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proposes a model-based control strategy for control problems with a single controlled variable and multiple, constrained manipulated variables.

INDUSTRIAL APPLICATIONS OF IDCOM

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Abstract. Predictive control techniques are being analyzed and applied in both academic and industrial environments today. These techniques are well suited to process control applications. One such technique, IDCOM, has been applied to the multivariable control of several refinery and petrochemical processes during the past decade.

An introductory discussion describes the basic IDCOM control structure. Process and control system descriptions for recent applications involving reactor controls are presented to show the general structure and strategies possible with IDCOM. These applications demonstrate the importance of dealing with constraints in complex control systems. Moreover, it is evident that economic incentives also need to be imbedded in the structures to fully realize potential benefits. These experiences indicate the need for predictive control algorithms that can solve constrained optimization problems with reasonable amounts of engineering and computing resources.

Keywords. Internal Model Control; Predictive Control; Computer Control: Digital Control; Industrial Processes; IDCOM.

INTRODUCTION

IDCOM (IDentification and COMmand) is a multivariable predictive control technique that has been applied to several industrial processes since the early 1970's. The technology was developed in France and initial applications were primarily in Europe with recent applications in the United States, Canada, and Japan. The basic philosophy of this control technique is to use an internal process model to predict the effects of past process inputs, both manipulated variables and measured disturbances, and to subsequently calculate values for future manipulated variables required to achieve a specified process response goal. IDCOM is usually implemented with linear process models obtained by process identification. The identified process is represented internally by discrete convolution models and therefore the methodology is applicable to arbitrarily complex (linear) dynamic systems. Extensions where process nonlinearities warrant nonlinear models are also possible.

Practical control applications often require strategies that must cope with constraints on manipulated and controlled variables and also on ancillary dependent variables that can override the normal control sequence. Similarly, the degrees of control freedom may vary dynamically for some multivariable control problems due to constraints or other factors. IDCOM provides a control structure whereby these types of practical problems can be accommodated in a flexible way which is usually dictated by operational or economic considerations.

IDCOM - A BRIEF DESCRIPTION

A brief description of IDCOM including comments on some similarities between IDCOM and other internal model-based controls is presented in this section. More detailed descriptions and comparisons are available in the literature (Martin, 1981; Mehra et al, 1980; Richalet et al, 1978.)

The internal model is structured as a discrete convolution model represented by the process impulse response. Model predictions are of the form:

$$s(n) = \Sigma a_i e(n-i) = A^T E(n) \qquad (1)$$

The elements a_i of the vector A are the coefficients of the discrete impulse response and the time dependent vector E represents the process input. The output at time n is s(n). The extension to the general multivariable case is reasonably straightforward but not necessary for understanding the basic control strategy.

The summation in (1) theoretically must be done over all non-zero terms. Since impulse response coefficients tend toward zero for asymptotically stable processes, a finite summation provides an adequate approximation in practice. With an unstable process, e.g. some level control applications, the problem can be restructured to avoid an infinite length impulse response model.

The convolution model is a non-minimal representation since there are more impulse response coefficients than parameters in an equivalent transfer function representation. For example, a first order process model is fully described by a gain and a time constant whereas a convolution model for the same process would theoretically require an infinite number of coefficients. In practice, the model is often approximated with fewer than 50 coefficients. The model structure is also order-independent since an arbitrary order process, including dead time or other non-minimum phase behavior, can be represented without additional effort. This characteristic is helpful when process identification tests must be run to establish a model without detailed knowledge of the process. In the final analysis, the impulse model structure provides a flexible way to handle general problems at the expense of extra computations and storage.

