Control of a solar dryer through using a fuzzy logic and low-cost model-based sensor

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Abstract

Solar drying is one of the important processes used for extending the shelf life of agricultural products. Regarding consumer requirements, solar drying should be more suitable in terms of curtailing total drying time and preserving product quality. Therefore, the objective of this study was to develop a fuzzy logic-based control system, which performs a ‘‘human-operator-like’’ control approach through using the previously developed low-cost model-based sensors. Fuzzy logic toolbox of MatLab and Borland C++ Builder tool were utilized to develop a required control system. An experimental solar dryer, constructed by CONA SOLAR (Austria) was used during the development of the control system. Sensirion sensors were used to characterize the drying air at different positions in the dryer, and also the smart sensor SMART-1 was applied to be able to include the rate of wood water extraction into the control system (the difference of absolute humidity of the air between the outlet and the inlet of solar dryer is considered by SMART-1 to be the extracted water). A comprehensive test over a 3 week period for different fuzzy control models has been performed, and data, obtained from these experiments, were analyzed. Findings from this study would suggest that the developed fuzzy logic-based control system is able to tackle difficulties, related to the control of solar dryer process.

Key words: solar dryer, fuzzy control, smart sensors.

1. Introduction

Regarding consumer requirements, solar drying should be more suitable in terms of curtailing total drying time and preserving product quality. It can be achieved by applying different kinds of model based control strategies. The first of them is a control strategy based on the classical optimal control theory. Although, classical optimal control theory is a mature mathematical discipline, many difficulties can be encountered when it is applied for finding a solar dryer control strategies, mainly, due to the following reasons: 1) often, it is not possible to adequately represent the system characteristic, such as nonlinearity, time delay, time-varying parameters, and overall complexity, 2) uncontrollable and unpredictable character of the environmental conditions, mainly, weather conditions (boundary conditions in terms of optimal control theory), 3) optimal controllers can be expensive in term of computation time, because during every sampling period an optimal control problem must be solved. In order to avoid difficulties encountered when the classical optimal control theory is applied, more general concepts of dryer control based on Artificial Neural Networks, Proportional-Integral-Derivative Controller (PID) theory and Fuzzy Logic are utilized. Today, these three approaches dominate the real-time intelligent control field (Mujumdar, 1987).

Fuzzy logic control (FLC) systems are utilized a knowledge-based control strategy that uses fuzzy linguistic variables into its rule set to model a ‘‘human-operator-like’’ control approach to cope with the uncertainty in process dynamics or the control environment (Mujumdar, 1987). These rules can be obtained from the knowledge of the plant functions, engineering principles, statistical information, from observing the skilled human operators, achieved by means of interviews, questionnaires, and online recording of human-initiated control actions (Mujumdar, 1987). FLC systems can be successfully applied for the systems, which can't be controlled in a satisfactory way with the traditional approaches, namely, by classical control theory, PID or ANN-based controllers (Oduk & Allahverdi, 2011). The following advantages of the FLC systems over the traditional approaches can be mentioned here: i) no need to have a mathematical model of the system; ii) no-linear plants control possibility; ii) fuzzy controllers are cheaper than model-based or other kind of ones; iii) fuzzy controllers are easier to understand and to modify.

Today, significant improvements in controls become also available, because of the development of better sensors and more sophisticated, computer-based control software or expert systems. Low cost sensors are most suitable for the supervision and control of system characteristic, and can be easily upgraded by including smart capabilities (Correa-Hernando et al., 2011).

Therefore, the objective of this study is to develop a fuzzy logic-based control system of a solar dryer, which performs a ''human-operator-like'' control approach through using the previously developed low-cost model-based sensor (Correa-Hernando et al., 2011).

2. Material and Methods

2.1. Solar dryer

An experimental solar dryer, constructed by CONA SOLAR (Austria) was used during the experiments (Correa-Hernando et al., 2011). This dryer has a capacity of 0.3 m^3, is equipped with a solar collector of 2 m^2, a 12 V DC fan, a chamber for drying, various metallic trays where samples of pine (Pinus sp.) wood were placed, a gate that controls the recirculation of air and a plenum chamber. The air comes into the dryer by one side, being heated in the roof, sucked into the plenum chamber and ducted to the fan which blows it into the drying chamber where the wood is placed on trays. For the experiments eight Sensirion sensors were used at different positions in the dryer: at solar collector inlet and outlet, at drying chamber inlet and outlet and between the wood planks. The sensors were connected by wire to a board with a Peripheral Interface Controller (PIC). In the PIC the signals were multiplexed and then sent to a computer via RS232.

