Increasing Customer Value of Industrial Control Performance Monitoring—Honeywell's Experience

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Abstract

Within the process industries there is a significant installed base of regulatory and multivariable model predictive controllers. These controllers in many cases operate very poorly. This paper documents the current state of industrial controller performance, identifies the sources and ramifications of this poor performance, and discusses required attributes of a Process Control Monitoring System (PCMS). Finally, research directions are suggested.

Keywords

Performance assessment, Prioritization, Regulatory control, Control valve, PID control, Industrial survey, Stiction

Introduction

In an oil refinery, chemical plant, paper mill, or other continuous process industry facility there are typically between five hundred and five thousand regulatory controllers. As shown in Table 1, there are over eight thousand of these facilities in the United States alone (US Department of Energy, 1997).

There are somewhere between two thousand and three thousand multivariable model predictive control (MPC) applications installed world-wide, based on data from Qin and Badgwell (1997), with the market growing at a compound annual rate of approximately 18% (ARC Advisory Group, 1998, 2000b). Although use of MPC is now widespread, proportional-integral-derivative (PID) is by far the dominant feedback control algorithm. There are approximately three million regulatory controllers in the continuous process industries (based on data from Industrial Information Resources (1999); ARC Advisory Group (2000a) and an estimated ten thousand process control engineers (the latter estimate is based on data from Desborough et al. (2000) indicating the typical control engineer is responsible for between two and four hundred regulatory controllers).

When MPC is implemented, its manipulated variables are typically the setpoints of existing PID controllers. At the regulatory control level there has been little impact from other control algorithms. The importance of PID controllers certainly has not decreased with the wide adoption of MPC. Based on a survey of over eleven thousand controllers in the refining, chemicals and pulp and paper industries (Desborough et al., 2000), 97% of regulatory controllers utilize a PID feedback control algorithm.

Several trends are appearing that suggest the gap between desired and actual controller performance is widening:

- Competitive, environmental, and societal pressures are expected to require more changes in manufacturing facilities in the next 20–30 years than has occurred in the last 70 years (Katzer et al., 2000; American Petroleum Institute, 2000).
- When manufacturing sites are large enough to warrant a dedicated control engineer, their time is increasingly being diluted across implementing and maintaining advanced control technologies, display building, process historian support, and traditional PID controller maintenance.
- Process control application engineers often lack process control troubleshooting and time series / spectral analysis training and experience.
- Studies have shown that only about one third of industrial controllers provide an acceptable level of performance (Ender, 1993; Bialkowski, 1993). Furthermore, this performance has not improved in the past seven years (Miller, 2000), even though many academic performance measures have been developed in that time (Harris et al., 1999).

Facility Type	Total
Oil Refineries	246
Pulp and Paper Mills	584
Chemical Plants	2994
Power Generating Stations	3043
Primary Metal Industries	1453
Total	**8320**

Table 1: Continuous process manufacturing facilities in the United States.

Outline of the Paper

Practical control performance monitoring is a complex subject. In an attempt to explain the current state and articulate future research directions, a control metaphor has been adopted (Figure 1):

Minimize the deviation between measurements (current control performance) and setpoints (business ob-

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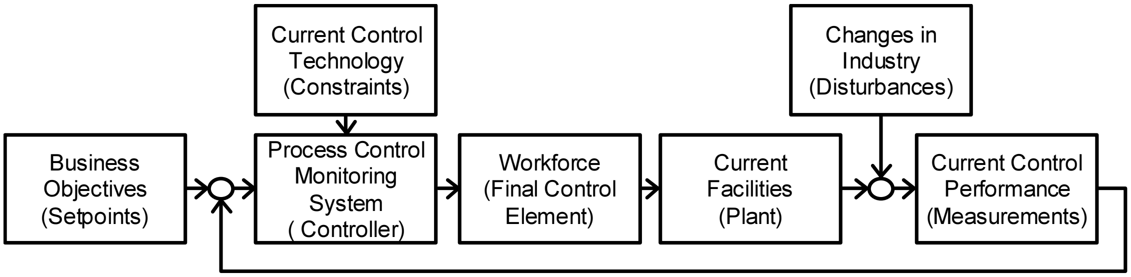

Figure 1: Control metaphor describing structure of the paper.

jectives) by implementing a controller (Process Control Monitoring System or PCMS) which is subject to constraints (current control technology). The PCMS changes the final control element (work activities of the control engineer) which in turn influences the plant (current facilities) and adapts to disturbances (changes in industry).

The outline of the paper is as follows:

- **Section 3: Current Control Performance (Measurements)**—the current control performance in industry is discussed based on a large worldwide sample of controllers.
- **Section 4: Business Objectives (Setpoints)**—the current business drivers within the continuous process industries are discussed.
- **Section 5: Current Control Technology (Constraints)**—the limitations of installed control systems and process models / testing are discussed.
- **Section 6: Workforce (Final Control Element)**—roles, responsibilities, and activities of industrial control engineers and other stakeholders are reviewed.
- **Section 7: Current Facilities (Plant)**—measurement types, facility uniqueness, and other issues are discussed.
- **Section 8: Changes in Industry (Disturbances)**—business, technology, people, and facilities factors expected to influence the direction of industrial control performance monitoring over the next decade are given.
- **Section 9: Process Control Monitoring System (Controller)**—the capabilities and characteristics of a Process Control Monitoring System (PCMS) are discussed.

Section 10 provides two industrial examples. In Section 11, research directions are suggested.

