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PRINCIPLES, APPLICATIONS AND PERSPECTIVES OF PREDICTIVE CONTROL

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ABSTRACT

Model-Based Predictive Control (MBPC or simply MPC) is a control methodology that makes use of the process model to predict the future outputs of the plant and based on it to optimize future control actions. In fact, predictive control cannot be considered as an independent control strategy, but instead, it integrates a whole family of control methods such as optimal control, process control with dead times, multivariable processes control, etc. This has allowed that the predictive control has had an important development both in the scientific and academic community, as in the industrial sector.

Keywords: control horizon, prediction horizon, process model, receding horizon.

1. INTRODUCTION

A few decades ago, the only really important goal in process control was to achieve a stable plant operation; however, today, the existence of a market, so variable and difficult to predict, has forced companies to improve their production processes as the market evolves, in order to remain competitive and profitable.

The competition at the various levels of industry, as well as society's growing interest in environmental problems arising from industrial processes, has led to the need for reliable techniques for the operation of the plant with a high degree of efficiency and flexibility.

At present, industrial control systems must meet production quality criteria simultaneously to meet certain specifications subject to a normally variable demand; with the economic criteria, associated with the maintenance of the variables of the plant and the minimization of a function of operating costs; with the safety criteria and with the environmental criteria.

Therefore, at present, the objective of a control system is to act on manipulated variables, so that multiple and changing operating criteria can be satisfied, in the presence of changes in the characteristics of the process. The various control methodologies that exist today, face the fulfillment of this objective.

Model-based predictive control (MBPC or MPC) is a powerful tool to address this challenge, since it accepts any type of model, cost functions or constraints, becoming the methodology that can more directly reflect the many relevant performance criteria in the process industry.

Predictive control is a set of control methods that has been developed around certain common basic principles such as:

- The explicit use of a process model to forecast the output of the system at future time points.
- The calculation of an optimal control action based on the minimization of one or more cost functions, with the possibility of including restrictions on the process variables.

Therefore, the different algorithms that are members of the extended family MPC differ mainly in:

- The type of model used to represent the process and its disturbances.
- The cost function that has to be minimized, with or without restrictions.

There are several notes on the predictive control applied to various processes, such as: steam generators [1], applications in the cement industry [2], distillation columns [3], clinical anesthesia [4] and robots [5].

Predictive control has a number of advantages over other methods, among which the following can be cited:

- The principles of operation are intuitive and design parameters are performance oriented, allowing concepts to be assimilated in a short time by plant operators, even if they have little knowledge in the area of control.
- Multivariable and non-linear control problems can be handled in a simple way.
- At present, it is the most natural approach to restricted control, an issue that is becoming increasingly important in the industrial sector (restriction of actuators, safety restrictions, and quality restrictions).
- It allows controlling processes with unusual dynamic behaviors, such as non-minimal phase processes, highly oscillatory processes or unstable processes.
- Its predictive character makes it compensate intrinsically the dead-times.
- It introduces a feed-forward control, and the measurable disturbances are naturally compensated.
- Although based on certain basic principles, it is an open methodology that allows extensions, contributions, alternatives and improvements for the future.

However, as expected, it also has some disadvantages:

ARPN Journal of Engineering and Applied Sciences

- Although its implementation is not complex, it is more difficult than the classic PID controllers.
- If the dynamics of the process is variable, the computational requirement to perform the calculations increases; however, with the power of current computers this is not really an impassable difficulty.

2. MATERIALS AND METHODS

The following describes the mathematical notation that will be used throughout the explanation:

- t represents the discrete time index ($t = 1,2,3, ...$)
- $u(t)$ represents the process input (manipulated variable)
- $y(t)$ represents the output of the process (controlled variable)
- $w(t)$ represents the setpoint
- $u(t+k|t)$ represents the future values of the input, calculated at time t
- $y(t+k|t)$ represents the future values of the output based on:
  - Measurements available at time t: $\{y(t), y(t-1), \ldots, u(t-1), u(t-2), \ldots\}$
  - Future values of the input at time t: $\{u(t), u(t+1|t), \ldots\}$

Figure-1 shows the basic principle of predictive control, which is characterized by the following strategy:

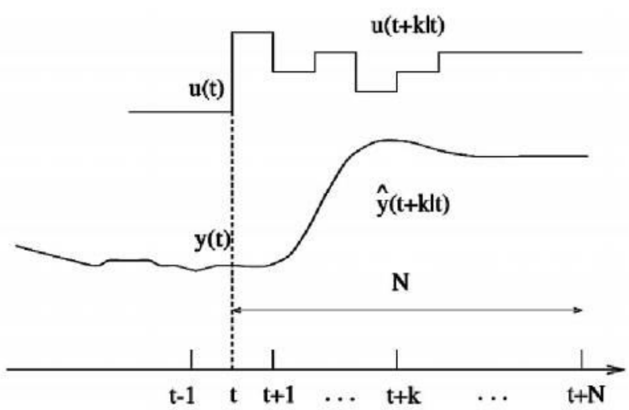

Figure-1. MPC strategy.

