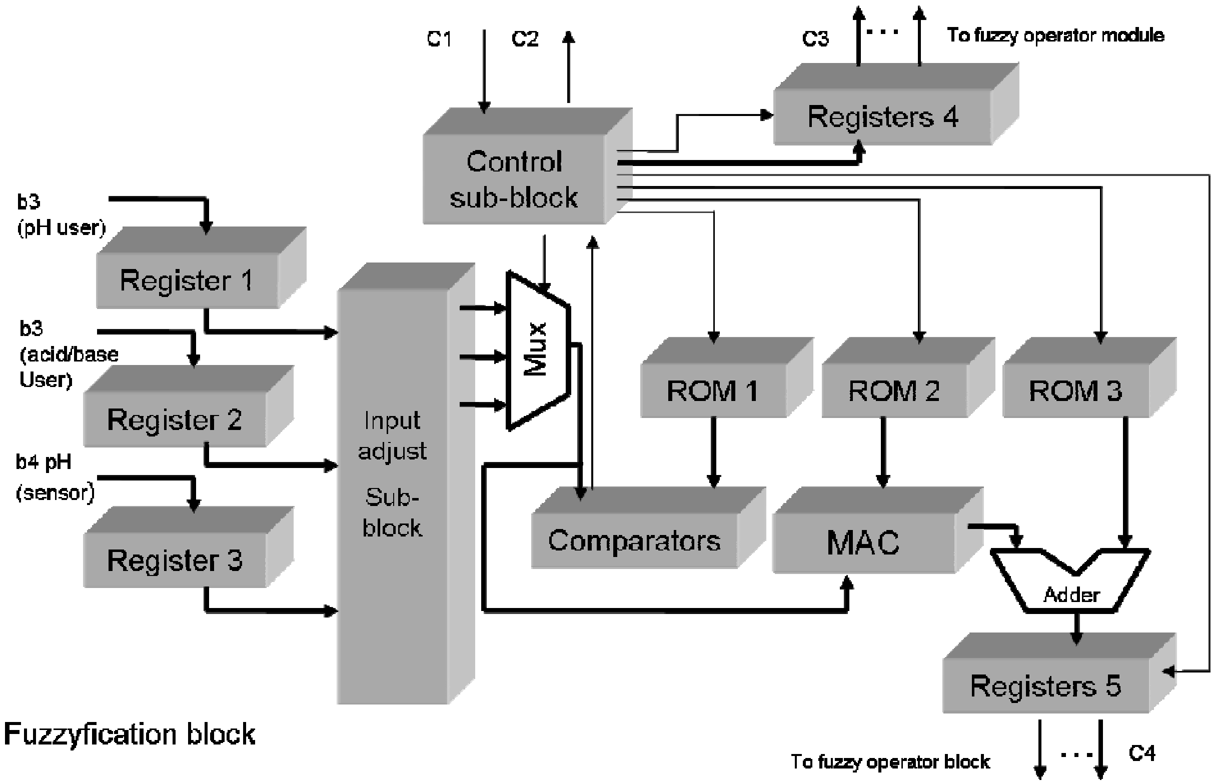

Figure 10. Structure of the fuzzyfication block.

belong to each of the fuzzy sets using membership functions. The output is a fuzzy degree of membership (interval between 0 and 1). The structure of this module is shown in Figure 10. For a process map, the inputs are stored in the registers 1, 2 and 3 afterwards each variable is fuzzified. The information coming from inputs b3 and b4 is sent to the sub-block. Input adjust where the real values of the pH fuzzy control inference unit, error pH (pH user to pH sensor, b3 to b4), variation error (pH/time, b4/time) and acid/base are calculated.

The input variables are selected by the control sub-block using a multiplexer (MUX). The variables are then compared with the stored values in the ROM block, which contains the membership functions. The ROM is a 2048 by 12 bit. The objective of this comparison is to determine to which membership function the input variable belongs. This information is stored in register 4. Depending on which membership function belongs to the variable, it is multiplied by the corresponding information coming from the second ROM 2. This function is carried out by a multiplier accumulator (MAC). The MAC block is 12 x 12 bits, and based on the sequential algorithm Radix-4 of Booth (Rubinfield, 1975). Later the result is added with the data stored in ROM 3 (variable membership degree) and stored in the register 5 which handle signal c4. The ROM 2 and ROM 3 contain the membership information of each variable.