2.2. Model based sensor SMART-1

The model based sensor SMART-1 proposed by Correa-Hernando et al., (2011) was used in this study simultaneously with one of the developed fuzzy logic models to control a water extraction rate. The model based sensor SMART-1 consists of two Sensirion sensors, located at the drying chamber inlet and outlet, respectively. The difference of absolute humidity of the air between the outlet H_{out} and the inlet H_{in} is considered to be the extracted water H_{ext} . At each time t the mass of extracted water per mass unit of dry air is computed according to:

$$H_{ext} = H_{out} - H_{in}.$$

Considering the air density as the inverse of the specific volume, and the flux of ventilator Q, the rate of wood water extracted can be computed as follows (Correa-Hernando et al., 2011):

$$\frac{dH_{ext}}{dt} = -\frac{1}{V_s(t)} Q H_{ext}(t).$$

2.3. Solar dryer fuzzy control models

Two fuzzy logic models were tested in this study: the first one was utilized for regulation of the temperature inside a solar dryer, and the second one — for control of the rate of wood water extraction basing on the model based sensor SMART-1.

2.4. Basic principles of the fuzzy logic

A fuzzy logic system can be defined as the nonlinear mapping of an input data set to a scalar output data. In general, the two following steps are involved in the implementation of a fuzzy logic controller: i) fuzzification of input, and ii) determination of output. Fuzzification involves dividing each input variable's universe of discourse into ranges called fuzzy subsets.

A function applied across each range determines the membership of the variable's current value to the fuzzy subset. Fuzzy controller is comprised of linguistic rules representing the relationship between input and output variables. The linguistic rules typically take the form of a set of if-then rules whose antecedents (if-parts) and consequents (then-parts) are propositions involving fuzzy membership functions. If X and Y are input and output universes of discourse of a fuzzy controller, the usual if-then rule has the following form:

Rule i: IF x is A_i *THEN y is* B_i,

where x and y represent input and output linguistic variables, respectively, A_i and B_i are fuzzy sets representing linguistic values x and y. In solar dryer control applications, the input x refers to the sensory data, for example, the inside temperature, and the output y — to the actuator control signal, for example, a speed of the solar dryer fun.

3. Results and discussions

3.1. Inside temperature controller

The objective of the developed fuzzy controller is to maintain a given optimal or desired temperature inside the solar dryer cabinet. The following variables were chosen for this controller as an input: T_{in} that is a solar dryer cabinet inside temperature (an average temperature of the sensors located between the wood planks), dT that is a difference between the solar dryer collector inside temperature and desired inside temperature. The desired inside temperature can be dependent, for example, on properties of the product to be processed or the quality criteria to characterize a drying process. The output variable (response) of the controller was a speed of the solar dryer fan v. Fig. 1 shows the labels of input variables and their associated membership functions. Table 1 shows a quantization levels for input and output linguistic variables.

The following set of the rules were utilized to derive the output of the developed fuzzy logic controller.

1: IF (Tin is optima) THEN speed of the fan is zero.
2: IF (Tin is men-q-opt) and (dT is optima) THEN (speed of the fan is max).
3: IF (Tin is men-q-opt) and (dT is positiva) THEN (speed of the fan is medio).
4: IF (Tin is mmen-q-opt) and (dT is optima) THEN (speed of the fan is max).
5: IF (Tin is mmen-q-opt) and (dT is positiva) THEN (speed of the fan is max).
6: IF (Tin is men-q-opt) and (dT is negativa) THEN (speed of the fan is zero).
7: IF (Tin is mmen-q-opt) and (dT is negativa) THEN (speed of the fan is zero).
8: IF (Tin is mas-q-opt) and (dT is positiva) THEN (speed of the fan is zero).
9: IF (Tin is mmas-q-opt) and (dT is positiva) THEN (speed of the fan is zero).