- At each instant of "present" time t, the output of the process is predicted over a time horizon $k = 1 \ldots N$. $y(t+k|t)$ indicates the future values and the value N is known as the prediction horizon. The prediction is made by means of the process model, so it must be available. This prediction depends on past inputs and outputs, but also on the future control scenario $\{u(t+k|t), k = 0, \ldots, N-1\}$; that is, the control actions that will be applied from the present moment t onwards.
- A reference path $\{r(t+k|t), k = 1, \ldots, N\}$, is defined on the prediction horizon, starting at $r(t|t) = y(t)$ and evolving towards the setpoint w. This describes how to guide the output of the process from its current value $y(t)$ to the setpoint w. In case the process presents dead-time, it is reasonable to start this trajectory after it.
- The control vector $\{u(t+k|t), k = 0, \ldots, N-1\}$ is calculated to minimize a specific cost function, depending on the predicted control errors $\{[r(t+k|t) - y(t+k|t)], k = 1, \ldots, N\}$.
- The first element $u(t|t)$ of the optimal control vector $\{u(t+k|t), k = 0, \ldots, N-1\}$ is applied to the real process at the current time instant. The other elements of the calculated control vector can be neglected since at the next sampling time all the time sequences are shifted and a new output measurement $y(t+1)$ is obtained by repeating the whole procedure again. This leads to a new control input $u(t+1|t+1)$, which is generally different from the previously calculated $u(t+1|t)$; This concept is known as a sliding horizon.

Figure-2 shows the structure necessary to implement the predictive control. There, a plant model is used, in order to predict the evolution of the process output from the known input and output signals. Future control actions are calculated with the optimizer, which considers the function of cost and possible constraints.

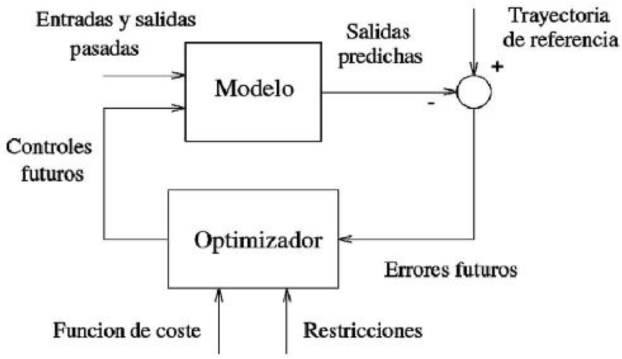

Figure-2. Basic structure of the MPC.

As can be seen, the process model plays a decisive role in the controller. This must be sufficiently elaborate to capture the dynamics of the process in the best possible way and thus accurately predict the evolution of the system; but at the same time, it should be simple enough to implement and understand, in order to reduce the computational load associated with the prediction process. The different predictive control methodologies differ fundamentally in the type of model used.

Another fundamental part of the structure is the optimizer, which allows to obtain the control actions to be applied. If the model is linear, the cost function is quadratic and there are no restrictions; then a quick and accurate solution can be obtained. If, on the other hand, this is not the case, numerical optimization algorithms must be used, which increases the computational load by requiring greater computational capacity.

Although the size of the resulting problem depends on the number of process variables, the control

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and prediction horizons chosen during the design, and the number of constraints considered, in general the resulting optimization problems are rather modest problems.

Finally, an analogy can be made between the predictive control strategy and the strategy used when driving a car: the driver knows the desired reference trajectory for a finite control horizon. Taking into account the characteristics of the car (mental model of the car) decides what control action to take (accelerator, brakes, steering wheel, gears) to follow the desired path. Only the first control action of the mentally calculated sequence is applied by the conductor at each instant and the procedure is repeated at successive instants using the concept of sliding horizon.

In contrast, when a classical control scheme such as PID is used, only the past signals are used. This way of driving the car would be like driving using the rear view mirror, as shown in Figure-3.

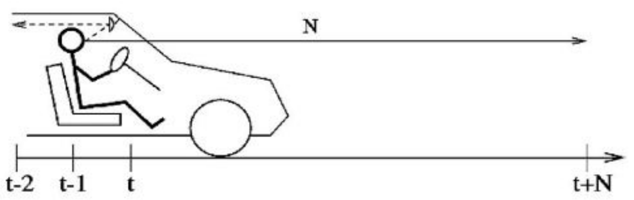

Figure-3. MPC analogy.

