PERSPECTIVES ON INDUSTRIAL REACTOR CONTROL 2: AN UPDATE FROM CPC 3

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Abstract

This paper will discuss the evolution of reactor control over the last 25 years within the DuPont Company and its subsidiaries. It will focus on high level trends in control philosophy, systems and approaches. These changes have been necessary in order to achieve higher rates, better yields, improved uptime and a more sustainable footprint. This paper is an update to an article that was presented twenty five years ago at CPC 3. The main focus will be on the use of Model Predictive Control (MPC) for reactor processes.

Keywords

Industrial, Reactor, Control, Model Predictive Control, MPC, Advanced Regulatory Control, ARC, Sustainment, Prototyping, Monitoring, Modeling.

Introduction

Schnelle and Richards (1986, 1988) presented a survey paper entitled "Perspectives on Industrial Reactor Control" during CPC 3. The purpose of this paper is to give an update on some aspects of this technology twenty five years later. The authors have worked for DuPont, during this time period, and have witnessed many changes in tools and approaches to reactor process control. More recently, Richards and Congalidis (2006a, 2006b) presented a paper specifically on "Measurement and Control of Polymerization Reactors" at CPC 7.

This paper will discuss how certain trends in industrial reactor control have changed during this 25 year time period, looking at specific examples of processes and how they were controlled then and now. DuPont does not still operate all the processes that where examined twenty five years ago, but the ones that are still in our company have changed significantly.

Several major changes have occurred in the control infrastructure during this time period. This was necessary to keep the processes up-to-date with changing control systems technology. For example, 100% of the processes surveyed then are now on a Distributed Control System (DCS) with some layer of a Data Historian (DH) or an Enterprise Management (EM) system layered on top of that. These upgrades have been important to help control the ever increasing demand for quality products and better integrate process and business operations.

Just deploying modern control systems does not guarantee that the process control philosophy or strategies have changed or have been upgraded as it has been said that "you can do poor control in a DCS as well as you can in an analog control system". One of the greatest disappointments that have frequently occurred is that the same control strategies are frequently repeated in brand new control hardware systems. Operations can justify replacing control hardware based on obsolescence but sometimes can't find the time or money to make use of these more powerful systems now to improve control. Fortunately this is not always the case. The new systems and software have, in many cases, made it possible for processes to make some major steps in improving operations and control.

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Model Predictive Control (MPC) has emerged, over the past 25 years, as a technology able to meet many of the challenges that were discussed by Schnelle and Richards (1986). We believe this is as true for reactor control as it is for other unit operations.

Literature Review of MPC

There is a tremendous literature which has arisen on MPC since it was developed. We will attempt to summarize some of the more recent contributions for MPC in general and then discuss literature specifically related to reactors.

There are several worthwhile books on the subject. Seborg et al. (2011) contains an introductory chapter on MPC methodology for those who want a quick start. Rawlings and Mayne (2009) offer a more comprehensive look at the theory and design of MPC.

The following is a sampling of recent journal review articles. Qin and Badgwell (2003) provide an overview of commercially available MPC technology, both linear and nonlinear, based primarily on data provided by MPC vendors. They report that by the end of 1999 there were at least 4500 industrial MPC applications worldwide, mainly in oil refineries and petrochemical plants. They also present a vision of the next generation of MPC technology, with an emphasis on potential business opportunities. Garriga and Soroush (2010) provide a review of the available tuning guidelines for MPC, from theoretical and practical perspectives. A talk by Badgwell (2010) briefly summarizes progress to date in the analysis and application of MPC technology, focusing on the process industries. The author proclaimed "In the past forty years, Model Predictive Control technology has progressed from textbook theory to its current dominant position in industrial practice". Lee (2011) reviews major developments and achievements during the last three decades and attempts to put a perspective on them. In a recent industrial example, Schnelle, et al. (2007) presented an application of state space MPC to a commercial scale Dilution / Pasteurization / Drying Process for soy protein isolates.

There are specific applications of MPC to reactors. A review of the application of linear MPC tools to a prototype continuous polymerization (CP) process was given by Schnelle and Rollins (1997, 1998), where the authors discuss in general why the MPC technology may be a good fit for continuous polymerization (CP) control problems (e.g., attempt to minimize settling time after rate changes or process upsets, compensate for significant multivariable interactions and handle unusual process dynamics). They concluded that:

- Multivariable control gave marginally better to significantly better control performance compared to PID control for their simulated process.
- The built-in optimization capability of MPC may be the most important reason to use this technique vs. PID control.
- Commercial MPC software and tools is becoming well integrated with lower levels of controls and easier to use, both off-line and online.