TABLE 1. Quantization levels for input and output linguistic variables.

Type of variable	Number of levels	Quantization level
Input 1:	5	(1) **mmen-q-opt**: the inside cabinet temperature is much less than desired temperature; (2) **men-q-opt**: the inside cabinet temperature is less than desired temperature; (3) **optima**: the inside cabinet temperature is optimal; (4) **mas-q-opt**: the inside cabinet temperature is higher than desired temperature (5) **mmas-q-opt**: the inside cabinet temperature is much higher than desired temperature.
Input 2:	3	**negative**: difference between the solar dryer collector inside temperature and desired inside temperature is negative; **optima**: difference between the solar dryer collector inside temperature and desired inside temperature is optimal; **positive**: difference between the solar dryer collector inside

		temperature and desired inside temperature is positive;
Output:	3	**zero**: speed of the fan is zero; **medio**: speed of the fun is medium; **max**: speed of the fun is maximum.

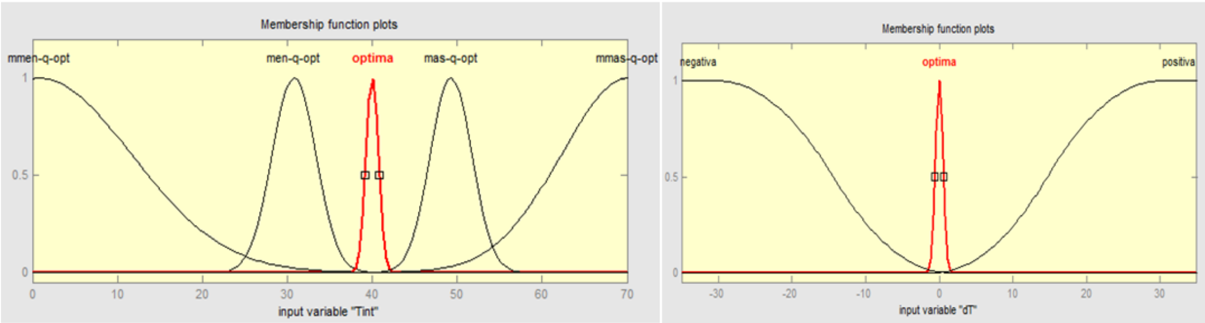

FIGURE 1. Membership functions for input linguistic variables T_{int} and *dT*.

3.2. Water extraction rate controller

In this case the objective of the developed fuzzy controller is to maintain a given optimal water extraction rate profile *T(t)* during the drying process. The function *T(t)* over the drying process time $t \in [0:t_f]$ is parameterized using N_p points, and during each time interval $t'_k = [t_k, t_{k+1})$, $k \in 0:(N_p - 1)$, the value of $T(t'_k)$ remains constant at u_k. The previous developed SMART-1 sensor (Correa-Hernando et al., 2011) was utilized to compute a water extraction rate. In order to be able to maintain a given optimal drying profile, we firstly developed a fuzzy logic controller for each of the given control value u_k, and then we used a fuzzy logic controller correspondent to the time interval $t'_k = [t_k, t_{k+1})$. The each of the developed controller has one input linguistic variable *HRate* that characterizes a water reaction rate, and one output variable *dt*, that characterizes a required change (negative or positive) of the actual speed of the solar dryer fan. Table 2 shows a quantization levels for input and output linguistic variables.

The following set of the rules were utilized to derive the output of the developed fuzzy logic controller.

1: IF (*HRate* is optimo) THEN (*dt* is zero)
2: IF (*HRate* is mmenos-q-opt) THEN (*dt* is inc++)
3: IF (*HRate* is menos-q-opt) THEN (*dt* is inc+)
4: IF (*HRate* is mmas-q-opt) THEN (*dt* is dec--)
5: IF (*HRate* is mas-q-opt) THEN (*dt* is dec-)

TABLE 2. Quantization levels for input and output linguistic variables.

