Biosystems Engineering (2006) **94** (2), 165–177
doi:10.1016/j.biosystemseng.2006.02.012
AE—Automation and Emerging Technologies

Available online at www.sciencedirect.com
SCIENCE DIRECT®

ELSEVIER

Fuzzy Greenhouse Climate Control System based on a Field Programmable Gate Array

Rodrigo Castañeda-Miranda; Eusebio Ventura-Ramos Jr.; Rebeca del Rocío Peniche-Vera; Gilberto Herrera-Ruiz

Biotronics Laboratory, Faculty of Engineering, Universidad Autónoma de Querétaro, Cerro de las Campanas s/n, Querétaro, Qro. México. CP., 76010, Mexico; e-mail of corresponding author: rcast@uaq.mx

(Received 25 January 2006; accepted in revised form 16 February 2006; published online 21 April 2006)

Fuzzy control is a practical alternative for the design of a great variety of control applications. It provides an advisable method for the design of non-linear controllers using heuristic information. This article presents the development of a greenhouse intelligent climate control system that uses a fuzzy controller, based on a field programmable gate array (FPGA). The FPGA has a great potential for use in agricultural technology development due to its characteristics to produce fast prototypes of complex hardware designs with an effective production cost. A low-cost intelligent system designed in a single chip with the task to carry out the complete functionality for the greenhouse climate control was developed. The system proposed here is a good option to unload the low-level tasks (monitoring of climate variables and operation of actuators, such as heaters and windows to control the greenhouse inside temperature) from the main control system, in order to leave to the main controller the high-level tasks as plant monitoring, control of vegetative development, production planning, irrigation system control, which need a high computational power. The system developed in this work consists of: a signal conditioning sub-system, a data-acquisition sub-system, digital/analogue conversion sub-system and a FPGA sub-system. The FPGA sub-system has three units: the synchronisation unit, the personal computer interface unit and the fuzzy logic unit, all implemented within a FPGA-integrated circuit, conforming to a system-on-a-chip (SoC). The design, compilation and simulation of the FPGA sub-system were carried out in the Active-HDL environment using the hardware description language VHDL. The Co-simulation Active-HDL/Simulink and experiments that show the performance of the complete system are presented.

1. Introduction

Under greenhouse production, the climate control is a tool used for crop yield manipulation which maximise the entrepreneurial benefits. Once the objectives that optimise crop growth and development are defined, the control engineer must design and implement automatic control systems that make possible to obtain a maximum crop yield at minimum production costs. In this sense, control engineering has undergone a considerable development. Researchers have used many control techniques in different fields, from the conventional or classic strategies [proportional integral derivative (PID) control, cascade], artificial intelligence (AI) (fuzzy control, neural networks, genetic algorithms), advanced control techniques (predictive control, adaptive), to robust control strategies, no-linear and optimal control. Specifically, they have been applied in the area of greenhouse climatic control (Lees *et al.*, 1996; Hanan, 1998; Tap, 2000).

Conventional control techniques are difficult to implement in greenhouse systems due to their multi-variable and non-linear nature, where inter-relations between internal and external variables are complex (physical non-linear phenomena that governs these systems dynamics are complicated). This provides justification for the use of intelligent control techniques as a good alternative. In this way, fuzzy logic as part of AI techniques is an attractive and well-established

Notation

A_g	covered ground surface, m^{-2}
A_r	roof to soil rate, $m^2 m^{-2}$
C	greenhouse heat capacity, $J K^{-1} m^{-2}$
C_j	consequence rules
C_p	air specific heat, $J K^{-1} kg^{-1}$
d_{et}	change in the error
e_i	internal mean vapour pressure, Pa
e_t	temperature error, °C
G	outside short-wave radiation, $W m^{-2}$
I_{LA}	leaf area index, $m^2 m^{-2}$
k_1, k_2	regression coefficients
L_j	fuggy set
m_{fmj}	minimum membership value
O_R	output result
p	parameter vector
q_h	heat input, $W m^{-2}$
R_i	internal relative humidity, %
R_o	outside relative humidity, %
r_s	stomatic resistance, $s m^{-1}$
r_a	aerodynamic resistance, $s m^{-1}$
S	model sensitivity
T_i	internal air temperature, K
T_c	crop temperature, K
T_g	ground temperature, K
T_o	external air temperature, K
T_r	roof temperature, K
T_s	set-point temperature, K
t	time, s
V_l	greenhouse air to soil area rate, $m^3 m^{-2}$
w	wind speed, $m s^{-1}$
x	measured value
x_i	internal absolute humidity, $kg m^{-1}$
x_g	soil absolute humidity, $kg m^{-3}$
x_o	external absolute humidity, $kg m^{-3}$
x_{sv}	state vector
y	calculated value
α_{ci}	convection heat transfer coefficient, $W m^{-2}$
γ	thermodynamic constant, Pa K
Δ_T	difference between inside and outside temperature, °C
Δ_R	difference between inside and outside relative humidity, %
δ	leaf slope, Pa K
ϕ_v	ventilation rate, $m^3 s^{-1}$
η	radiation conversion factor
λ	water vaporisation energy
μ_j	membership value
ρ_a	air density, $kg m^{-3}$

Superscripts

*	indicates that considered quantity is saturated at vapour pressure

approach to solve control problems (Lee, 1990). Fuzzy logic provides a formal methodology to represent, manipulate and implement expert heuristic knowledge for controlling a system. Also, in a fuzzy controller, robustness and low cost are inherent (Passino, 1998). There are a great number of successful applications in different disciplines that confirm the capabilities of fuzzy logic controllers (FLC) (Yen *et al*., 1995; Gottschalk *et al*., 2003; Zhu *et al*., 2005). Advances obtained in these techniques have been applied to important commercial applications, such as Canon's camera auto-focus control, Honda's and Nissan automatic transmission, Mitsubishi's room air conditioner control, Panasonic's clotheswasher control and Toshiba's elevator control (Piero, 1997). Some other contributions have been reported around the FLC application to bio-processes (Horiuchi, 2002), as well as to the greenhouse climate control (Lafont & Balmat, 2002). The use of FLC represents on the other hand a powerful way to diminish greenhouse energy costs as heating (Caponetto *et al*., 2000), which are important aspects to consider in greenhouse climate control.

For the implementation of agricultural technologies (innovations in control systems, remote monitoring, information management), robustness, low-cost and real-time capabilities are needed. In this sense, field programmable gate arrays (FPGAs) present as a good option for greenhouse technology development and implementation, because FPGAs allow fast development of prototypes and the design of complex hardware systems. These devices have been used in many real applications (Vega-Rodriguez *et al*., 2004). Through FPGAs, fast tests, modifications accomplishment, updates using single software modifications and an effective production cost (relation performance-price is very favourable) are obtained. In the same sense, reduction in development and commercialisation time is accomplished. On the other hand, for fuzzy controller implementation, which can be based on software or hardware, FPGAs are an alternative that keep both benefits, hardware speed and software flexibility.

Research made around these devices has experienced an enormous development, in the academic field as well as in the industrial area. There is a great number of