The idea behind the IDCOM control calculations can be explained by reference to the following equation.

$$s(n+k) = \Sigma_f a_i e(n+k-i) + \Sigma_p a_i e(n+k-i) \qquad (2)$$

The process output at k time steps into the future is s(n+k). This value depends on input contributions that have already occurred represented by the past sum, Σ_p, and on future inputs whose contribution is represented by Σ_f. The control algorithm must then determine the future values for e that will result in the output, s(n+k), satisfying the control goal. The goal used by IDCOM is that the output should be at some reference point at time (n+k). There will be at least one solution if k is greater than the dead time. A unique solution is found if the future inputs at (n,n+1,...n+k-1) are assumed to be equal. In this case, the control output is:

$$e_f = [r(n+k) - \Sigma_p a_i e(n+k-i)]/\Sigma_f a_i \qquad (3)$$

The desired reference point is r(n+k) and the term $\Sigma_f a_i$ is a constant. The control input, e_f, is applied at time (n) and the entire procedure is repeated at time (n+1). Thus, different values are calculated and applied at each time increment even though the calculation is done as if only a single step will be applied. Notice that the numerator in (3) is a predicted error at some time in the future.

The division by $\Sigma_f a_i$ in (3) shows that the algorithm must effectively invert part of the process model to determine the control action that will satisfy the goal. This inversion is possible when k is chosen greater than the dead time or non-minimum phase response time. (The criteria in the multivariable case is more complex, but the idea of inverting part of the model still applies.) Other model-based control strategies have similar requirements. For example, the design approach for internal model control (IMC) requires an inversion of the process model but this is limited to the "invertible part" of the model. Likewise, Dynamic Matrix Control (DMC) requires a prediction horizon that is greater than the dead time. All of these requirements are results of physical realizability considerations. The reference point used to calculate the control action is normally computed such that this point is on a reference trajectory which defines the path the process would take in returning to the setpoint if no further disturbances were encountered. Figure 1 is a diagram that indicates how the response to a setpoint change might look for a specified reference trajectory. The reference trajectory is often specified to be a first order response with a dead time equal to the process dead time. For the multivariable case, each controlled variable may have a unique reference trajectory. The reference trajectory used by IDCOM is basically the same as the filter that is used in the IMC design procedure. The reference trajectory time constant plays a vital role in practical IDCOM applications. It is a tuning parameter that can be adjusted in an intuitive way to establish the tradeoff between control system performance and robustness. Also, the activity of the manipulated variable which often enters into subjective tuning criteria is directly affected by the reference trajectory time constant. Simulation of the process and the control system has proven to be an effective tool for establish initial tuning and for gaining insight into response characteristics when there is mismatch between the internal model and the process.

IDCOM APPLICATIONS

The following list summarizes the process control applications of IDCOM.

- PVC Plant - Reactors and Distillation (1971)
- Fluid Catalytic Cracker Main Fractionator (1973)
- Power Plant Steam Generator (1976)
- Crude Oil Fractionators (1976-1978)
- Oil Hydrotreater/Hydrocrackers (1981-1985)
- Fluid Catalytic Cracker Regenerator (1985)
- Catalytic Reformer (1985)

Applications in other areas such as military weapons and a ship control system have also been reported.

Some early industrial applications of IDCOM have been documented by Richalet et al (1978). The first application involved control of a PVC plant in France. The system involved cracking oven temperature control with feedforward compensation based on measured and calculated disturbances. Two distillation columns were also controlled. For one column, impurities of two components in the distillate were controlled by manipulating reflux. Composition feedback was provided by a GC and control was based on the impurity which was closest to its specification limit. For the other column, the IDCOM strategy was configured to supervise two analog temperature controllers that in turn manipulated boilup and reflux. Cloud point (a diesel oil property) control on a crude oil atmospheric distillation column was another early application of IDCOM. There were three levels of cascade control. The lowest level was simply an analog flow controller. Next, was an IDCOM controller, including feedforward and feedback, for a tray temperature. The highest level controller was an IDCOM feedback controller based on an on-line cloud point analysis. This cascade/feedforward structure demonstrates how IDCOM can be used in familiar control system arrangements.

A fluid catalytic cracking fractionator column is similar to a crude oil atmospheric distillation column. In this application, IDCOM was applied to the multivariable control of two key column temperatures that relate closely with product quality. An internal pan level in the column is affected by various disturbances and also by the manipulated variables (the side draw flow rates). An important objective of the control strategy was to ensure that this level did not fall below a safe minimum. This is a case where the predictive nature of the the IDCOM was used to allow the level to vary within bounds but also override the product quality control objective if predictions indicated that the level limit would be violated.

A power plant steam generator control system was built using IDCOM technology. The system provided control of steam pressure and two superheat temperatures. This was an interesting application in that there were non-minimum phase responses in the process.

