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Real-time Efficient Operation of Decatizing Processes via a Geometric-based Extremum Seeking Control

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Abstract: Finishing is one of the fundamental steps of textile production and still, nowadays, it largely depends on empirical knowledge. Aim of finishing processes is to impart the required functional properties to the fabric and, in particular, decatizing is the process that lends the fabrics dimensional stability, enhances the luster, and improves the so-called fabric hand, corresponding to the sense of touching a textile. In order to properly treat the textile while minimizing the process energy consumption, suitable decatizing operating conditions, such as air temperature and humidity in the steaming section, have to be set. In this paper, because of the limited knowledge of certain process parameters and the difficulty of developing, implementing, and using effective a-priori process models, the problem of determining the set-points for the main controlled process variables is formulated as a constrained optimization problem and this is faced by means of a model-free approach. More precisely, we consider a constrained Extremum Seeking Control (ESC) scheme, using a geometric approach. In this preliminary study, first, we develop a Matlab-based simulation environment for the textile decatizing process and then we exploit it to design and test the ESC scheme. The in silico results confirm the effectiveness of the proposed approach.

Keywords: Textile Processes, Modelling and Simulation, Computer Aided Control System Design, Model-free Control, Extremum Seeking Control

1. INTRODUCTION

Any operation for improving the appearance or usefulness of a fabric after it leaves the loom or knitting machine can be considered a finishing step. In particular, finishing is the last step in fabric manufacturing and it represents the phase when the final fabric properties (concerning appearance, shine, handle, drape, fullness, usability, etc.) are developed (Choudhury, 2017; Majumdar et al., 2012). Decatizing is an example of finishing process that is mainly carried out on wool fabrics, because of the particular natural properties of its fibers. Wool is hygroscopic, therefore relative humidity and temperature of the surrounding air influence the amount of water taken up. However, only the core of the wool fiber can absorb water whereas the fiber surface is water repellent. This apparently contradictory behaviour results in the particular wool-moisture-management, which is responsible of the well-known comfort of wool. By exploiting the elastic properties of wool fibers and interacting with the wool keratin chemical bonds (such as the peptide, hydrogen, ionic and disulphide bonds (Bunsell, 2009), this treatment provides the following characteristics to the processed fabric (Rovero et al., 2019; Blackburn and Lindley, 1948): dimensional stability; reduction of possible glazing effect after calendering, thanks to fiber swelling caused by steam; modification of the hand, which is much more consistent after the treatment; high levels of setting stabilization. The intensity of set reached depends on process parameters such as temperature, moisture content (also called regain, which is the mass ratio of water to the oven-dry wool mass, expressed as a percentage) and mechanical action. Aim of decatizing is to permanently set the fabric, bringing its temperature and regain above a particular curve, called permanent glass transition curve, that will be introduced and better explained as follows.

The considered textiles decatizing process takes place in an industrial machine such as the one depicted in Fig. 1, where the fabric is interleaved in a wrapper which leads it in a steaming section (composed of drum, vessel and sealing devices) and an aspirating one. The machine production parameters and setpoints are chosen by experienced technicians that, known the fabric initial properties and the final quality it has to fulfil, deduce, for example, the appropriate air temperature and relative humidity setpoint in the steaming section. This first parameters choice is then followed by many trial and error tests to tune the final parameter values. On the other hand, this approach is also characterized by drawbacks. For example, the empirical method is not a formal proof of the fact. It rather yields, supports or rejects hypotheses and decisions. However, the results are always afflicted with uncertainty. Moreover, to support or reject hypotheses and decisions the empirical approach requires a lot of experiments which are time and energy consuming.

The aim of this paper is to pave the way for adopting automatic decision processes with the support of available information such as online measurements, performance indexes, constraints, etc. Specifically, we want to automatically set the best steam temperature and relative humidity that ensures a final (desired) fabric temperature and regain over a wide range of operative and boundary conditions and type of textile materials, while minimizing the consumptions related to the steam production process. Given certain boundary conditions (e.g. the ambient air temperature, the fabric thickness), the problem of determining in real-time the appropriate set points for the controlled variables, while trying to minimize the value of a so-called cost function, is a non-trivial task. In our scenario, this task is formulated as a constrained optimization problem and due to the limited knowledge of certain process parameters and the difficulty of developing, implementing, and using effective process models, we use a model-free approach. In particular, we resort to the Extremum Seeking Control (ESC) method (Ariyur and Krstic, 2003). ESC can search for the unknown or slowly varying optimum input with respect to certain performance index and it is effectively a dynamic realization of the gradient search based on a dither demodulation scheme, (Rampazzo et al., 2019).