Academic researchers continue to discuss the application of nonlinear MPC to polymer reactors. Richards and Congalidis (2005, 2006a, 2006b) discuss some of the aspects of ARC and MPC as applied to polymer reactors. Richards and Congalidis (2006b) refer to the polymerization process benchmark problem previously set forth in Congalidis et al. (1989) as being useful for control system design and testing for many authors. Several academic researchers such as Maner and Doyle (1997), Özkan et al. (2003), and Bindlish and Rawlings (2003) have designed and implemented nonlinear MPC controllers for the Congalidis et al. (1989) benchmark problem. These controllers were used successfully for plant startup, minimization of off-grade product during grade transitions and regulation around a set point.

Major Trends in Industrial Reactor Control

This paper will focus on MPC for reactor control, and it will present a partial list of the major tends that have taken place in the DuPont company over the last 25 years. Some of these trends include:

- 100% of reactor processes use Distributed Control Systems (DCS) with data historian. Some systems also incorporate demand driven enterprise level systems.
- There is large scale use of control loop performance monitoring system both Single Input Single Output (SISO) PI control structures and for MPC.
- There is more use of Product by Process (PxP).
- There is more use of automated Statistical Process Control (SPC).
- There is a growing percentage of processes running under MPC.
- The cost and capabilities of MPC have improved.
- There is better awareness of control and process modeling capabilities.
- There are better tools, more PC based on-line systems and more powerful software.
- There are more flexible manufacturing processes running requiring flexible control configurations.
- There are more batch vs. continuous reaction processes.
- There is an ever present need to make more products, cheaper and faster in a safe and environmentally responsible manner.

Not all of these trends pertain or have led to the increased use of MPC for reactor control. Some have certainly helped make a better case for MPC. But the real driver is the need for better operational performance. On the other hand, some technologies that have been attempted but have not caught on include:

- AI and expert systems for on-line applications
- Neural networks for inferential sensing
- Large scale use of first principles models on-line working as inferential sensor or what if tools.

Although promising initially, these techniques have turned out to be more complex in the deterministic model category or limited in predictability in the empirical model category than originally envisioned. Some companies report success using large scale models for Real Time Optimization (RTO) applications.

MPC in Reactor Control

In recent years DuPont is utilizing much more MPC for reactor control. The following list summarizes some reasons why MPC adoption is on the rise. After these reasons are enumerated, a sampling of MPC controlled reactors will be classified by which of these reasons / advantages (attributes) the reactor application is taking advantage of.

Table 1. Reasons for MPC (Attributes).

Technology opportunity	*Code*
Multivariable	M
Constraint Riding	C
Optimization	O
Dynamics Problem	D
Inferential Sensor / Filtering	I
Transition Control	T
Inventory / Recycle	R

Table 2. Examples of reactors using MPC technology and attributes are being utilized.

Reactor	*Attributes*
Polymer CP	M, D, I, T, R
Solid Phase polymerization	M, D, I
Tubular Reactor	M, D, R
Fluidized bed reactor	M, D, C, I, T, R
Rotating Kiln Reactor System	M, D, I, R
Low conversion, high recycle polymer reactor	M, D, C, I, R
Cracking Furnaces	M, C, O, I, T
High Pressure Copolymer Reactor Systems	M, I, T, R
Finishing reactor	M, I
Protein Isolation and Enrichment	M, D, C, I, T, R

As can be seen in Table 2, MPC has been used in many types of reactor problems and for many different purposes. The multivariable nature of reactor control appears to be the dominant attribute followed closely by complex dynamics and constraint riding requirements.

By contrast, this same list of reactors is compared to how they were controlled twenty five years ago in Table 3. Since none of these reactors were on MPC twenty five years ago, all the attributes shown on this list were being achieved using ARC strategies such as Smith predictors, decoupling, feedforward control, overrides and inferential sensing.

Table 3. List of reactors from Table 2 and what ARC Technology was being used 25 years ago.