Fuzzy operator block: In this block the rules set is applied. The rules are of the type “if A is X then B is Y”, where, A and B are fuzzy variables, and X and Y are fuzzy terms. The section of the rule “*x* is *A*” is called the *antecedent* and the section of the rule “*y* is *B*” is called the *consequent*. The outputs of the fuzzy operator module represent the result of the antecedent for that rule. The structure of this module is shown in Figure 11. The information inputs c3 and c4 come from the fuzzyfication block and it implies which membership function each variable and its membership degree belongs to. Next to the information is selected by the control sub-block through a set of multiplexers and compared to information stored in a ROM that contains the system fuzzy rules. The fuzzy logic operators are applied to the value that indicates degree of membership. The resulting values are then again selected by a multiplexer. The result of this operation is a value between 0 and 1 which represents the weight of each rule. This result is stored in a set of registers and available as signal d3.

Implication block: This block has as its input the weight of each rule coming from the fuzzy operator block (d3) and as an output (e3) the result of the multiplication of each rule weight by the rule consequence which is stored in a ROM. The structure of this module is shown in Figure 12. The weight of each rule is selected by a control module block through a multiplexer and multiplied by the rule consequence. This multiplication is done by a MAC. The MAC block is 12 x 12 bits and based on the sequential algorithm Radix-4 of Booth (Rubinfield, 1975). The result is stored in a register and available through signal e3.

Defuzzyfication block: The purpose of this block is the calculation of the pH fuzzy control inference output. For this stage, the defuzzyfication is calculated by the centers average method Equation 1:

$$\text{Outputs} = \frac{\sum e3}{\sum d3} \qquad (1)$$

The structure of this module is shown in Figure 13. The block receives information from the fuzzy operator block (d3) which transmits the weight of each rule to the defuzzyfication module.

