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PREDICTIVE CONTROL OF AN OLIVE OIL MILL WITH MULTI-OBJECTIVE PRIORITIZATION

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Abstract: This paper presents a multi-objective controller applied to an olive oil mill. The practical experience using a Generalized Predictive Controller (GPC) in the real plant showed the necessity of including objectives, with different priorities, in the process control. The analysis demonstrates that GPC with prioritization objectives can control the process and fulfill the specified operational conditions. The results are illustrated with some simulations that compare the traditional GPC to the multi-objective one. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Nowadays, a control system must be able to operate the process in such a way that multiple and changing operational criteria (economical, safety, environmental or quality) can be fulfilled in the presence of changes in process characteristics. Model Predictive Control (MPC) is the most popular advanced control technique in industry (Camacho and Bordons, 1999), due to its ability to meet this challenge and the intuitive control problem formulation.

Most MPC strategies are based on optimizing a single objective cost function, which is usually quadratic, in order to determine the future sequence of control moves that makes the process behave best. However, in many control problems the behaviour of the process cannot be measured by a single objective function but, most of the time, there are different, and sometimes conflicting, control objectives. The reasons for multiple control objectives are varied:

- Processes have to be operated differently when they are at different operating stages. For example at the start up phase of the process, a minimum start-up time may be desired, while once the process has reached the operating regime, a minimum variance of the controlled variables may be the primary control objective.
- Even if the process is working at a particular operating stage, the control objective may depend on the value of the variables. For instance the control objective, when the process is working at the nominal operating point, may be to minimize the weighted sum of the square errors of the controlled variables with respect to their prescribed values. But if the value of one of the variables is too high, because of a sudden perturbation for example, the main control objective may be to reduce the value of this variable as soon as possible.

Furthermore, in many cases, the control objective is not to optimize the sum of the squared errors, but to keep some variables within specified bounds. Notice that this situation is different to the constrained MPC,

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as the objective is to keep the variable there, although excursions of the variable outside this region, though not desirable, are permitted. In constrained MPC the variables should be kept within the prescribed region because of physical limitations, plant safety or other considerations. Constraints which cannot be violated are referred as *hard* constraints, while those which can are known as *soft* constraints. These types of objectives can be expressed by penalizing the amount by which the offending variable violates the limit.

Sometimes all control objectives can be summarized in a single objective function. Consider, for example, a process with a series of control objectives $J_1, J_2, \cdots, J_m$. Some of the control objectives may be to keep some of the controlled variables as close to their references as possible, while other control objectives may be related to keeping some of the variables within specified regions. Consider all objectives to have been transformed into minimizing a quadratic function J_i, subject to a set of linear constraints on the decision variables $\mathbf{R}_i\mathbf{u} \leq \mathbf{a}_i$. The future control sequence can be determined by minimizing the following objective function:

$$J = \sum_{i=1}^{m} \beta_i J_i$$

subject to $\mathbf{R}_i\mathbf{u} \leq \mathbf{a}_i$; for $i = 1, \cdots, m$.

The importance of each of the objectives can be modulated by appropriate setting of all β_i. This is, however, a nontrivial matter in general as it is very difficult to determine the set of weights which will represent the relative importance of the control objectives. Furthermore, practical control objectives are sometime qualitative, making the task of determining the weights even more difficult.

In some cases, the relative importance of the control objectives can be established by prioritization. That is, the objectives of greater priority, for example objectives related to security, must be accomplished before other objectives of less priority are considered. Objectives can be prioritized by giving much higher values to the corresponding weights. However this is a difficult task which is usually done by a trial and error method.

In (Tyler and Morari, 1999) a way of introducing multiple prioritized objectives into the MPC framework using propositional logic is given. These ideas were extended in (Bemporad and Morari, 1999) using the new *mixed logic dynamic* (MLD) framework, which allows one to represent systems which can be described by interdependent physical laws, logical rules and operating constraints.

This work applies these ideas to an olive oil mill. This is a multivariable plant which several objectives to be fulfilled, which are also logic-dependent. The process has extra degrees of freedom, which allows different control strategies. The practical experience in the real plant demonstrated that the process can be controlled by a constrained GPC, limiting the manipulated variables. However, the possibility of including objectives, with different priorities, in the process control, could improve the industrial performance.

The paper is organized as follows. In section 2 a description of the process is presented. The model identification is described in section 3. Multi-objective optimization is presented in section 4, showing the controller used in this framework, based on prioritized objectives. The control strategy applied to the model are described in section 5, including the control priorities. Section 6 is dedicated to presenting some simulation results and finally the conclusions are presented in section 7.