Reactor	*Attributes*
Polymer CP	I, T
Solid Phase polymerization	
Tubular Reactor	D
Fluidized bed reactor	D
Rotating Kiln Reactor System	
Low conversion, high recycle polymer reactor	M, I, R
Cracking Furnaces	C, I, T
High Pressure Copolymer Reactor Systems	I
Finishing reactor	
Protein Isolation and Enrichment	

MPC offers some useful integrated or implicit control functionality (M,C,O,D,I and T) that can be utilized to enhance reactor control and allow for better overall plant operation. It should also be mentioned that the support and maintenance of MPC allows for better utility of these more complex applications, than does ARC, because of the implicated functionality and well designed support tools provided.

The benefits of MPC are not limited to reaction applications. The generic benefits of more supportable complex control applications are also true for a wide variety of non-reactor processes. The following list is generic in nature but the MPC attributes have shown to be helpful on these processes. Table 4 shows some examples used in DuPont.

Table 4. Non-reactor MPC examples.

Reactor	*Attributes*
Distillation	M, D, C, I
Drying	M, C, O, I
Cross and Machine directions Web and Thickness control	M, T
Rate and Inventory	M, C, O

Wastewater Outfall	M, C, D, O, I
Cryogenic Separations	M, D, O
Feed Ingredients Preparation	M, C, T, I

It should be noted that the nature and size of the MPC applications being deployed at DuPont may be considerably different than the applications published by other MPC users. Most of these MPC applications are smaller in size, typically no more than five independent input variables and seven dependent output variables. Some are smaller but all are high value.

The nature of most of the reactor problems are small dimensionality, highly interactive, measurement poor (lack of continuous or noisy critical measurement) and requiring running up against a “difficult” constraint. “Difficult” constraint is intended to mean that the process is being asked to run as close as possible to a point of interlock due to equipment limitations, product specifications or environmental permit. Operations are required to run close to these constraints for maximum profit, but are reluctant to do so because of consequences of interlocking the reactor down.

Processes that are measurement poor are also an important characteristic of many DuPont reaction systems. The new integrated inferential sensing / lab tracking / filtering capabilities of the MPC tools have been an important enhancement. Being able to control tightly between long lab sample delays and being able to design more optimal filters for critical controlled variables (CV) has translated into better more profitable control.

Aspects of MPC that We Prefer for Reactors

DuPont has standardized on two commercially available MPC technologies / providers as part of its guide-lining Best Practice. Because of the heavy use of MPC for reactors, the tools required for reactor control were an important consideration. This standardization was done to keep tool proliferation at the plant sites under control, to leverage central resources and expertise, to optimize vendor relations on pricing, training, tool enhancement and to keep our toolset as current as possible. We have selected vendors that have tools which meet the functional requirements for the bulk of the MPC project that are encountered. The attributes listed in Table 1 are a minimum essential capability for these tools.

Also important are features, not listed as control attributes, which play a very important role. These include a straightforward flexible yet powerful development environment, performance and model monitoring capability, within-tool pre and post variable calculation capability, extensibility, flexible interfacing tools and templates, robust plant step testing tools and data handling, built in nonlinear modeling tools and of course the cost of the tool is always an important consideration. This is a tall order, but suppliers are providing more capable, cost effective tools every year.

Methods for Application Selection and Best Practice

DuPont technical staff is using some novel techniques to select, evaluate and role out MPC applications. Like all companies in industry, DuPont is trying to improve productivity and cut costs by optimizing plant staffing and leveraging technical resources as much as possible. Process control resources at plant sites are becoming more of a critical bottleneck. No one can afford to install technology that does not work reliably or can not be supported. The applications that are installed must be good applications that make sense, that provide good benefits versus the costs, and must work with high utility and reliability.

Spending upfront time studying the potential implementations has paid off in successful applications. This is accomplished by following an established Best Practice developed by our Corporate Process Control Centers of Competency. The Best Practice involves standardizing on well understood vendor tools, application value assessment, and rapid prototyping tools for concept development and training. This is followed up by using simple performance monitoring tools (asking the question is it working or not?) and where necessary follow-up with more in-depth analysis and maintenance tools. These approaches are important to insure that there is not a proliferation of unsupportable applications and that there is the best use of our leveraged resources.

Conclusions

We have endeavored here to review briefly some of the previous literature on reactor control and attempted to show how MPC technology has become the controller of choice for many high value applications in our company. MPC has been shown, under the right conditions, to be preferable to other higher level supervisory control applications due to its commercial availability, wide range of in-the-field practical applications, and adaptability to solving many of the complex control issues of the past in one framework.

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