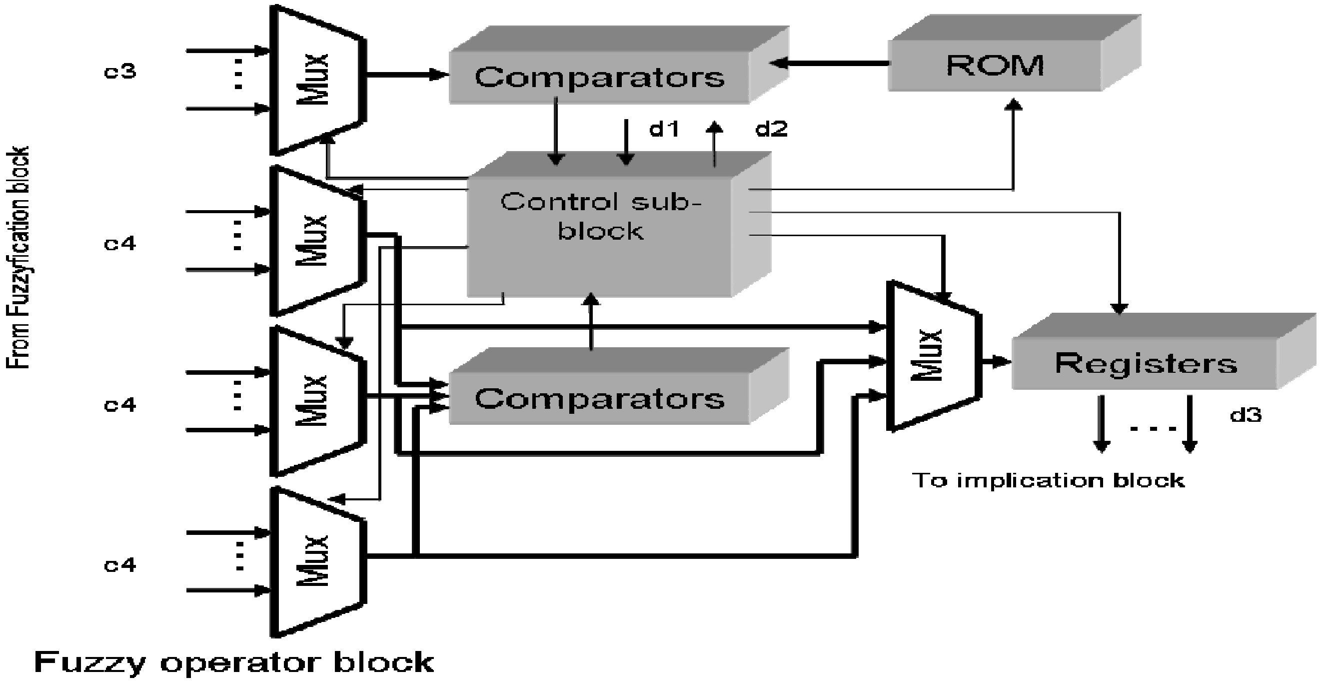

Figure 11. Structure of the Fuzzy operator block.

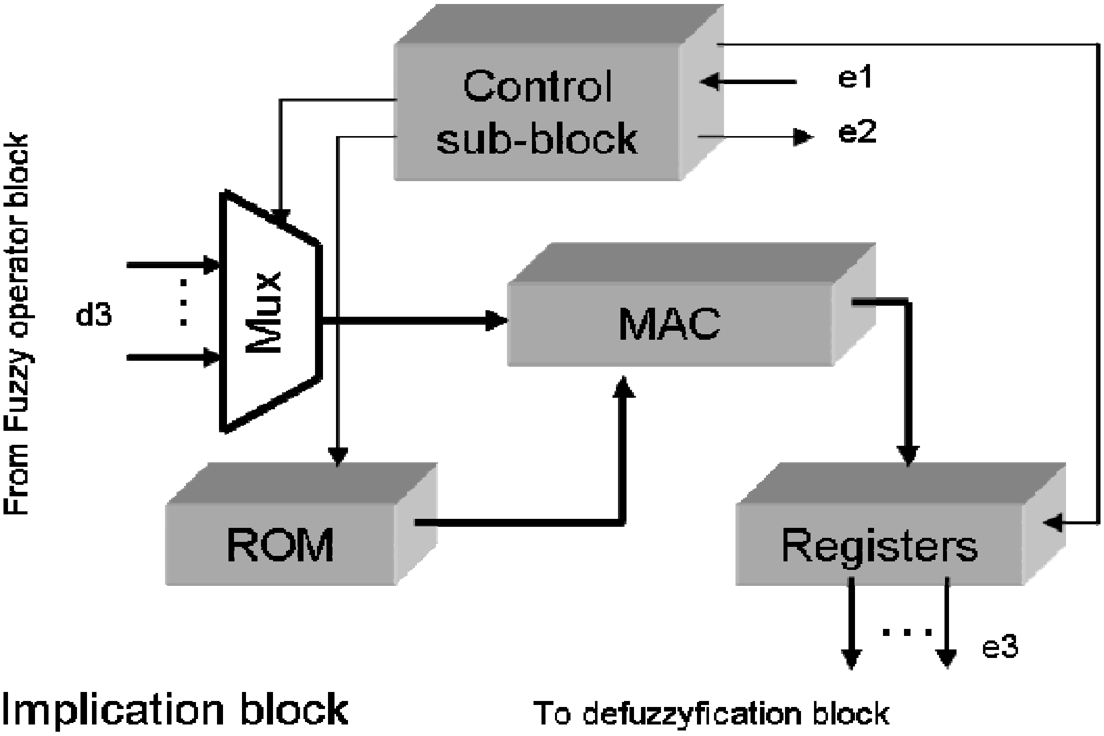

Figure 12. Structure of the implication block.

This weight is selected by a control module block through a multiplexer. The defuzzyfication block also receives information from the implication module block (e3), which sends the result of the multiplication of the weight by the consequence rule. Both inputs are added and stored. The result of this operation is the numerator and denominator which are used as input for the division