Type of variable	Number of levels	Quantization level
Input 1:	5	(1) **mmen-q-opt**: the water extraction rate is much less than desired water extraction rate; (2) **men-q-opt**: the inside water extraction rate is less than desired water extraction rate; (3) **optima**: the water extraction rate is optimal; (4) **mas-q-opt**: the water extraction rate is higher than desired water extraction rate (5) **mmas-q-opt**: the water extraction rate is much higher than water extraction rate temperature.
Output:	5	**dec--**: double decrement of speed is required for the solar dryer fan; **dec-**: single decrement of speed is required for the solar dryer fan; **zero**: there is no need to change the speed of solar dryer fan;

		inc+: single increment of speed is required for the solar dryer fan; **inc++**: double increment of speed is required for the solar dryer fan.

3.3. Fuzzy logic control software

Fuzzy Logic Toolbox of MatLab and Borland C++ Builder tool were utilized to develop a required control system (Fig. 2 and 3). In order to perform a required control the developed Borland C++ Builder GUI software communicates with the Fuzzy Logic Toolbox of MatLab via text file.

3.4. Water extraction rate controller testing

Figure 9 shows the temperature and relative humidity charts, obtained for the optimal control profile of the solar dryer fan to achieve the following randomly selected water behavior profile (300, 70, 300, 150, 250, 70, 150, 250). Experimental water extraction rate was computed according to the SMART-1. From Fig. 2 we can see that the developed controller is able to perform the randomly chosen profile for the water extraction rate.

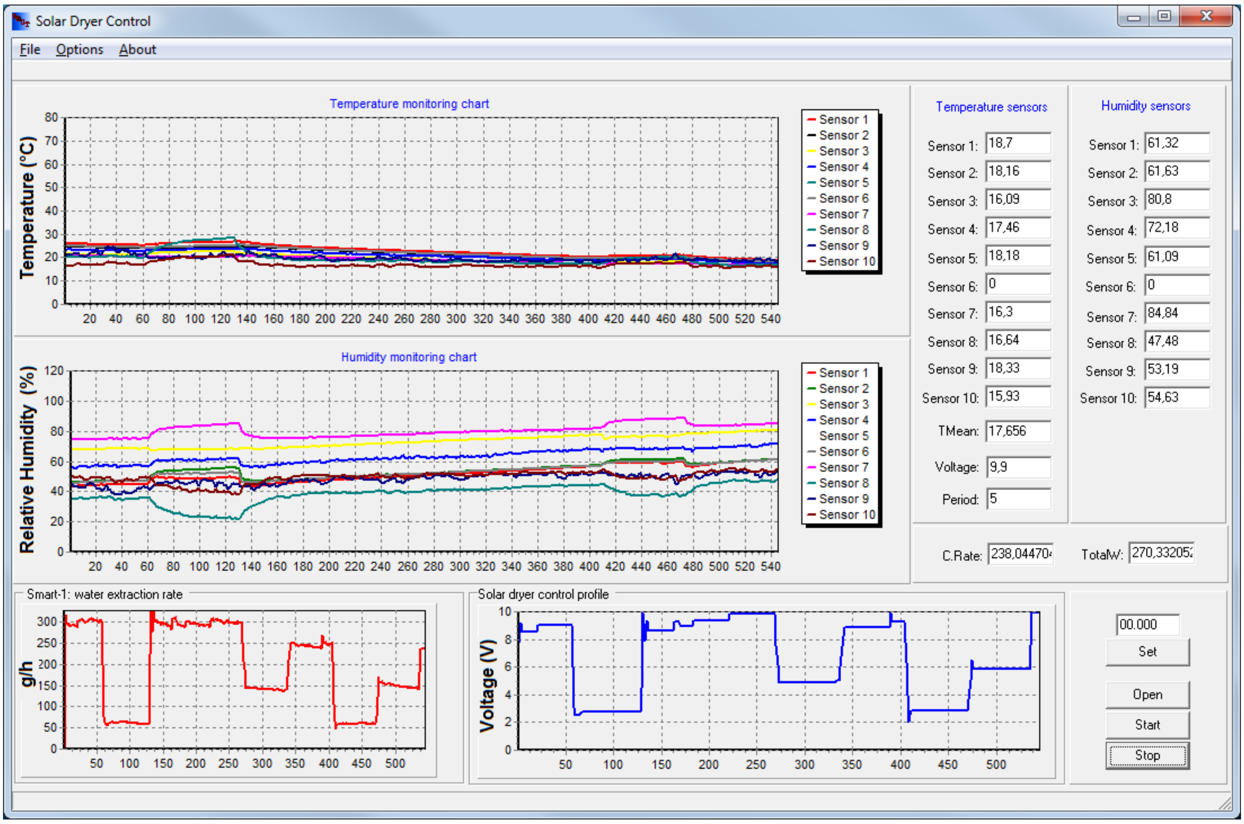

FIGURE 2: Developed fuzzy logic control software. Temperature and relative humidity charts obtained for the optimal control profile of the solar dryer fan to achieve randomly selected water behavior profile; experimental water extraction rate SMART-1.