2. PROCESS DESCRIPTION

The automatic control of the extraction of oil out of olives is still an open field, since many installations are usually operated in manual mode. As olive oil mills are becoming bigger the chances for automation are increasing, therefore it is important to acquire the necessary knowledge of the process behaviour in order to design the appropriate control strategies.

The process is composed of several operations: reception of raw material (olives), washing, preparation, extraction, and storage of the produced oil (Civantos, 1999). Figure 1 shows the most important phases of the process.

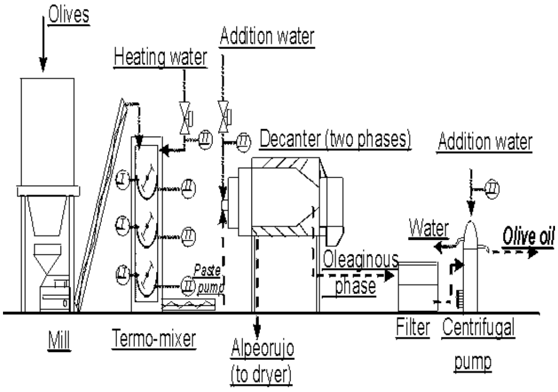

Fig. 1. Olive oil mill - process description

The preparation phase consists of two subprocesses. The first one is olive crushing by an special mill, whose objective is to destroy the olive cells where oil is stored. The second one aims at homogenizing the paste by revolving it while its temperature is kept constant at a specified value (around 35^{o}C). This is performed in a machine called *thermomixer*, which homogenizes the three phases of the paste (oil, water and by-product (*alpeorujo*)) while exchanges energy with surrounding pipes of hot water. This is done in order to facilitate oil extraction in the following process: mechanical separation, or extraction, in the *decanter*.

Homogenization is really important in the whole process, because bad operation conditions in the *thermomixer* can dramatically reduce the quality and quantity of the final product. The paste is heated in order to facilitate mixing since the paste turns more fluent when temperature rises. However, there exists an upper temperature limit behind which olive oil loses quality (flavour, fragrance, etc.) due to the oxidation process and the loss of volatile components. Therefore, keeping low values of temperature will be a high-priority objective. Experiences of modeling and predictive control of this phase are described in (Bordons and Cueli, 2001).

The next stage is based on the separation of the product phases by means of a centrifuge. This is a continuous process which separates the different components that constitute the paste by means of centrifugal force. This separation is made in the horizontal centrifuge or *decanter*. There are two types of *decanter*: the three phases *decanter*, and the two phases one. The first one separates two liquid components (oil and waste water) from a solid phase (solid by-product). The second one, that is the most used and the one that exists in the plant that is controlled in this work, separates olive oil from by-product.

In order to perform a good separation, the paste that enters the *decanter* must be accommodated. Its flow must be controlled to a setpoint that depends on operating conditions and some water must be added depending on the properties of the raw material.

Finally, the last stage of the system consists of the storage and the conservation of the obtained oil.

Several variables take part in olive oil extraction process. The final product quality and the industrial yield are influenced by different process variables. Next, the most important variables will be described:

- Temperature in the *thermomixer*. The heating of the paste has to be constant and gradual since abrupt changes affect negatively the quality of the final product. Two main difficulties appear: the first one is the existence of large delays due to the thermal nature of the process and the second one is caused by the on-off mechanism of feeding the paste.
- Residence time. Another important fact to be considered is the mixing time (residence time) inside the *thermomixer*. A short time drives to incomplete mixing and a long one can give rise to emulsions, which interfere with the extraction process.
- Paste consistency. The paste consistency gives information about the paste fluidity degree, which is associated to the olive moisture. This value has a great influence in the water that must be added before the paste enters the *decanter*.
- Paste flow to *decanter*. The paste flow to *decanter* and the water/mass proportion determine the maximum industrial yield. The mass flow is adjustable according to the olive type.
- Water flow to *decanter*. This also determines the extraction effectiveness. The amount of water that is introduced in the *decanter* must be constant; that is, the sum of the vegetation water of the olive plus the added water must be constant. As is well known, the raw material does not contain a homogeneous moisture, which forces the water flow to be continually adjusted in order to obtain the maximum oil in the *decanter*.