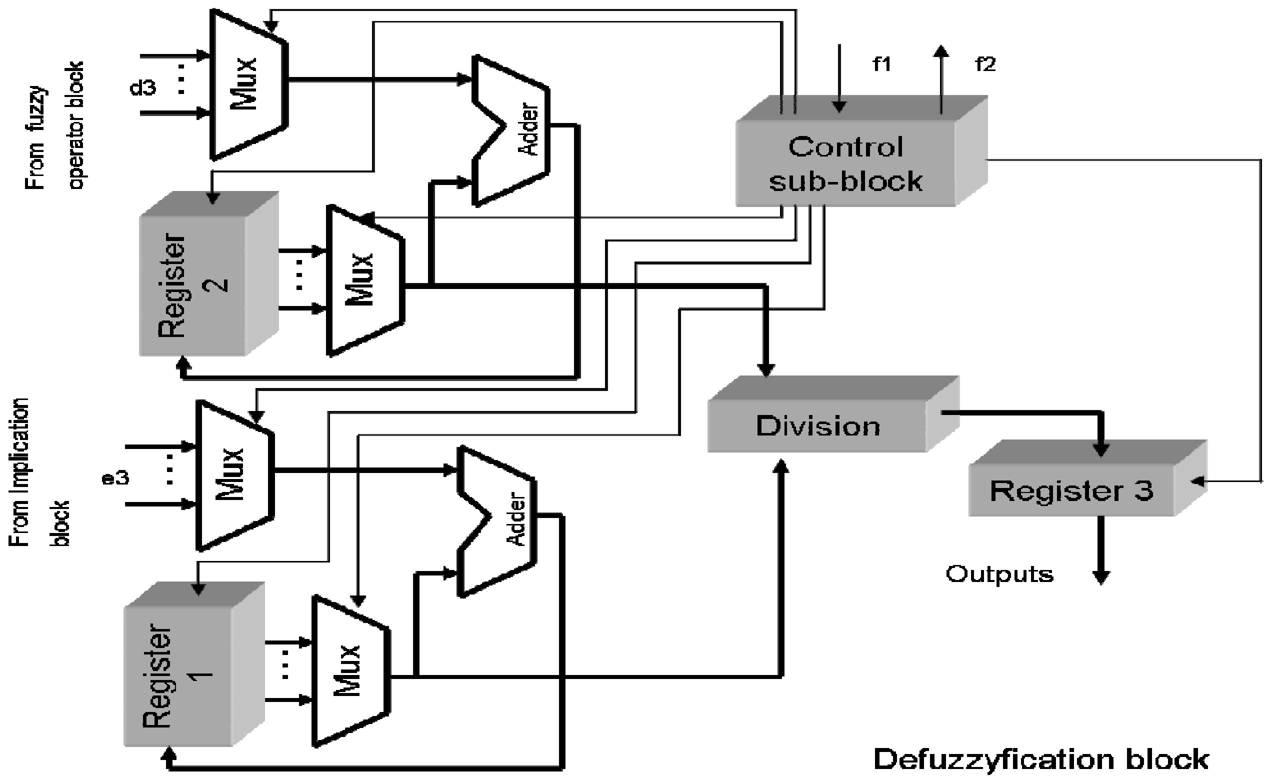

Figure13. Structure of the defuzzyfication module.

sub-block. This sub-block generates the pH fuzzy control inference output which is stored in register 3.

EC monitoring and DCSF Inference

The EC monitoring and DCSF inference block has the role of monitoring EC and to calculate the flow for each valve of the concentrated nutrient solutions. In other words, it calculates the amount of the concentrated nutrient solutions against the total flow of the nutrient solution (Figure 14). The signals b3 and b4 are stored in registers and are used to calculate the flow from each concentrated nutrient solution tank and to monitor the EC. The information stored in registers 1, 2 and 3 are multiplied by the total flow by a MAC with the output being sent to the valve fuzzy control inference unit. The information stored in register 5 goes through an error module block where it is compared with the information stored in register 6 with the purpose of determining if the EC signal falls within the tolerance range. The signal is then sent to the synchronization unit.

Valve fuzzy control inference unit

There are three sub-units in this module, the valve fuzzy control inference sub-unit 1, the valve fuzzy control inference sub-unit 2, and the valve fuzzy control inference sub-unit 3. Each one of the sub-units is independent to open or close of valve of a particular concentrated nutrient solution. In other words, every tank of concentrated nutrient solution has one independent valve (Figure 15). Each sub-unit has a similar scheme as depicted in Figure 9, including the same blocks but with only two inputs, in this case error and variation error.