3.5. Inside cabinet temperature controller testing

The objective of this experiment was consisted of maintaining an average desired inside cabinet temperature equal to 35 °C. Fig. 3 shows the temperature profiles of each solar dryer sensors and the obtained control profile. The results obtained from this experiment would suggest, that the developed controller is able to maintain a desired inside cabinet temperature.

4. Conclusions

A fuzzy logic-based system (FCS) for a solar dryer has been developed performing in a 'human-operator-like' control approach. This FCS is based on a previously developed low-cost model-based sensor. Findings from the study would suggest that the developed FCS is able to tackle the inherent difficulties, related to controlling a solar dryer process (large daily temperature variations). The future trends consist on implementing the FCS for drying specific food product according to model-based quality estimations, which drive the adjustment of operating parameters.
This work presents the feasibility of linking together a smart sensing and smart control strategies.

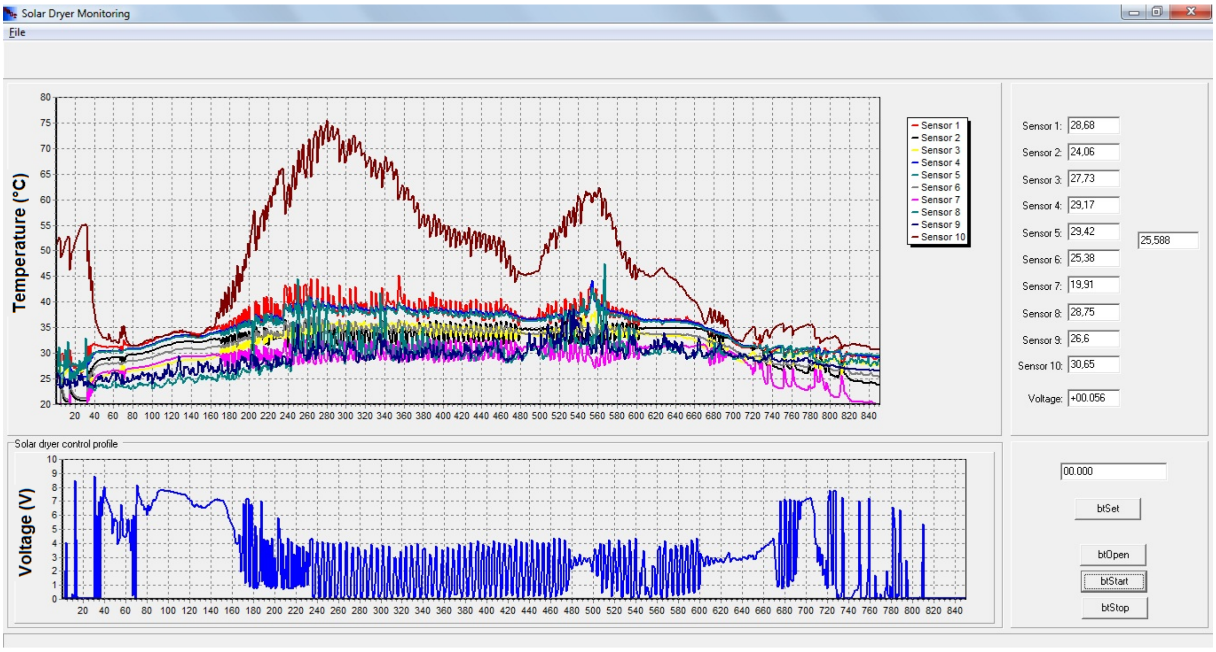

FIGURE 3. Results obtained for the inside cabinet temperature fuzzy controller.

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