There have been several recent applications of IDCOM. Among these is a hydrocracker control system described by Martin and Van Horn (1984). There are three applications of the basic process and

control system shown in Fig. 2. The overall control objective is to maintain a weighted average bed temperature which relates to the reaction severity and is a key parameter that determines product quality and yield. Feed is heated in a fired heater before entering the first catalyst bed where an exothermic reaction occurs. Hydrogen is injected at the inlet to subsequent beds both to quench the reaction and add more reactant. Reactor products are processed in a downstream fractionation section. There are three levels of control cascade in this system. First, bed inlet temperatures are controlled using standard PID algorithms in a distributed control system. At the next level are three IDCOM controllers implemented in a minicomputer that control the outlet temperature of beds two through four. The deadtime between bed inlet and exit was one reason for choosing an advanced control technique at this level. The weighted average temperature control block supervises one first level controller and the other IDCOM controllers. The ability to handle valve position constraints with a dynamic prediction are an important part of this highest level control function. The strategy also provides feedforward compensation for changes in feed rate or hydrogen partial pressure.

An extension to this basic control system has been applied to a case where it was desirable to adjust the reaction severity to maintain a ratio between fresh feed and a recycle stream from the bottom of a downstream fractionator. Ratio control was implemented in a distributed control system and one task of the IDCOM controller was to maintain the level in a recycle surge drum within an acceptable operating zone. This was done by manipulating the weight average temperature setpoint of the previously described control system. The transfer function between the weight average temperature and the level included an integrator. In this case, it was necessary to effectively remove the integrator from the process by using an estimated derivative of the level as the controlled variable. This approach results in an internal model that is asymptotically stable.

IDCOM has recently been applied to the supervisory control of the regenerator in a fluidized bed catalytic cracking (FCC) process (McPherson et al 1985). A simplified process diagram including the basic instruments used by the IDCOM control algorithm is shown in Fig. 3. The process is designed to upgrade low value heavy oil into lighter products such as gasoline. Fresh feed and recycle oil are fed to the "risers" which are essentially plug flow reactors. Here, oil and solid fluidized catalyst are mixed and the endothermic cracking reactions quickly occur. A reaction by-product is "coke" which deactivates the catalyst. Reaction products are separated in the reactor (a misnomer since the reaction occurs in the risers) and routed to a fractionation column while the deactivated catalyst is returned to the regenerator. Here, the coke is burned off of the catalyst at a high temperature, typically 1,300 degrees F. Combustion air is supplied by a large air blower. An important operating objective is to supply the right amount of combustion air to satisfy the coke burning demand. Alternately, it is sometimes desirable to adjust the coke generation to match available air blower capacity.

There are many physical and economic interactions in the typical FCC process that can result in different control system objectives. In this application, there was incentive to control excess oxygen in the flue gas by adjusting either air rate or reactor severity. Riser temperatures, recycle rate, and feed preheat temperature are all operating parameters which affect severity and hence the amount of coke deposited on the catalyst. Therefore, the air/coke balance as measured by flue gas oxygen could be controlled by adjusting any of these quantities as well as direct control of air rate.

The IDCOM structure applied to this control problem is shown in Fig. 4. There are five potential manipulated variables and two potential controlled variables. Control logic determines which manipulated variables to use based on operator input, the availability of the individual manipulated variables, and on an economic priority. Flue gas oxygen is the primary controlled variable while the flue gas temperature becomes a controlled variable in case of high temperature excursions. The temperature is constantly being predicted so that preventative control action can be taken to avoid an actual temperature limit violation.

SOME OBSERVATIONS

There are important observations about these applications related to degrees of freedom and constraints. Industrial multivariable control problems involve more than simply regulating an N X N process. It is not unusual to have extra degrees of freedom for the manipulated variables. Operational and economic considerations determine how these degrees of freedom should be used. However, encountering manipulated variable constraints can result in degrees of freedom being changed in real time and the control system must accommodate this possibility. It is also possible for constraints to result in an uncontrollable system. In this case, the controller performance must be allowed to degrade by relinquishing control on one or more variables. Constraints also apply to dependent variables that are normally not controlled. These dependent variables effectively become controlled variables when they reach a limit and sometimes override the normal control sequence. The internal model must be maintained for these dependent variables both to predict potential constraint violations and to assure a smooth transition when an override is necessary. Since the optimum operating point often turns out to be on one or more constraint boundaries, it is common for the control system to have to be continuously dealing with constraints and varying degrees of freedom.