EXPERIMENTAL RESULTS

In order to test our prototype of a fuzzy irrigation control system based on a FPGA, a number of experiments were conducted and performance indicators collected. The synthesis (analysis) of the FPGA showed a use of 1570 combinational cells from 1800 available and 520 sequential cells from 1080 available for a 72% utilization. The system operates with a base clock of 10 MHz The simulations were made using MATLAB Simulink tool and tested in a hydroponic commercial tomato greenhouse unit with an area of 5000 square meters and a plant density of 2.6 plants per square meter. The nutrient solution used for the tomato crop was a standard hydroponic fertilizer. The experimental system is made up of four solution tanks, namely: A concentrated calcium nitrate solution, other (non-calcium) macronutrients solution, micronutrients and concentrated sulfuric acid for pH regulation.

In the simulation and in the experiment of the pH control, we used different inputs which oscillate between 5.5 and 6.5, which is the recommended pH for most commercial crops. We also used different percentages of the acid solution to determine the performance of the system. Figure 16 shows the results of the simulation and the real experiment. For the simulation and real experiment of the EC control, it is important to mention that the user chooses the concentration of the nutrient

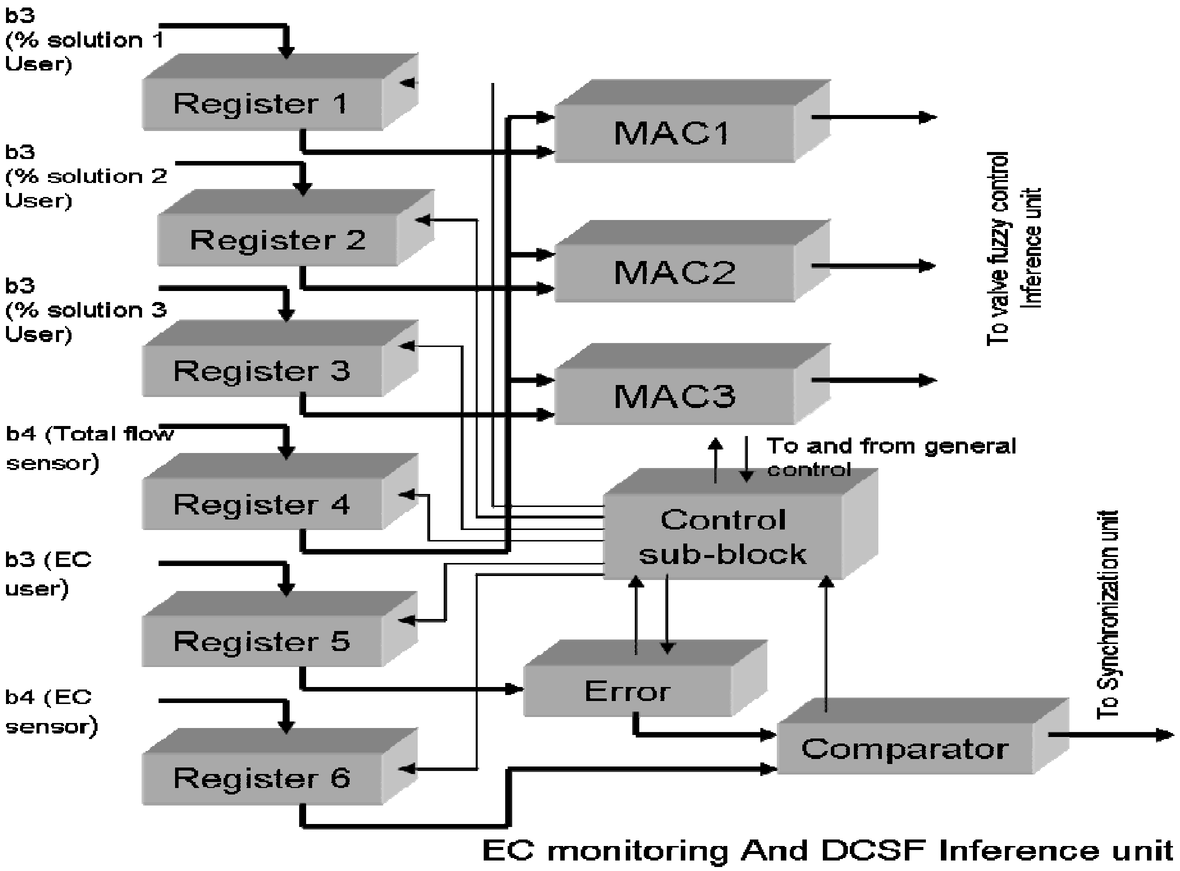

Figure 14. EC monitoring and DCSF inference unit.