It is a common practice, in the design of advanced control systems, to make extensive use of Computer Aided Control Systems Design (CACSD) software tools. These tools allow to simulate the main relevant system characteristics for the first assessment of different control strategies. In this preliminary study, we firstly develop a Matlab-based simulation environment for the steaming section of a textile decatizing process and for the energy consumptions related to the steam production, and then we exploit it to design and test the ESC. Simulations results confirm the effectiveness of the proposed approach.

The remainder of this paper is organized as follows. In Section 2 the mathematical model of the process and the energy consumptions is introduced. The constrained Extremum Seeking Control scheme is described in Section 3, whereas Section 4 includes the simulation results of ESC applied to the decatizing model. Finally, some concluding remarks are given in Section 5.

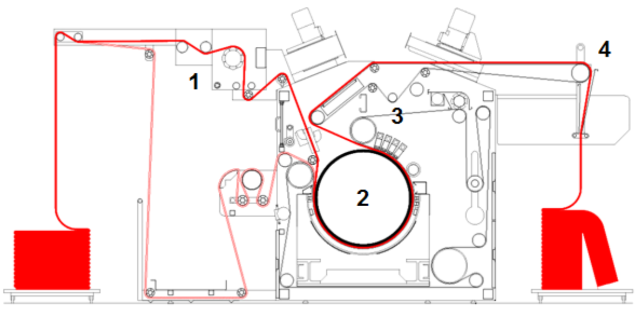


Fig. 1. Example of decatizing machine, composed of an entry unit (1), a steaming section (2), an aspirating section (3) followed by an exit one (4).

2. PROCESS ANALYSIS AND MODELLING

To ensure the wool fabrics proper handle characteristics, set fibers and yarns, and stabilized fabric dimensions, the textiles undergo a series of steam treatments. These treatments are based on the fundamental concept of setting: the set is said to be cohesive if it is lost when the fabric is immersed in water at room temperature whereas it is permanent if it is maintained when the fiber is relaxed at 100 °C, (Blackburn and Lindley, 1948). The intensity of set reached depends on process parameters such as temperature, moisture content (during steaming) and mechanical action (during decatizing). In particular, wool glass transition curves, that correspond to the redistribution of fiber hydrogen bonds and disulphide bonds, could be expressed by the following relationships, where the permanent set temperature T_p and the cohesive set temperature T_c are expressed as exponential functions of the fabric moisture content M and where the numerical coefficients are taken from literature (Wortmann et al., 1984):

$$T_p = -27.05 + \exp(5.25 - 0.04M), \tag{1}$$
$$T_c = 66.63 + \exp(5.04 - 0.07M). \tag{2}$$

Aim of decatizing is to permanently set the fabric, bringing its temperature and regain above the permanent glass transition curve. To estimate the wool fabrics conditions during decatizing, heat and moisture transfer processes are considered. In particular, during steaming, when the steam comes into contact with wool fibers, it condenses if the temperature of wool is below the saturation temperature of steam. This involves the transfer of an amount of heat equal to the latent heat of condensation from steam to wool. If the fabric regain is below the equilibrium regain, the condensed water is absorbed into the wool and an extra amount of heat, called the differential heat of absorption, is released. The transient equilibrium condition is established when the wool temperature reaches the steam temperature. The heat balance for the adsorption of condensed water into wool can be expressed as (Le and Ly, 1992):

$$C\partial T_f = (Q_d + L_v)\partial M, \tag{3}$$

where,

$$C = 0.068 + 0.85M + 0.00077T_f, \tag{4}$$
$$Q_d = \exp(-11.3009M + 5.7064), \tag{5}$$

and L_v varies with temperature, as given in the steam tables (Wagner and Kretzschmar, 2008). It is therefore possible, thanks to the above equations and given an increment of the absorbed moisture, to calculate the fabric temperature rise. The temperature rise stops when the wool temperature reaches the steam temperature or when the moisture regain in wool exceeds the equilibrium regain at the process steam relative humidity. This behaviour is depicted in Fig. 2, where the black dotted line represents the equilibrium regain at different steam temperature T_g and steady steam relative humidity Y_g.

The just mentioned fabric equilibrium regain is the amount of moisture absorbed at any specified humidity of the

NOMENCLATURE

C	Specific heat of moist wool [cal g^{-1} K^{-1}]
L_v	Latent heat of condensation of water [cal g^{-1}]
M	Fabric moisture regain [%]
Q	Heat of adsorption [cal g^{-1}]
R	Universal gas constant [J mol^{-1} K^{-1}]
T	Temperature [°C]
W	Power [kW]
X	Steam quality [-]
Y	Relative humidity [%]
$\dot{m}$	Mass flow rate [kg s^{-1}]
γ	Adjustable parameter
λ	Weighting factor [°C^2]
ω	Control perturbation frequency [Hz]
$\boldsymbol{\theta}$	Control inputs vector
c_{eq}	Equality constraint [°C^2]
c_{in}	Inequality constraint [°C]