CONCLUSIONS

Observations in the previous section point out areas for further developments in multivariable predictive control. The IDCOM structure is very flexible and provides a framework for building control systems that deal with constraints and varying degrees of control freedom. While some applications involving these factors can be accommodated with little or no additional effort, other more complex ones require special attention. Additional control tools that can handle increasingly difficult problems with a general structure are a definite need. Furthermore, the tools should provide a means to translate physical and economic objectives into control system objectives in a straightforward manner. Control engineers need proven tools that can be applied without undue effort. End users need controllers that are robust and can be maintained and tuned by local personnel.

Industrial multivariable control applications pose difficult problems that demand both sound engineering and reasonable maintenance practices to ensure long term success.

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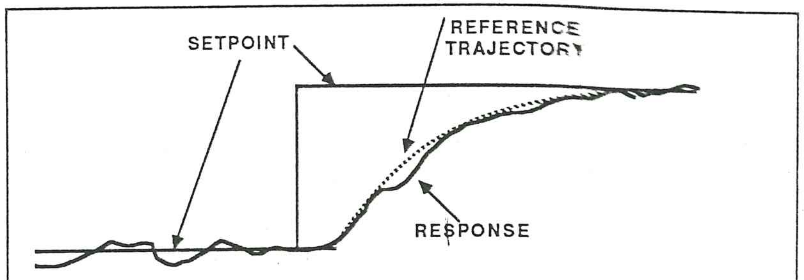