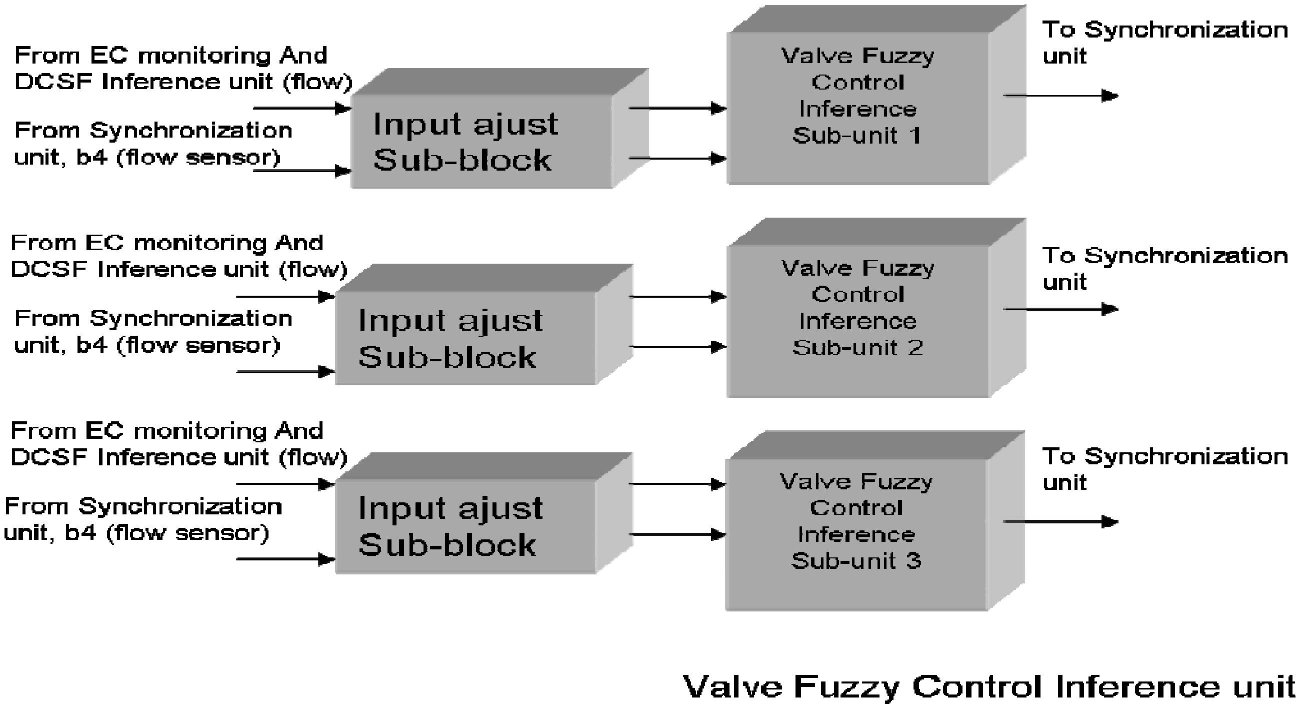

Figure 15. Valve fuzzy control unit.