Subscripts

a	Air from the environment
$boil$	Boiling
c	Cohesive
d	Differential
e	Equilibrium
f	Fabric
$fast$	At the end of the heat transfer front
g	Gas stream penetrating the fabric
$init$	Initial
m	Average
p	Permanent
r	Reference
s	Steam from the boiler
sup	Super-heating
tot	Total
vap	Vaporization
w	Water

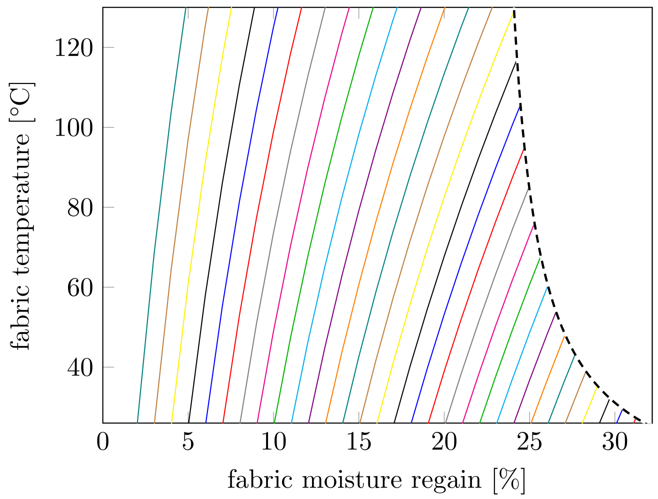


Fig. 2. Temperature rise predicted as steam condenses and absorbs into wool fabric during steaming, shown at different fabric initial regains (coloured lines).

external environment. It depends on environment relative humidity and temperature according to the following equation:

$$M_e = M_{e,r} \frac{\exp\left[\frac{Q_m}{R}\left(\frac{1}{T_g} - \frac{1}{T_r}\right)\right]\left[1 + \gamma Y_g \exp\left(\frac{Q_m}{RT_r}\right)\right]}{1 + \gamma Y_g \exp\left(\frac{Q_m}{RT_g}\right)}, \tag{6}$$

where the term $M_{e,r}$ is the reference equilibrium moisture fitted to adsorption data at 20 °C, (Le and Ly, 1992; Downes and Mackay, 1958). By using (6) the isosteres of temperature versus regain at constant relative humidity can be plotted, Fig. 3.

This diagram is very useful in the considered context because it shows important information in steaming or decatizing wool fabric, i.e. the regain change as a function of temperature and at constant humidity. For example, a characteristic that can be easily noticed is that the equilibrium regain in wool at given humidity changes markedly with temperature, with the fibers absorbing less moisture at high temperatures.

2.1 Definition of the steaming efficiency

Our purpose is, given a wool fabric with specific initial characteristics (i.e. initial regain), to find out the best steam temperature T_g and relative humidity Y_g that leads the textile transient conditions directly towards the equilibrium point M_e. In fact, if the fabric has low initial regain, it is still absorbing moisture as fabric reaches the steam temperature and the rate of adsorption ad this stage is influenced by the slow dissipation of the heat of adsorption (McMahon and Downes, 1962). On the other hand, if the fabric has high initial regain, it reaches the saturation regain before getting to the steam temperature; in this case, any further rise in fabric temperature requires a large amount of heat to reduce the equilibrium moisture regain in the fabric.

Fig. 4 is representative of these two situations. In particular, if the steaming process works at 100 °C and 95% relative humidity and given the raw wool at different initial regains, we notice that, if M_{init} = 12%, the fabric is still

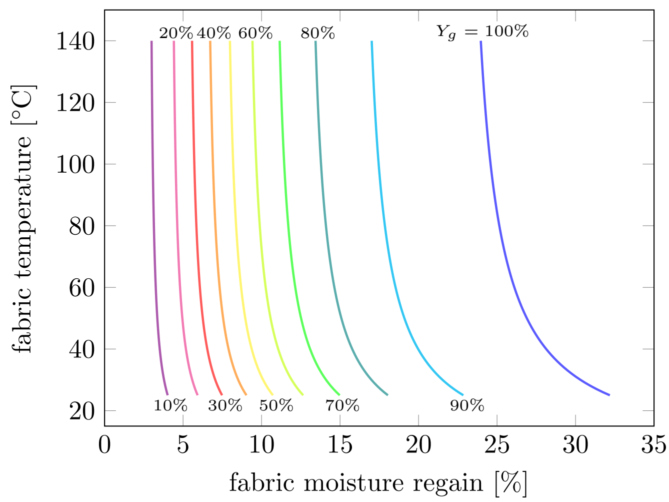


Fig. 3. Adsorption of moisture in wool at various relative humidities predicted by equation (6).

absorbing moisture when it reaches T_g (green star in curve (a)), on the other hand if its initial regain is $M_{init} = 17\%$, the fabric saturates before getting to T_g (green star in curve (b)). Another aspect to take into account when defining the process efficiency is related to the glass transition temperatures. In particular, to permanently set the fabric, its temperature during steaming must be equal or higher than the permanent glass transition temperature.

