OPERATOR INTERACTION WITH MODEL-BASED PREDICTIVE CONTROLLERS IN PETROCHEMICAL REFINING

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ABSTRACT

In this paper, we compare the advanced automation characteristics of Model-based Predictive Controllers (MPC) employed in process control to the more thoroughly studied Flight Management System (FMS) employed in airline cockpits. Our analysis shows that operator interaction with cockpit automation and MPC automation may differ in terms of the level of the control loops at which human control actions are directed. Cockpit automation appears to afford human control actions at outer loops through the specification of a flight path or selection of control modes and flight-path parameters. Inner loops, such as the control of flight surfaces, are controlled by the automation. In contrast, MPC affords operator control at the control variable level because operators are required to manipulate limits on those variables. Outer loops are managed by the automation. These differences in level may explain why we observed refinery operators asking questions of the automation pertaining to control intervention whereas reported studies of pilots' interaction with cockpit automation do not. This could also explain why we did not observe refinery operators having difficulty with automated mode changes, whereas reports from FMS interaction show that mode discrimination is a difficult and challenging task.

Keywords: Cognitive task analysis; Process control; Predictive control; Optimization.

INTRODUCTION

The many challenges of human-automation interaction have been well documented and empirical research is making steady inroads to understanding how this interaction can be better supported (see reviews by Parasuraman and Riley, 1997; Parasuraman, 2000). However, a majority of the field and laboratory studies of advanced automation have come from the domain of transportation, most notably in aviation with Flight Management Systems (FMS). Advanced automation is proliferating in other domains as well, often bringing with it human-automation interaction problems similar to those observed with FMS. In this paper we discuss the challenges of operator interaction with Model-based Predictive Controllers (MPCs), a class of automation technology that is being employed with increasing frequency in refining, pulp and paper, and grinding operations worldwide. We present the results of a field study of MPC use, discuss similarities and differences in the nature of operator interaction with MPC and FMS, and offer some implications for advanced automation design and research.

MODEL-BASED PREDICTIVE CONTROL

MPCs are multi-input, multi-output advanced controllers that are designed to push the process to the limits of the process parameter constraints. These controllers employ an empirically derived model of the controlled process and optimization algorithms to plan and execute control actions. While these controllers have enjoyed enormous success in the petrochemical industry, they have introduced new challenges for the operators and engineers responsible for maintaining, monitoring, and directing them.

MPC consist of two major parts: 1) an optimization algorithm, which defines the best place to run the process at steady state, and 2) a dynamic control algorithm, which defines how to move the process to the steady state optimum in a smooth way, without violating any constraints. The controller algorithm runs at a set interval (e.g., once a minute) and will use the current state of the process, as well as its predictive model, to determine if all control variables (e.g., reactor temperatures) are predicted to remain within constraints over the prediction horizon. If this can be achieved, then it will optimize the process according to the optimization algorithm, essentially setting a new steady state target for each of the control variables. The dynamic control algorithm will then determine how to set the manipulated variables (e.g., feed flow rates) for this control iteration so as to move the process in a slow, steady fashion to the new operating target, minimizing the chance of a process upset due to rapid control changes. At each iteration, the controller re-runs its algorithms to continue to control and optimize the process.

MPC differs from other types of automation in that it is constraint-based. Instead of establishing a target setpoint (e.g., an operating temperature or waypoint), a constraint-based controller seeks to guide a process through a dynamically managed operating space. The structure of that space is determined by the operators through their interaction with the control limits of the individual process variables.

It may be apparent to the reader from this description that MPC automation differs from advanced controllers in aviation. Several valuable studies of pilot interaction with advanced cockpit automation have been reported in the literature (Sarter and Woods, 1992; 1994). However, we are not aware of any studies of operator interaction with advanced automation in the process industries. The goal of this article, then, is threefold. First, to report on a series of field observations of MPC in use. Second, to characterize similarities and differences between user interactions with MPC and advanced cockpit automation. Third, to map some of those differences to engineered characteristics of the automation and draw research and design implications for advanced automation in general.

FIELD OBSERVATIONS

We conducted a series of field observations and interviews with engineers and operators using MPC in daily operations at four refineries. We supplemented our field observations by consulting with design engineers and reading user manuals to understand how user comments corresponded to the automation functionality. With this combination of approaches, we were able to develop an understanding of both the functionality of the automation and the nature of the monitoring and control task.

The Control Task

Refinery operators are tasked with controlling one or more units in a refinery. They view the process via a distributed control system which generates process schematics, trend graphs, and alarm pages. MPCs are typically designed to run a functional sub-section of a unit, so one board operator may have one or more MPCs that have been commissioned and installed on his/her unit. Thus, in addition to the routine process schematics, trend, and alarm pages, each MPC will have an additional set of display pages associated with it.