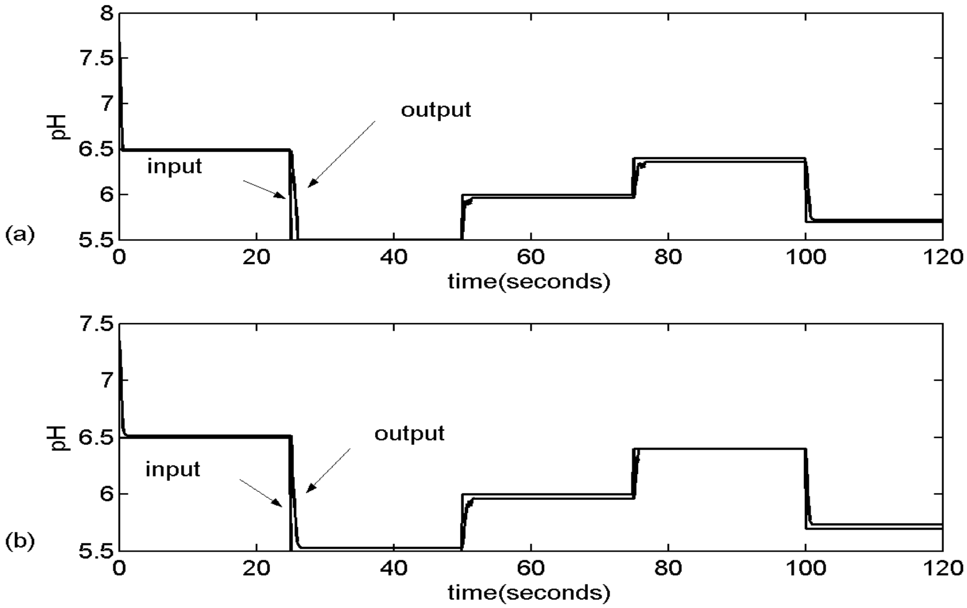

Figure 16. Results of the pH fuzzy controller: (a) acid concentrated solution at 2%, (b) acid concentrated solution at 4%.

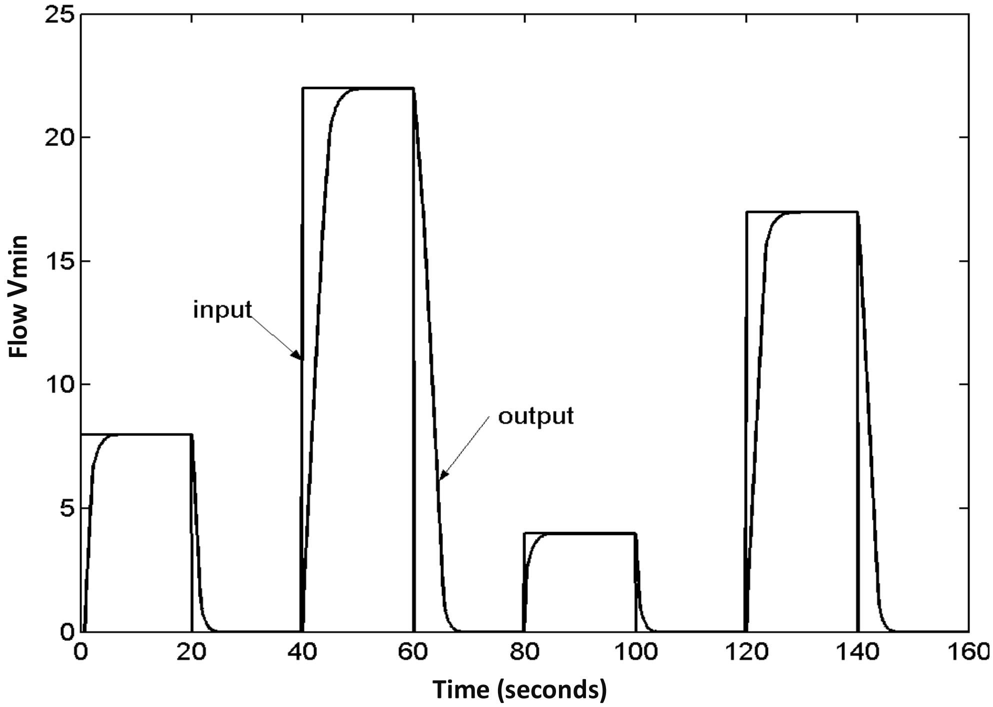

Figure 17. Result of the valve fuzzy controller.

solution in each tank that should be applied to the system. The amount of solution provided by each tank increased the EC and it is important that the user selects the exact amount to be used at each step of crop production. Failure to do so will lead to toxicities and deficits of some elements and results in reduced yields. We used inputs to the system in the range of 4 to 25 l/min which is equal to a range of nutrient solution concentration of 10 to 300% when compared to the standard nutrient solution used in greenhouses (see above). Figure 17 shows the simulation and the real experiment of the valves to control the amount of nutrient solution injected in the system.