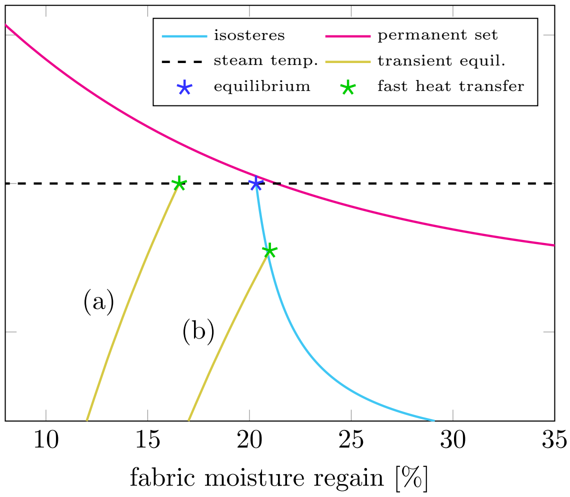


Fig. 4. Temperature rise (yellow curves) predicted when the initial regain is low (a) or high (b) and comparison with the equilibrium isosteres, enlightening the temperature the fabric should reach for being permanently set (magenta curve).

2.2 Mathematical model of the consumptions

Aim of this subsection is to give a brief overview of the power consumptions related to the thermo-hygrometric conditions of steam at the machine steaming unit. In particular, the characteristics of the gas stream penetrating the fabric are determined by the properties of two fluxes that are mixed together:

(1) the flux of steam coming from the boiler, characterized by a certain temperature T_s, a certain quality X_s and a flow rate $\dot{m}_s$;
(2) the flux of air coming from environment, characterized by a certain temperature T_a, a certain relative humidity Y_a and a flow rate $\dot{m}_a$.

Assuming that air has fixed T_a, Y_a and $\dot{m}_a$ and that the boiler generates steam with fixed quality $X_s = 1$, the variables that determine a change in T_g, Y_g and in the power consumptions is the steam flow rate $\dot{m}_s$ and the steam temperature T_s. The numerical values of these two variables are computed solving some standard mass-energy balance equations. Once found the values of steam temperature and flow rate that guarantee the desired characteristics of the penetrating gas stream, it is possible to compute the boiler consumptions. These latter are expressed as follows:

$$W_{tot} = W_{boil} + W_{vap} + W_{sup}, \tag{7}$$

where the term:

- W_{boil} is the power needed to heat the mass of water entering the boiler from its initial temperature $T_{w,init}$ to the water boiling temperature $T_{w,boil}$ at the boiler working pressure.
- W_{vap} represents the process of vaporization at constant temperature, where the heat provided brings water from the liquid to the dry saturated steam state. The enthalpy variation of this step is the saturated water vapor differential enthalpy, easily recoverable from the steam tables (Wagner and Kretzschmar, 2008).
- W_{sup} is the power used to have a superheated steam, bringing its temperature from $T_{w,boil}$ to T_s (this term is null if $T_s \leq T_{w,boil}$).

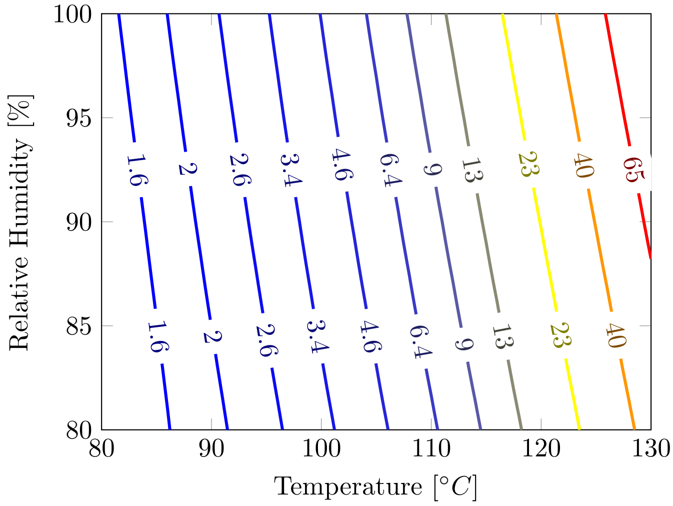


Fig. 5. Normalized power consumptions as a function of T_g and Y_g.