In the majority of olive oil mills, the process is controlled manually, since there are many factors that affect production. There are many objectives to be fulfilled and the operator must use his experience to have the process under control. This situation justifies the use of a multivariable predictive controller that is able to manipulate several actuator in order to obtain the desired performance. The control strategies applied to this plant are described in section 5.

3. MODEL IDENTIFICATION

Most processes in industry when considering small changes around an operating point can be described by a linear model of, normally, very high order. These models would be difficult to use for control purpose but, fortunately, it is possible to approximate the behaviour of such high order processes by a system with one time constant and a dead-time (Camacho and Bordons, 1999). Therefore, the chosen mathematical structure for the identification of the system is based in the systems dynamics of first order with delay.

The data used for the variables identification, have been obtained experimentally from a real olive oil mill. These real data have been treated (filtered, sampled, normalized) suitably to reach a acceptable model.

The input variables and the measurable disturbances have been excited with different steps, in order to identify the real system. The parameters of the system model are determined by recursive least squares estimation and the reaction curve method.

The process matrix fraction description can be seen in equation (1), where the controlled variable y is the oil flow, the manipulated variables u_1, u_2 and u_3 are, respectively, the temperature in the *thermomixer*, the paste flow to *decanter* and the water flow to *decanter*, and the measurable disturbances d_1 and d_2 are related to the olive type. These measurable disturbances have a great influence in the performance, because they represent the olive features for the *thermomixer*. These measurements have effect on the decision making in the plant control.

$$[\mathbf{y}] = [G_{u_1} G_{u_2} G_{u_3}]\,\mathbf{u} + \left[G_{d_1} G_{d_2}\right]\mathbf{d} \qquad (1)$$

To exemplify the identification of the system model, figure 2 shows how was obtained the model of the oil flow in function of the temperature in the *thermomixer*. The data values are normalized. The first graphic shows the temperature applied to the system (and to the model). In the second graphic the simulated output (dashed line) is compared to the real one (solid line). In the following graphic, the model error signal can be observed.

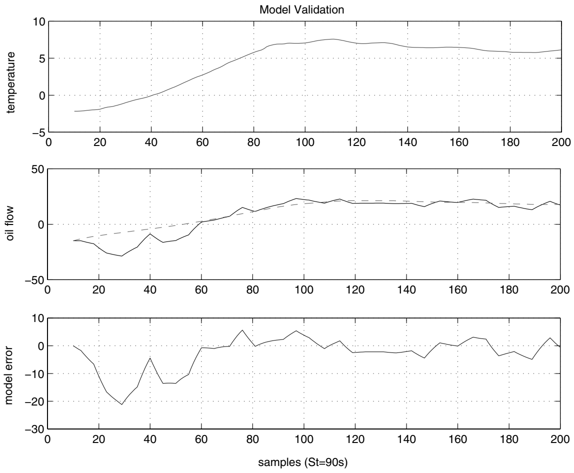

Fig. 2. Modeling of the oil flow respect to the temperature in the *thermomixer*

To get more information about the plant model identification, see (Núñez-Reyes *et al.*, 2001) and (Bordons and Cueli, 2001).

4. MULTI-OBJECTIVE OPTIMIZATION

One of the strengths of MPC is its ability to incorporate constraints in the control formulation. Frequently a disturbance drives the system into a region where the MPC problem is infeasible and hence no control action can be computed. Feasibility can be recovered by softening the constraints using slack variables. In many applications, the control objectives and constraints can be assigned a hierarchy of levels of priority. Often, a disturbance or a fault occurs, resulting in some constraints or objectives being violated. Inadequate handling of this situation might result in component or even system-wide failures (Kerrigan *et al.*, 2000). In (Tyler and Morari, 1999), it is presented a method for handling multi-objective prioritizations for model predictive control, combining propositional logic using integer variables with quantitative models.

The method presented in (Tyler and Morari, 1999) consists of describing the qualitative information in terms of propositional logic and, using integer variables, translate the propositions into linear constraints. For control problems, the qualitative knowledge may be incorporated within the model predictive control framework by appending the prioritization constraints to the control calculation problem.

This method consider a process with a series of m prioritized control objectives O_i. Suppose that objective O_i has a higher priority than objective O_{i+1} and that the objectives can be expressed as: $\mathbf{R}_i\mathbf{u} \leq \mathbf{a}_i$. The main idea consists of introducing integer variables L_i which take the value one when the corresponding control objective is met and zero otherwise. Objectives are expressed as:

$$\mathbf{R}_i\mathbf{u} \leq \mathbf{a}_i + K_i(1 - L_i) \tag{2}$$

where K_i is a conservative upper bound on $\mathbf{R}_i\ \mathbf{u} - \mathbf{a}_i$. If objective O_i is satisfied, $L_i = 1$ and the reformulated objective coincides with the original control objective. By introducing K_i, the objective (constraint) is always satisfied even when the corresponding control objective O_i is not met ($L_1 = 0$).