Conclusions

We described a simple approach to fuzzy control implemented in a FPGA for the purpose of automating and controlling fertigation in greenhouses. First, we explained the operation of the general system and its components with low cost and reliability of the design in mind. An important advantage of our system is the modularity of its sub-modules. In fact, each sub-module unit can be operated as an independent one; this simplified the present development and will enable us to further enhance, adjust, and add modules as needed. Some examples were presented to prove that the system operates within the proper range of what would be required to produce crops and to demonstrate its stability.

It is important to notice that this system has the potential to save a significant amount of water and nutrients making it a very economical fertigation control option compared to conventional systems based on its outstanding correlation between simulated crop demand and nutrient solution delivery. The fuzzy control is adaptable, simple, and easily implemented and therefore represents an excellent tool to be applied to the optimization of fertigation systems. The use of a FPGA allows the development of a system in a short time period, at low cost, and allows the integration of an engineering solution on-a-chip (SoC). The fuzzy controller structure is an efficient option for its FPGA implementation. According to the experimental analysis, the system showed excellent performance and should allow for optimal fertigation control in a variety of greenhouses with crops that have different nutritional needs. The system can be easily incorporated into a standard irrigation system, an option that may be quite attractive to growers.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Rene Romero Troncoso, Dr. Roberto Gomez, Dr. Juan J. Garcia, for their collaboration and support of this work.

REFERENCES

Actel Corporation (2001). SX-A Family FPGAs Datasheet. Actel Corporation, USA.

Ali L, Sidek R, Aris I, Ali A, Suparjo BS (2004). Design of a micro-UART for SoC application. Comput. Electrical Eng., 30: 257-268.

Burr Brown Corporation (1998). ADS7862 Datasheet. Burr Brown Corporation, USA.

Castañeda-Miranda R, Ventura-Ramos E, Peniche-Vera R, Herrera-Ruiz G (2006). Fuzzy Greenhouse Climate Control System based on a Field Programmable Gate Array. Biosyst. Eng., 94(2): 165-177.

Yang CC, Chao K, Chen YR, Kim MS, Chan DE (2006). Development of Fuzzy Logic Based Differentiation Algorithm and Fast Line-scan Imaging System for Chicken Inspection. Biosyst. Eng., 95(4): 483-496.

Gieling ThH, Janssen HJJ, Van Straten G (2000). Identification and simulated control of greenhouse closed water supply systems. Comput. Electron. Agric., 26: 361-374.

Kell K, Beck M, Frenz FW (1999). Automated ecological fertilisation and irrigation of soil grown crops in greenhouses with a computer controlled system (KLIWADU). Acta Hortic., 481: 609-616.

Lee CC (1990). Fuzzy logic in control systems: fuzzy logic controller-(parts I and II). Trans. Syst. Man Cybern., 20: 404-432.

Leilei Pan, Simon XY (2007). Analysing livestock farm odour using an adaptive neuro-fuzzy approach. Biosyst. Eng., 97(3): 387-393.

Luthra SK, Kaledhonkar MJ, Singh OP, Tyagi NK (1997). Design and development of an auto irrigation system. Agric. Water Manage., 33: 169-181.

Mendoza-Jasso J, Ornelas-Vargas G, Castañeda-Miranda R, Ventura-Ramos E, Zepeda-Garrido A, Herrera-Ruiz G (2005). FPGA-based real-time remote monitoring system. Comput. Electron. Agric., 49: 272-285.

Passino M (1998). Fuzzy Control. Department of Electrical Engineering. Addison-Wesley, Longman Inc, California, USA.

Romero-Troncoso R, Herrera-Ruiz G, Terol-Villalobos I, Jáuregui-Correa JC (2004). FPGA based on-line tool breakage detection system for CNC milling machines. Mechatronics, 14: 439-454.

Rubinfield LP (1975). A proof of the modified Booth's algorithm for multiplication. IEEE Trans. Comput., 25(10): 1014-1015.

Synplicity (2001). Synplify Pro Reference Manual. Synplicity Inc, California, USA.

Vega-Rodriguez MA, Sanchez-Perez JM, Gomez-Pulido JA (2004). Special issue on FPGAs: applications and designs. Microprocessors Microsyst., 28: 193-195.