Fig. 5 shows how consumptions change at different final air characteristics, highlighting the intuitive trend according to which lower values of T_g and Y_g lead to a lower consumptions level, whereas an increase of T_g and Y_g makes the consumptions increase as well.

3. CONTROL

3.1 Problem formulation

In this work, we consider the problem of designing a control system to operate efficiently the decatizing process. The goal is to automatically determine in real-time the optimal steam temperature T_g and humidity Y_g values that give desired temperature T_f and moisture content M in textile materials while minimizing the power consumption W_{tot}:

$$(T_g^*, Y_g^*) = \arg \min_{(T_g, Y_g)} W_{tot} \tag{8a}$$
$$\text{s.t. } M_e = M_{fast}, \tag{8b}$$
$$T_e = T_{fast}, \tag{8c}$$
$$T_e \geq T_p(M_e). \tag{8d}$$

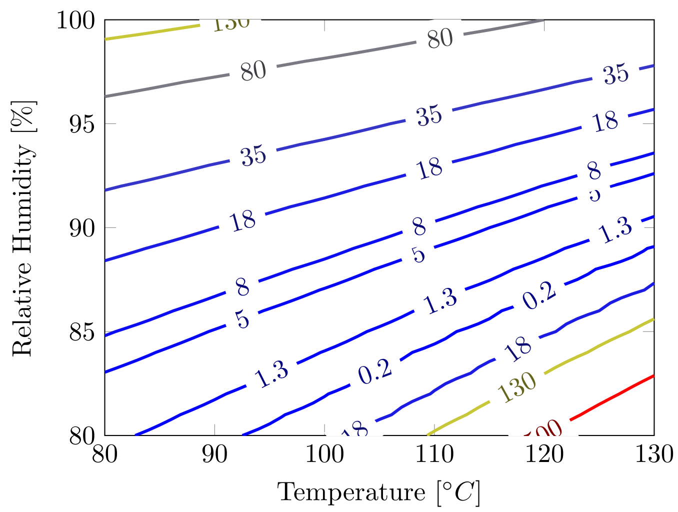


Fig. 6. c_{eq} as a function of steam relative humidity Y_g and steam temperature T_g.

The constraints (8b), (8c), and (8d) give the desired optimal conditions of the textile materials and they follow from the considerations made in Section 2.1. To deal with the equality constraints (8b) and (8c) and to quantify the efficiency of the decatizing process, we have defined a function c_{eq} indicating the effort needed to reach equilibrium when the fast heat transfer front has finished its effects:

$$c_{eq} = (T_e - T_{fast})^2 + \lambda(M_e - M_{fast})^2, \tag{9}$$

where λ is a weighting factor. Fig. 6 depicts the contour lines of c_{eq}, when the steam penetrates a fabric with initial regain of $M_{init} = 10\%$ and when $\lambda = 1\,°\mathrm{C}^2$, highlighting the region of interest where the function is minimized.

Similarly, to deal with the inequality constraint (8d), we have introduced a function to quantify the gap between the minimum required temperature T_p and the fabric temperature at equilibrium:

$$c_{in} = T_p(M_e) - T_e, \tag{10}$$

and it should be equal or less than zero. Given a fabric with initial regain $M_{init} = 10\%$, Fig. 7 depicts the values of c_{in} as a function of T_g and Y_g.

In the considered approach, we face the convex optimization problem (8) by using an ESC scheme to estimate the gradients of the cost function and the measurable constraints. The former indicates the most profitable direction, while the latter are, from a geometrical point of view, the vectors normal to the tangent plane to the space of feasible points. Following the geometrical approach proposed by (Atta et al., 2019), a projection step combines this gradient information to design an input update rate that steers the system over feasible trajectories toward a local extremum. The considered approach is schematized in Fig. 8 and, as it can be observed, its main components are the gradient estimators and a projection block.

3.2 Gradient estimator

The estimation of the gradients of the cost and constraints functions is performed by means of a classic perturbation-based ESC scheme, which has been first introduced by (Ariyur and Krstic, 2003). The main idea behind this algorithm is to perturb the m plant inputs with additive sinusoidal perturbation signals ($a_i \sin(\omega_i t)$, $i = 1, \dots, m$) and exploit the measurements of the resulting objective function to estimate the components of its gradient. This gradient information is then used to adapt the plant inputs to seek the extremum of the targeted objective function. The gradient estimation scheme when $m = 2$ is depicted in Fig. 9, where y is the signal representing the measurements of the objective function while u_1 and u_2 are the two plant input signals.