The prioritization of objectives can be established by imposing the following constraints:

$$L_i - L_{i+1} \geq 0 \ \ \text{for}\ i = 1, \cdots, m-1 \tag{3}$$

To improve the degree of the constraint satisfaction of objectives that cannot be satisfied, the set of constraints (2) can be modified. In order to come as close as possible to satisfying a failed objective O_f, a slack variable α satisfying the following set of constraints is introduced:

$$\mathbf{R}_i\mathbf{u} \leq \mathbf{a}_i + \alpha + K_i \left[(i-1) + \ (1 - L_i) - \sum_{j=1}^{i-1} L_j \right] \tag{4}$$

and the objective function to be minimized, subject to (2), (3), (4), is:

$$J = -K_\alpha \sum_{i=1}^{m} L_i + f(\alpha) \tag{5}$$

where f is a penalty function of the slack variable α (positive and strictly increasing) and K_α is an upper bound on f. The optimization algorithm will try to maximize the number of satisfied objectives ($L_i = 1$) before attempting to reduce $f(\alpha)$. The optimization method will optimize the degree of satisfaction of the first objective that failed only after all more prioritized objectives have been satisfied. Notice that $L_i = 0$ does not imply that objective O_i is not satisfied, it only indicates that the corresponding constraint has been relaxed.

5. CONTROL STRATEGY

The control strategy that has being used to control the olive oil mill can be seen as two control levels, as a cascade structure. A multivariable constrained GPC was implemented to track the oil flow to a desirable reference, modifying the manipulated variables that are the reference signals to an inner loop which operate with classical monovariables controllers PID.

The industrial implementation of the GPC have shown the importance of including economical and control objectives in the oil production system (Núñez-Reyes *et al.*, 2001).

The multi-objective algorithm implemented to the olive oil mill presents four control (and economical) objectives. The control priorities are related to the operator entries in the plant. These entries are called $\mathbf{y}_{op}$ to the setpoint and $\mathbf{u}_{op}$ to the desirable manipulated variables. The performance criteria selected in order of decreasing importance are given as follow:

(1) keep the *thermomixer* temperature as near as possible to the optimum value to guarantee the best oil characteristics:

$$\mid u_1 - u_{1op} \mid \leq \epsilon_{u_1} \tag{6}$$

(2) maximize the extracted oil:

$$\mid y - y_{op} \mid \leq \epsilon_y \tag{7}$$

(3) keep the paste flow as close as possible to the operator reference (reduce the necessary flow):

$$\mid u_2 - u_{2op} \mid \leq \epsilon_{u_2} \tag{8}$$

(4) reduce the water flow necessary in the production:

$$\mid u_3 - u_{3op} \mid \leq \epsilon_{u_3} \tag{9}$$

where ϵ_i ($i = u_1, u_2, u_3, y$) are very small positive scalars, representing the maximum tolerance admissible to attend the objectives.

The first objective is the most important one, since the variation of u_1 can change the final product characteristics. The second objective is the adjustment of the output variable to be controlled to its setpoint. The third and the last objectives are related to the energy savings in the production. Each one of these objectives is associate to a distinct L_i, $i = 1, \cdots, 4$, with different prioritization weights. The design of weights is an arbitrary procedure, guided by the heuristic.

In order to apply this procedure to MPC, for each time in the prediction horizon, the prioritization problem is recalculated. The optimum values obtained from the objectives prioritization are used as desirable goal to a GPC controller. The cost function implemented in GPC consists of a weighted sum of squares of the individual objectives, expressed as

$$J = (y - y_{op})^2 + \gamma(\mathbf{u} - \mathbf{u}_{op})^2 \tag{10}$$

6. SIMULATION RESULTS

To illustrate the application of this approach, consider the olive oil mill described in section 2. The controller uses three manipulated variables, *thermomixer* temperature, paste flow and water flow, to adjust the control variable, oil flow. The control priorities are implemented as described in section 5.

The multi-objective approach was compared to a traditional constrained GPC using a cost function consisting of a weighted sum of squares of the manipulated variables. The desirable operational conditions ($\mathbf{y}_{op}$, $\mathbf{u}_{op}$) are used as optimal reference to the multi-objective controller.