Fig.1. Example setpoint response

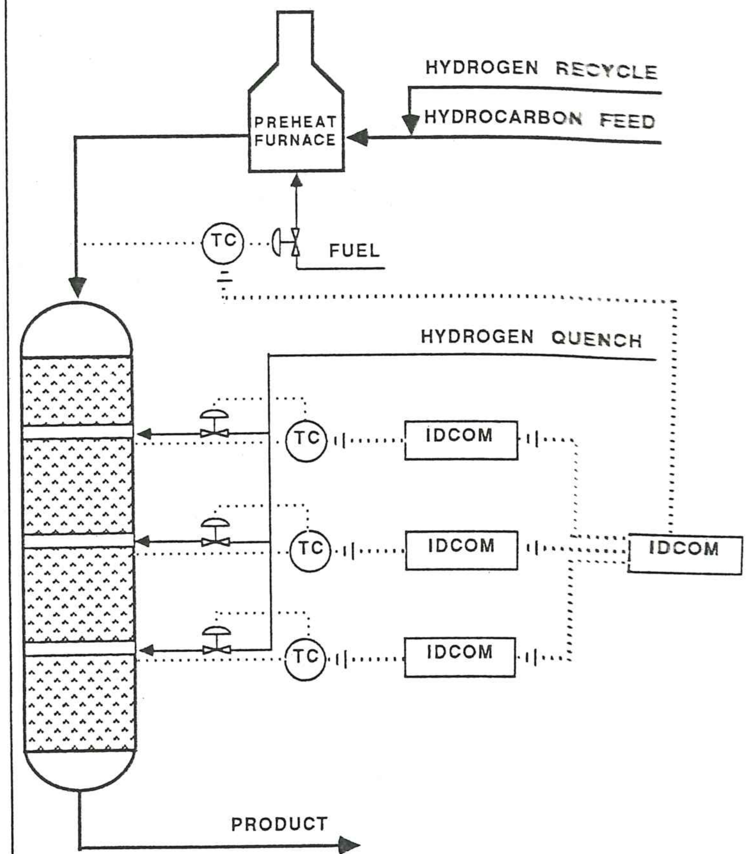

Fig. 2 Hydrocracker control system

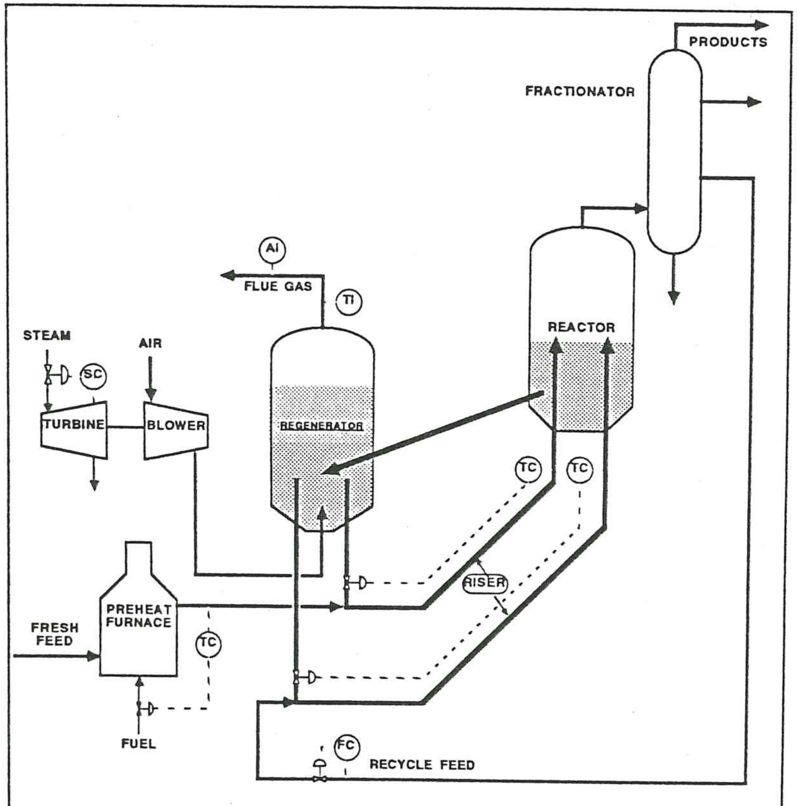

Fig. 3 Typical FCC process configuration

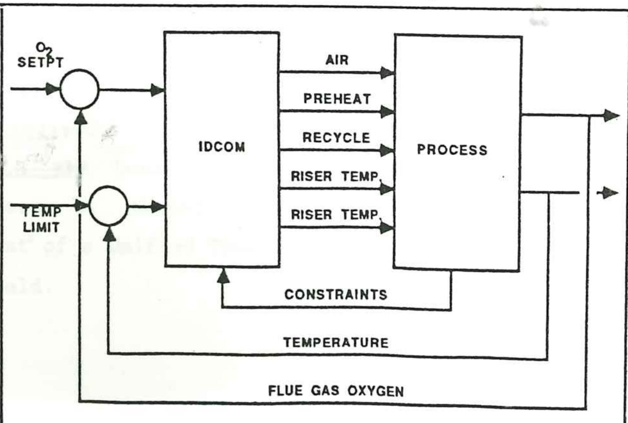

Fig. 4 IDCOM FCC control structure

ADVANCES IN INDUSTRIAL MODEL-PREDICTIVE CONTROL

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Abstract. Due to the economically sensitive condition of the chemical and petroleum industries, we can no longer afford to operate with the inefficiencies of the past. Over the last 15 years we have found that on-line optimization implemented with model-predictive control recognizing process and operating policy constraints, provides the best means for achieving the profit potential of our plants. Only model-predictive controllers permit the flexibility required to handle the constantly changing performance criteria, in particular the enforcement of operating constraints. However, the performance criteria of today's problems are becoming harder to quantify, while optimization systems are driving the processes over a wider range of operating conditions than ever before. Therefore, there is a need to improve the model-predictive control techniques so that practical performance criteria based on engineering judgement can be transparently specified, and that model inaccuracies are considered explicitly in the problem formulation. In this paper the state-of-the-art in industrial model-predictive control is presented. An attempt is made to propose a path of evolutionary development in process control that will converge to a **Unified Theory** replacing many of the ad-hoc solutions developed over the last thirty years. New techniques for multi-objective optimization and robust control are described that have the potential to allow us to improve the current technology in order to solve the control problem at hand. It is concluded that the complex control problems of today can only be