Operators have the ability to change the low and high limits on any variable in the MPC, or enforce setpoint control (rather than range control) for any variable. They can take "non-critical" variables out of control, meaning that the algorithm will no longer worry about keeping those variables within limits. An operator can also turn off the whole controller, and go back to regulatory control. Control engineers support the operators by assuring that the empirical model used by the controller remains accurate and that the controller sustains the flexibility to respond to process disturbances.

In general, the cognitive tasks of the MPC operator are not well supported by the existing automation displays. For example, data is presented in multi-page tabular format, control detail information is distributed across several display pages, and historical information about control actions is difficult to obtain. Elsewhere we have described a design effort to improve the effectiveness of the operator interface (Guerlain, Jamieson, and Bullemer, 2000; Guerlain, Jamieson, Bullemer and Blair, in review). In this article, we focus on the nature of the interaction between the operator and the control technology itself.

Questions

Our cognitive task analysis revealed that operators frequently ask themselves a series of questions about the automation (see Table 1, column 1). We can reduce this series of questions to four basic queries about the automation (Table 1, column 2); What is it doing?, Why is it doing that?, What will it do next?, and How and when should I interact with it?. By further abstracting these questions (Table 1, column 3) we find that this set of questions is indicative of the fundamental tasks of human operators in supervisory control (see Moray, 1986).

Table 1. The cognitive challenges of working with MPC.

Operator Questions about MPC Automation	*Generic Question Asked of Advanced Automation*	*Operator Task*
What is the overall health of the controller? Is the controller in a feasible region? Is the current model correct?	What is it doing?	Monitor
Why is MPC making a set of moves to a primary variable, e.g., Why is it cutting feed?	Why is it doing that?	Diagnose
Will MPC be able to handle a disturbance, or should it be taken off line?	What will it do next?	Predict
How and when should individual variables in the controller be manipulated to improve the performance of the controller?	Do I need to intervene?	Control

A Brief Comparison with FMS

The first three questions listed in the second column of Table 1 map directly onto the questions that Wiener (1989) is reported to have observed in pilots using advanced aviation automation. These three questions can be abstractly characterized as relating to Monitoring, Diagnosis, and Prediction (Table1, column 3). However, the fourth common question asked by MPC operators relates to Control: "Do I need to intervene?" Why did Wiener (1989) not include this fourth kind of question in his list?

Sarter and Woods (1992) confirmed the importance of Wiener's (1989) questions in their studies of pilots interacting with advanced cockpit automation. They later expanded the original list by adding the question "How…did we…get into that mode?" (Sarter and Woods, 1995). In our observations of MPC operators, mode confusion was <u>not</u> a factor in the difficulties they experienced in interacting with the advanced automation. Why are Sarter and Woods' (1995) observations not replicated in MPC use?

SIMILARITIES AND DIFFERENCES BETWEEN FMS AND MPC

Wiener's (1989) exclusion of a control-related query and our failure to observe mode-related interaction difficulties suggest that there may be some fundamental differences between MPC and cockpit automation. In this section, we attempt to characterize the differences between the structure of the automation and how that might lead to the observed human-automation interaction. Many of our observations are driven by a control-theoretic perspective (Jamieson and Vicente, 1998).

The Question of Control

Control engineers treat automation as a series of nested control loops (Wiener and Curry, 1980). For example, inner control loops include aircraft attitude control by way of flight surfaces or a process flow rate via a diaphragm valve. Outer loops might include aircraft navigation and efficiency optimization in refining. Our review of the FMS literature and our observations of MPC use suggest that operator interaction with cockpit automation and MPC automation may differ in terms of the level of the control loops at which control actions are directed. Cockpit automation appears to afford human control actions at outer loops through the specification of a flight path or selection of control modes and flight-path parameters. Inner loops, such as the control of flight surfaces, are controlled by the automation. In contrast, MPC affords operator control at the control variable level because operators are required to manipulate limits on those variables. Outer loops are managed by the automation. Thus, refinery operators have a wide range of possible control interaction opportunities and the challenge of understanding how those actions will propagate to outer control loops. Pilots have a narrower range of control interaction opportunities and the challenge of understanding how those actions descend to inner control loops. This could explain why we observed refinery operators asking questions of the automation pertaining to control intervention whereas reported studies of pilots interaction with FMS do not.

A related difference between FMS and MPC automation is the nature of the pilot or operator interaction. With the FMS, the activity of the pilot is often characterized as a programming task (Sarter and Woods, 1992). With the highest levels of automation, the pilot generates a flight path and communicates a series of targets to the computer by way of data entry and mode selections. At lower levels of automation the pilot enters values for lower level flight-path parameters and then directs the automation to match those values through the selection of particular modes. In contrast, the MPC operator's task is more of a 'corralling' task. In this case, the interaction is always at the process variable level (in some ways similar to the low level automation case in FMS). However, the refinery operator rarely sets exact values for these variables because that reduces the degrees of freedom available to the automation. Instead, allowable ranges for each variable are established. The high level planning activity is performed by the automation rather than the human. Again, this difference could help explain why refinery operators ask questions about control intervention whereas pilots have not been reported to do so.