To performance the plant simulations, model uncertainties are considered (model dead-time differs for the process delay in 40%) without changing the tuning of the controllers. The closed loop behavior for GPC and the multi-objective controller are showed in the figures 3 and 4. In all cases, the solid lines correspond to the GPC and the dashed lines to the multi-objective controller. For the simulation, a 85% step reference has been applied at $t = 100$, another 9% step reference at $t = 370$ and a 2% step disturbance has been applied at the input of the plant at $t = 500$.

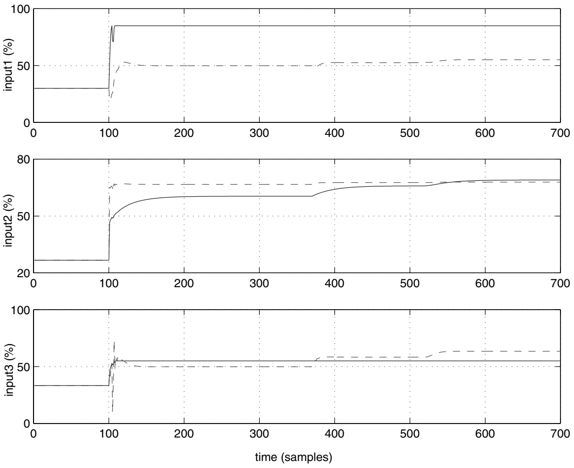

Fig. 3. Manipulated variables

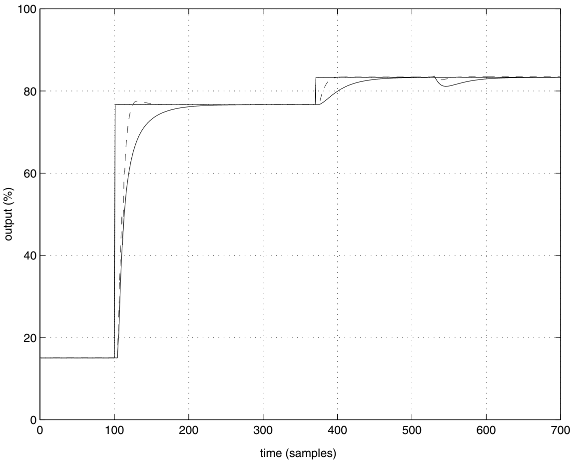

Fig. 4. Controlled variable

It is important to note that the responses are similar and both controllers are well adjusted, having a good tracking response. The multi-objective GPC presents even a faster response. But the special approach provided by this controller is the guarantee that objectives are fulfilled. Notice that all the objectives are satisfied until the second reference changes. At this point, the controller can satisfy three of the objectives, according to the priorities, so the water flow do not reach the optimum. When the disturbance is included, the *thermomixer* temperature is the only variable that is satisfied, controlled in the desired value (50%). Therefore, this approach is capable of prioritizing constraints as well as altering the control objective depending upon the positions of control inputs. As can be observed, the traditional GPC can control the system, but the manipulated variables are distinct from the desired values $\mathbf{u}_{op} = [50\%\ , 70\%, 50\%]$.

The application of the multi-objective GPC controller in the real plant can be justified by:

- The controller provides a faster response;
- The manipulated variables often get the optimum values;
- The main objective is always reached;
- As the water flow and the paste flow are minimized, the energy is saved.

The only inconvenient on that approach is the abrupt response, related to the fact that no dynamic is included in the prioritization algorithm. When a dynamic in the controller was introduced, the problem became computationally intractable, as commented in (Tyler and Morari, 1999).

It was also implemented a multi-objective weighted GPC, with no prioritization, using the same cost function (10), obtaining similar results. By contrast, the only design parameters needed for the prioritization GPC algorithm are bounds on the variables of interest. In weighted GPC, the weights adjustment must be chosen by trial and error, through numerical simulations, or via other *ad hoc* approaches in order that more objectives be satisfied. This procedure depends on heuristic, and usually takes much more time than the prioritization algorithm implementation.

7. CONCLUSIONS

This article has investigated the possibilities of applying a multi-objective GPC controller in an olive oil mill. Using the propositional logic, by including integer variables representing the objectives satisfaction, it is possible to combine logic based control decisions within the MPC framework. By implementing such strategy, the controller performance can be improved. The simulation results for the oil plant show that the manipulated variables fulfill the objectives according to the priorities.

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