The considered scheme provides as outputs the estimates of the components of the gradient $\widehat{\nabla y}$:

$$\widehat{\nabla y} = \left[\widehat{\frac{\partial y}{\partial u_1}} \; \widehat{\frac{\partial y}{\partial u_2}} \right]^\top, \tag{11}$$

and, as it can be observed in Fig. 9, the estimation step is performed by properly filtering the measurements of the objective function y. For each plant input u_i, the measurements of the cost function are first filtered through a band-pass filter BPF_i, then the resulting signal is multiplied by a sinusoidal demodulation signal having the same frequency ω_i of the input perturbation, and finally the demodulated signal is filtered through a low-pass filter LPF_i which gives as output an estimate of the derivative $\partial y/\partial u_i$. The design of the filters is crucial in order to estimate the gradient correctly. More specifically, the center frequency $\omega_{BPF,i}$ of each band-pass filter must be close to the corresponding perturbation frequency ω_i and the cut-off frequency $\omega_{LPF,i}$ of each low-pass filter must be much smaller than the corresponding perturbation frequency ω_i.

In the control scheme considered in this work and depicted in Fig. 8, we include three gradient estimators that provide

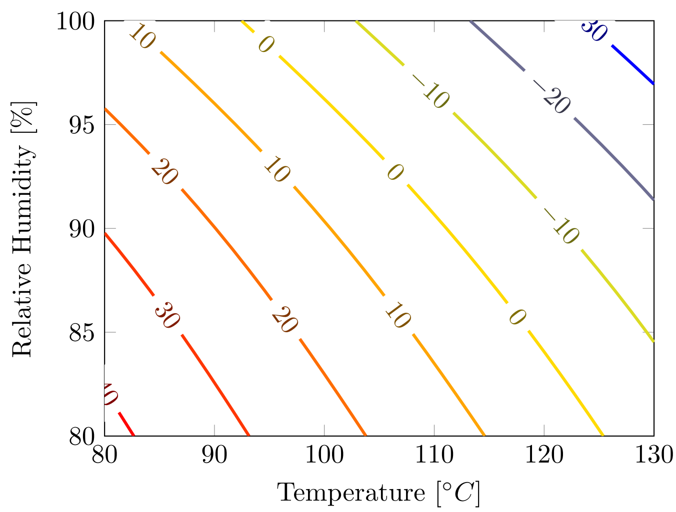


Fig. 7. c_{in} as a function of steam relative humidity Y_g and steam temperature T_g.

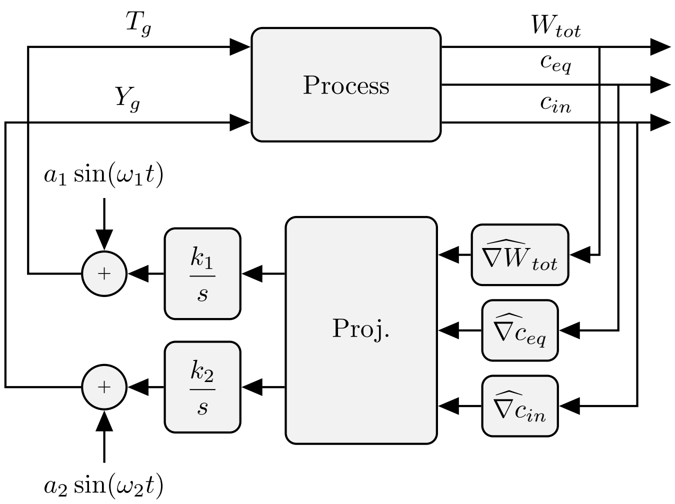


Fig. 8. Schematic representation of the geometric constrained ESC approach.

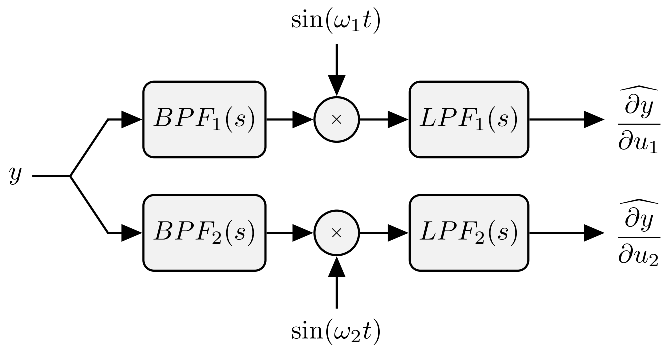


Fig. 9. Gradient estimation in the classic ESC scheme with $m = 2$.

the estimates of the gradients of the cost function $\widehat{\nabla W}_{tot}$ and of the constraints functions $\widehat{\nabla c}_{eq}$ and $\widehat{\nabla c}_{in}$, with respect to the control inputs vector $\boldsymbol{\theta} = [\, T_g \;\; Y_g \,]$. This information is then exploited by the projection block to compute an inputs update $\tilde{\boldsymbol{\theta}}$ that improves the objective without violating the constraints and finally this direction is used to update the control inputs through the integrator blocks with gains $\mathbf{k} = \mathrm{diag}([\, k_1 \;\; k_2 \,])$, i.e., $\dot{\boldsymbol{\theta}} = \mathbf{k}\tilde{\boldsymbol{\theta}}$.