The Question of Modes

Differences in the design of the automation also provide some insight into why we may not have observed MPC users asking questions about what mode the automation is in. Jamieson and Vicente (1998) showed how the introduction of modes in automation expanded the set of possible connections between the components in the feedback control loops. Sarter and Woods (1995) have demonstrated that setting these modes, monitoring their interactions, and interpreting their influence on the aircraft are error prone tasks for pilots using FMS. While advanced cockpit automation contains an abundance of mode configurations, MPC automation has only two independent mode classes; variable modes and controller modes. For example, the controller can assume more or less two modes of operation, Optimizing or Handling Constraints. Optimizing takes place when all control variables fall within the limits specified by the operator. In this mode, the linear or quadratic optimization algorithms are free to generate new target vales for the controlled variables to achieve. The controller assumes Handling Constraints mode (via an uncommanded mode transition) whenever a control variable is predicted to move outside of its operator-set limits. In this mode, the controller may make more dramatic changes to control variables.

MPC does not have the sort of combination mode settings that have been shown to be particularly difficult in understanding FMS (Sarter and Woods, 995). The MPC's variable modes and controller modes do not combine to generate qualitatively different automation behaviors.

Differences between the mode characteristics of FMSs and MPCs run deeper than the number of modes and their possible combinations. Jamieson & Vicente (1998) demonstrated that it is important to distinguish between classes of modes, those that discriminate between control tasks versus those that discriminate between strategies to achieve functions. The various modes in MPC discriminate between different controller tasks, whereas in FMS modes are used to discriminate both tasks and strategies for accomplishing tasks. For example, Sarter and Woods (1995) point out that, with FMS, a pilot can choose between five different methods (i.e., multiple strategies) to change altitude (i.e., a single function). In the case of the MPC controller mode noted above, the automation is performing a qualitatively distinct control task in each mode.

These differences in mode usage may explain why mode confusion, a prevalent problem in FMS use, was not mentioned as a difficulty for MPC use. Refinery operators did not query the mode state of the automation. Thus, the designers of MPCs appear to have (perhaps unintentionally) avoided the problem of mode confusion by a) designing few modes into the automation, and b) using modes to distinguish between controller tasks as opposed to strategies.

IMPLICATIONS

From our field observations, we can draw a number of implications for the design of automation technologies and directions for future empirical study.

Automation Design Implications

Designers of future evolutions of MPC technology should be wary of introducing more modes of operation. Observations of the impacts of modes in FMS lead us to believe that proliferation of modes leads to human-automation performance degradation. Sarter and Woods (1992, 1995) point out that the designer's intention of providing additional flexibility often has the unintended side effect of increasing the cognitive demands of the monitoring task.

Should the introduction of new modes be deemed necessary, the design of those features should take notice of two mode characteristics that appear to be most insidious. The first is mode combinations and the hidden interactions that they sponsor. The second is the distinction between modes that add new task capabilities to the controller versus those that add new strategies for accomplishing old tasks.

Automation designers in general may look to MPC for what appear to be some good practices in automation design. First, there may be some advantage to allowing the user to interact with the automation at the control variable level, allowing actual regulation of those variables and high level planning to be performed by the automation. Second, constraint-based control may be a means of granting that variable-level access without over-constraining the automation and hindering its ability to optimize the process. Third, the use of few, independent, mode classes that distinguish control tasks as opposed to control strategies appears to preempt mode confusion problems.

Implications for Automation Research

Our findings are typical of field observations in that we can only draw associative connections between the observed operator behavior and the underlying characteristics of the technology. Some of these associations appear to corroborate many of the observations and empirical findings of automation reported in other domains. However, some of them are different. We have conjectured that the sources of these similarities and differences lie in the structure of the automation technologies under observation. Automation technologies that require operator intervention at the control level force operators to know how and when to intervene with the controller, whereas automation technologies that require operator intervention at the strategy level force operators to know how and when the automation has switched modes. Comparative field and laboratory studies would be useful in establishing whether these functional differences in the automation technologies account for the observed differences in performance.

CONCLUSION

Both FMS and MPC are so complex that even the design engineers profess a partial lack of understanding of the automation's behavior. Yet pilots and operators are stuck with the automation at critical moments when "the designers are home tucked safely in bed." Our observations suggest that there may be characteristics of automation design that are conducive to effective human-automation interaction. Verifying those characteristics presents itself as a valuable contribution to be made by cognitive engineers to the design of advanced automation.

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