3. RESULTS AND DISCUSSIONS

Some companies use predictive controllers that have been developed to improve the processes within their companies and do not offer them externally; however, there are others that do provide such controllers. The following are some of them, indicating the acronym of the product they provide:

- **Aspentech:** Dynamic Matrix Control (DMC).
- **Adersa:** Identification and Command (ID-COM), Hierarchical Constraint Control (HIECON) and Predictive Functional Control (PFC).
- **Honeywell profimatics:** Robust Model Predictive Control Technology (RMPCT) and Predictive Control Technology (PCT).
- **Setpoint Inc.:** Setpoint Multivariable Control Architecture (SMCA) and IDCOM-M (multivariable).
- **Treiber controls:** Optimum Predictive Control (OPC).
- **ABB:** 3dMPC.
- **Pavillion technologies Inc.:** Process Perfecter.
- **Simulation sciences:** Connoisseur.

It should be noted that each product is not only an algorithm, but is accompanied by additional packages for plant identification or testing.

There are several applications of predictive control in the industry. Most applications are in the petrochemical sector [6], [7] in refining processes, but there are also numerous applications in the pulp and paper, food processing, gas, mining, furnace, metallurgy, aerospace and automotive industries. An extensive theoretical collection on predictive control directed primarily to experienced industry personnel in control can be found in Rawlings [8].

The results of a study carried out for the Society of Instrumentation and Control Engineering [9] are indicative of the future needs of the industry in the field of control. This report analyzes the main control problems in the process industry, the state of application of advanced technologies, the level of user satisfaction with each of them and the expectations they generate. According to the report, the main problems that arise in the industrial sector have to do with the delay or dead time, the disturbances and the interaction between variables. From the cited report it can be concluded that almost all users of predictive control are satisfied.

It is also interesting to try to quantify the future evolution of the different techniques. In Figure-4 it is tried to show the technical possibilities and the expectations aroused by each one of them.

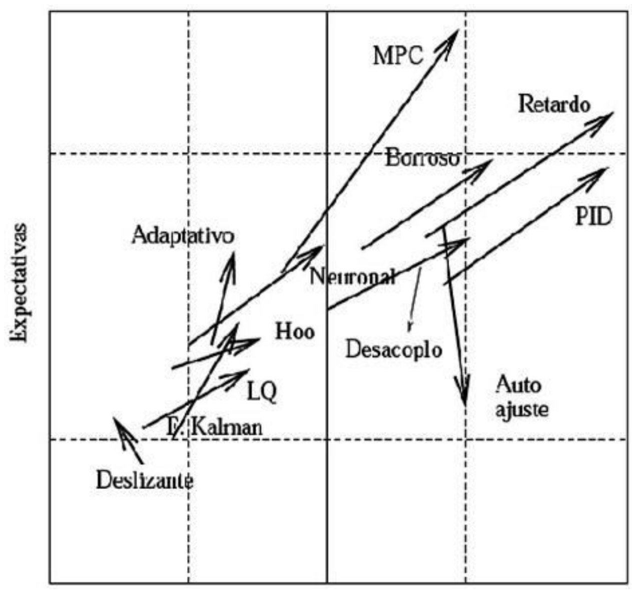

Figure-4. Expectations and technical possibilities.

Technical possibilities refer to ease of implementation, and expectations, to the expected effect in the use of each technique. This article interprets the arrow as a future trend. Accordingly, advanced PID, delay compensation, fuzzy, and MPC will be widely used techniques with high expectations. Neural control raises great expectations but has certain implementation difficulties, while self-tuning is easily implemented, but it loses expectations. Techniques such as LQR, Kalman filter, H∞ and adaptive are maintained "without too many expectations and not easily implemented".

Predictive control is considered a mature strategy in the case of linear processes, and is used quite successfully in the industry. However, predictive control cannot be considered as a discipline already closed to research, but rather, it is a branch of control engineering with a great boom today. This can be verified by the fact that in all control congresses in recent years there are always specific sessions of predictive control and there is very little number of control journals in which there is no article on this topic.

Predictive control is still very difficult to implement in real time for nonlinear processes, hybrid processes or very fast processes, so these issues are the subject of research. In the case of nonlinear and hybrid systems solutions have appeared for particular and usually small issues, but there are no general solutions. However, in the case of linear processes, the predictive control can be applied even when they present very fast dynamics.

A great problem still not solved is the stability and robustness analysis of the predictive controllers; That is, even if the controllers are implementable, analyze how their stability can be ensured in the nominal case or in case the model is not accurate. In addition, in the case that the optimizer was able to find a solution, the stability of the closed loop is not guaranteed.

Results have been obtained using robust control techniques in the context of predictive controllers. The basic idea is to take into account the uncertainties about the process in an explicit way and to design the predictive controller to optimize the objective function in the worst possible situation of the uncertainties.

In any case, these results require the computation of invariant regions which, except in the case of linear systems, are difficult to calculate.

These promising results suggest that predictive control would experience greater dissemination in both academia and industry in the coming years.

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