3.3 Projection block

The inputs update $\tilde{\boldsymbol{\theta}}$ that improves the objective without violating the constraints is computed as follows:

$$\tilde{\boldsymbol{\theta}} = \tilde{\boldsymbol{\theta}}_{eq} + \tilde{\boldsymbol{\theta}}_{in}, \tag{12}$$

where the term $\tilde{\boldsymbol{\theta}}_{eq}$ drives the system to feasible points with respect to the equality constraint, while $\tilde{\boldsymbol{\theta}}_{in}$ steers the system to points which satisfy the inequality constraint. The update term related to the equality constraint $\tilde{\boldsymbol{\theta}}_{eq}$ is given by:

$$\tilde{\boldsymbol{\theta}}_{eq} = \tilde{\boldsymbol{\theta}}_{eq,proj} + \tilde{\boldsymbol{\theta}}_{eq,corr}, \tag{13}$$

where $\tilde{\boldsymbol{\theta}}_{eq,proj}$ is the projection term:

$$\tilde{\boldsymbol{\theta}}_{eq,proj} = \widehat{\nabla W}_{tot} - \frac{\widehat{\nabla c}_{eq}\widehat{\nabla c}_{eq}^{\top}}{||\widehat{\nabla c}_{eq}||^2}\widehat{\nabla W}_{tot}, \tag{14}$$

and $\tilde{\boldsymbol{\theta}}_{eq,corr}$ is the correction term:

$$\tilde{\boldsymbol{\theta}}_{eq,corr} = -K^c \widehat{\nabla c}_{eq}. \tag{15}$$

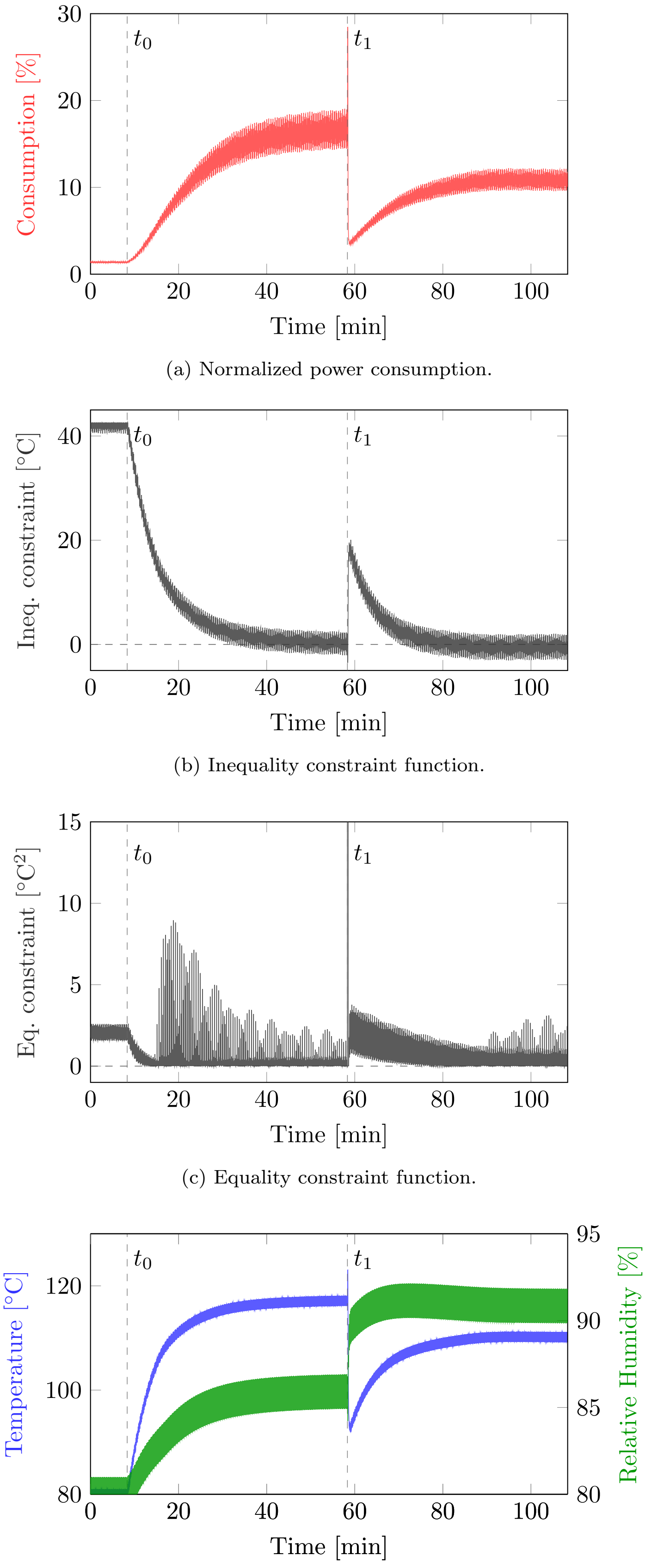
The parameter K^c in equation (15) is a gain used to ensure that the system remains in the space of feasible parameters. If the current value of the input satisfies the equality constraint, then we find a new direction to ensure that the new input stays on the same set and $\widehat{\nabla W}_{tot}$ gives the direction of maximum improvement of the objective function. In the case that the equality constraint is not satisfied, the term $\tilde{\boldsymbol{\theta}}_{eq,corr}$ ensured that the system returns to the constraint set. A slightly different approach is used to compute the term $\tilde{\boldsymbol{\theta}}_{in}$, i.e.:

$$\tilde{\boldsymbol{\theta}}_{in} = \begin{cases} \widehat{\nabla W}_{tot}, & \text{if } c_{in}^{+} \leq \bar{c}_{in}, \\ \tilde{\boldsymbol{\theta}}_{in,proj} - \tilde{\boldsymbol{\theta}}_{in,corr}, & \text{otherwhise,} \end{cases} \tag{16}$$

where $c_{in}^{+} = c_{in} + \tau^c(\widehat{\nabla W}_{tot})^{\top}\gamma\widehat{\nabla c}_{in}$ represents an approximation of future prediction (after $\tau^c \in \mathbb{R}^+$ seconds) of the constraint, $\tilde{\boldsymbol{\theta}}_{in,proj}$ and $\tilde{\boldsymbol{\theta}}_{in,corr}$ are defined as in the equality case, and $\bar{c}_{in}$ is a constant used to prevent the violation of the constraints due to the dither signals. If the current point is not violating the constraint, the controller operates as an unconstrained ESC. If the system reaches an infeasible set, the direction is selected using a mechanism similar to the equality case in order to avoid the constraint violation.

4. SIMULATION EXAMPLES

By exploiting the Matlab-based simulation environment designed according to the models related to the process consumptions and the decatizing efficiency level, we can simulate the constrained ESC under different conditions (i.e. fabric initial regain). The ESC parameters have been chosen by conducting meaningful simulations: the amplitude of the dither signals is set to $a_1 = 1°\mathrm{C}$ and $a_2 = 1\%$, while the dither time period is about 8 s for the temperature and 10 s for the relative humidity. Fig. 10 depicts how the ESC algorithm operates in real-time under different wool conditions. The initial moisture content is $M = 10\%$ and the initial steam setpoints are chosen by experience equal to $T_g = 80°\mathrm{C}$ and $Y_g = 80\%$. The ESC, after an initial exploration phase, increases the steam temperature to $T_g = 117°\mathrm{C}$ and the relative humidity to $Y_g = 86\%$, leading to a rise in the power consumptions (see Fig. 10a), which is however justified by the attempt of reaching the allowed values for both the constraints. In fact, the constraint function c_{eq} (Fig. 10c) is reduced to zero, which entails the satisfaction of the equality constraints. Similarly, also the inequality constraint function c_{in} (Fig. 10b) is reduced to zero. It is worth noting that also negative values of c_{in} would entail the satisfaction of the inequality constraint, but they would lead to higher power consumptions. When the wool initial moisture content has been changed to $M = 12\%$, the new optimal values become $T_g = 110°\mathrm{C}$ and $Y_g = 91\%$. From Fig. 10a we can notice that an increase in the moisture regain leads to a decrease in the power needed to satisfy the constraints.



(a) Normalized power consumption.

(b) Inequality constraint function.

(c) Equality constraint function.

(d) Control inputs.

Fig. 10. Time evolution of the normalized power consumption, the constraint functions, and the control inputs during the simulation. ESC is activated at time t_0, while at time t_1 the initial regain is increased by 2%.

5. CONCLUSIONS

In this paper, a model-free approach has been used for the on-line optimal setting of the steam temperature and humidity in industrial textile decatizing machines. In this way, we want to minimize the power consumptions related to the steam generating process, while satisfying some constraints related to the decatizing effectiveness. The optimization problem has been tackled by using a geometric-based constrained Extremum Seeking Control scheme. The performance of the proposed control strategy has been assessed by means of simulations, by exploiting a mathematical model of the system and a Matlab-based simulation environment designed accordingly. The in silico results confirm the effectiveness of the proposed control strategy and its effectiveness over different operative conditions. It is worth observing that, the control scheme could be easily applied to real systems by properly tuning its parameters, thanks to its interesting plug and play characteristics.

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