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Research Paper

A novel intelligent control system for flue-curing barns based on real-time image features

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Most intensive tobacco curing systems are manually operated requiring the curers to frequently observe the status of tobacco leaves and in order to achieve the desired temperature and relative humidity, curers adjust the setpoint values of dry and wet bulb temperatures and the time to change to the next setpoints. Control is therefore subjective and it is difficult to maintain consistent high quality curing. A novel intelligent control system based on the real-time image processing of the tobacco leaves images to monitor the status of the tobacco leaves was developed. A neural network based approach was designed to identify the setpoints for the dry and wet bulb temperatures, and the time to change to the next setpoints. Inputs were 12 extracted image features obtained from an image processing algorithm and the measured dry and wet bulb temperatures in the barn. Without any manual intervention by curers, the developed intelligent control system achieved real-time monitoring and management of the curing process. The effectiveness of the developed intelligent control system was demonstrated by simulation and experiment.

1. Introduction

Intensive tobacco curing systems have been widely used in the tobacco industry all over the world. The flue-curing process, which is designed to produce a thin and yellow tobacco that provides an aromatic smoke, highly influences the quality and fragrance of flue-cured tobaccos (Hayes et al., 2007). The flue-curing process is affected by many factors, such as the setpoints for dry and wet bulb temperatures at different curing stages, the duration of current curing stage, and the dehydration speed of tobacco leaves (Gong, Wang, et al., 2005; Gong, Zhou, et al., 2005; Meng, Nie, Xiao, & Tang, 2006; Song et al., 2010; Wahlberg et al., 1977). In order to meet the required conditions in the curing barns, appropriate temperature and relative humidity inside the curing barns must be maintained during the curing stages (Alvarez-López, Llanes-Santiago, & Verdegay, 2005). The relative humidity can be calculated from the dry and wet bulb temperatures inside the barns. The traditional curing systems require curers to manually control the curing process. The curers need to observe the states of tobacco leaves whenever necessary and decide the time to change from one stage to the next. The curers adjust the setpoint values of dry-bulb temperature and wet-bulb

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Nomenclature

a_i	i-th observation for k-means
$c(\cdot)$	geometric closeness function
E	squared error for neural network training
e_k	error of k-th target value and prediction output
$\mathbf{f}$	input image of a bilateral filter
H, S, I	hue, saturation and lightness of an image in the HSI (hue, saturation and lightness) colour model
H_{TL}, S_{TL}, I_{TL},	hue, saturation, and brightness in HSI colour model of tobacco leaves image
H_avg, S_avg, I_avg	mean values of hue, saturation, and brightness in HSI colour model of tobacco leaves image
H_std, S_std, I_std	standard deviation of hue, saturation, and brightness in HSI colour model of tobacco leaves image
$\mathbf{h}$	output image of a bilateral filter
h_j	output of the j-th hidden neuron
i, j, k	index numbers
J	within-cluster sum of squares k-means
$k(\cdot)$	normalization factor for bilateral filtering
M	number of hidden neurons
MAE, MRE, MSE, ARE	mean absolute error, mean relative error, mean squared error and absolute relative error for each output of the neural network
m	number of observations for k-means
N	number of input neurons
N_{TL}	number of calculated pixels in the image of tobacco leaves
n	number of data samples
Q	number of output neurons
R	correlation coefficient
R, G, B	red, green and blue components of an image in RGB colour model
R_{TL}, G_{TL}, B_{TL}	red, green and blue components in RGB colour model of tobacco leaves
R_avg, G_avg, B_avg	mean values of the red, green and blue components in RGB colour model of tobacco leaves image
R_std, G_std, B_std	standard deviation of the red, green, and blue components in RGB colour model of tobacco leaves image
$s(\cdot)$	photometric similarity function
$t, \bar{t}$	target value and its mean value
u_j	j-th set for k-means
v_{ji}	connection weight from the i-th input to j-th neuron in hidden layer
w_{kj}	connection weight from the j-th neuron in hidden layer to k-th neuron in output layer
$\mathbf{x}$	neighbourhood centre for bilateral filtering
X	input variable
$y, \bar{y}$	predicted output and it mean value
α	learning rate
ε_j	variable for calculating v_{ji}
ϑ	nearby point of neighbourhood centre
μ_j	cluster centre of j-th set for k-means
σ	standard deviation of ARE

temperature in the curing barns. These control setpoint values may vary, depending on particular conditions of the tobacco to be cured and are determined by the curers' experience. The curers make the decisions on the change of stages according to the observed state of the tobacco leaves. This kind of curing method is highly affected by the knowledge and experience of curers. The system has following disadvantages: (1) Observation: The curers observe the status of the tobacco leaves through a small window. The tobacco leaves near the window are seen more clearly, while leaves further away are less visible. This limited observation might affect the curers' judgement on the overall state of tobacco leaves in the curing barn; (2) Subjectivity: The conditions of the tobacco leaves are judged relying on the knowledge and experience of curers; and (3) Cost: The need to employ curers.

It is desirable to develop an intelligent curing system that can automatically control the dry and wet bulb temperatures, without relying on subjective and costly estimates from curers. The principle of the system should be that acquires images of tobacco leaves and other necessary information in real time, extracts the features of the image that represent the curing conditions of the tobacco leaves, and it adjusts the dry and wet bulb temperatures according to the extracted image features.

There has been much research on extracting features from tobacco leaves by image processing technology. Most research has focussed on quality evaluations and the classification of the leaves (Yawootti & Kaewtrakulpong, 2005; Zhang, Fang, & Cai, 2000; Zhang, Sokhansanj, Wu, Fang, & Yang, 1997; Zhang & Zhang, 2011). Little research has been done to extract the features of tobacco leaves during curing. Song et al. (2012) analysed the morphological features of tobacco leaves during curing based on image processing. Their system did not have real-time data acquisition since it acquired the tobacco image by removing a tobacco leaf from the curing barn and taking a photograph of the leaf in a special cabinet. This method was therefore not suitable for real-time monitoring of curing barns. Zhang, Jiang, and Chen (2013) proposed an intelligent tobacco curing control approach by adopting colour identification of the tobacco leaves, where the hue, saturation and lightness (HSI) colour space was used for colour segmentation and recognition and fuzzy logic was used for decision making. Details of the fuzzy control rules and the control results were not given in their paper, which are the important parts for their method. Also, the fuzzy decision method relies greatly on the experience and knowledge of the curers, which is not robust to uncertainties. The model results using this system would be highly dependent on the domain knowledge and experience of the curers. Thus it is desirable to develop an intelligent real-time control system that can automatically learn the effective curing process.

Neural networks have been widely used for prediction in various systems (Martynenko & Yang, 2006; Pan & Yang, 2007; Pan, Yang, Otten, & Hacker, 2006; Wu et al., 2007) and have been extended to use in the tobacco industry over the last decade. For