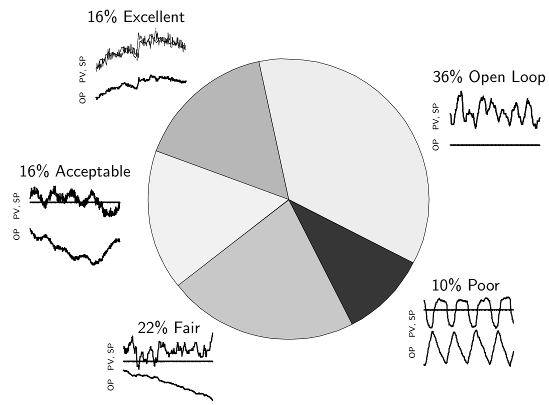

Figure 2: Global multi-industry performance demographics.

Current Control Performance (Measurements)

Performance demographics of twenty six thousand PID controllers collected over the last two years across a large cross sample of continuous process industries are shown in Figure 2 (Miller, 2000). An algorithm combining a minimum variance benchmark and an oscillation metric tuned for each measurement type (flow, pressure, level, etc.) was used to classify performance of each controller into one of five performance categories. These classifications were refined through extensive validation and industry feedback to reflect controller performance relative to practical expectations for each measurement type. Unacceptably sluggish or oscillatory controllers are generally classified as either "fair" or "poor" while controllers with minor performance deviations are classified as "acceptable" or "excellent". A level controller's performance is difficult to classify without knowing its objective—regulation, servo control, or most commonly surge attenuation. The above analysis assumes that level controllers have a surge attenuation objective, meaning they receive a "poor" classification if they transfer excessive variability to the manipulated variable (e.g. the flow out of the surge vessel). Controllers receive an "open

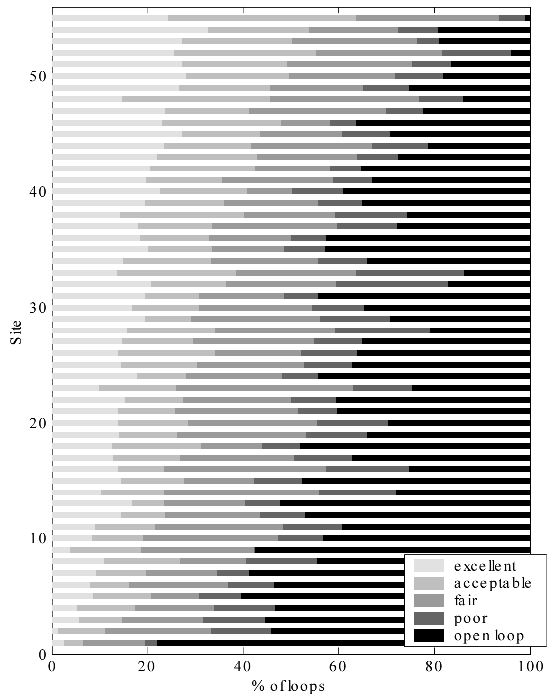

Figure 3: Site wide performance distribution.

loop" classification if they are in manual mode or the output is saturated (stuck at a limit) for more than 30% of the dataset (five thousand samples at the dominant time constant).

Only one third of the controllers were classified as acceptable performers and two thirds had significant improvement opportunity. Some controllers classified as open loop are truly in their normal mode, for example, a bypass flow controller used only during startup. However, many of the controllers under manual control are obsolete or cannot be closed due to an operability problem.

Business Objectives (Setpoint)

The major US process industries spend about thirty billion dollars annually on energy (see the Appendix) and over one hundred billion dollars on facility maintenance (Industrial Information Resources, 1999). Even a 1% improvement in either energy efficiency or improved controller maintenance direction represents hundreds of millions of dollars in savings to the process industries.

Businesses are measured by macroscopic metrics such as share price and customer orders. These are in turn affected by key performance indicators (KPI's) such as product quality, product consistency, throughput, energy efficiency, and lost time injuries. The majority of all business decisions in a continuous process facility are implemented by changing the signal to a control valve, almost always through the action of a regulatory controller. Thus regulatory control has a profound impact on key performance indicators and ultimately business value. Understanding the operational context of a particular controller is key to the success of a control performance monitoring work practice. Relating controller performance to KPI's requires a system-level view of regulatory control:

1. impact—does a particular subset of controllers impact bleach plant brightness more than others? Often these impacts are qualitative, descriptive, or immeasurable.
2. mode—is the facility in high production, startup, shutdown, or energy efficiency mode? Mode can often have profound impact on controller performance and vice-versa, as different procedures employ different controllers. As an example, MPC is not usually used in startup and shutdown mode because it often has a low turndown ratio.
3. grade—is the facility running heavy versus light crude or making newsprint instead of catalog paper? Differences in the active constraint set, objective function and process model from one grade to the next can significantly affect controller performance.
4. objective—does the tight tuning of level controllers in surge vessels accentuate rather than attenuate destabilizing unit-to-unit interactions? Controller objectives include servo control, regulatory control, constraint control, and surge attenuation.

The above-mentioned extrinsic effects of the controller are as important for a PCMS to address as the intrinsic controller performance itself. By tying individual controller performance to the effect that performance causes, the process control engineer can make an informed decision as to the priority of resolution. There will always be more work to be done than time available to do it.

Controller performance is often defined narrowly as the ability of the controller to transfer the proper amount of variability from the controlled variable (CV) to the manipulated variable (MV). While variability transfer is a very important contributor to a controller's performance, there are others as well:

- Alarms—almost every industrial PID controller or multivariable controller is configured with alarms to alert the operator when an unacceptable process deviation has occurred. Commonly configured alarms include process value high, low, rate of change, manipulated variable high, low, or frozen, and off normal control mode. These alarms are presented in a special alarm summary page on the control system's user interface, on panel-mounted enunciator boards, or as audible sirens or bells. Due to the ease with which alarms can be configured, there has been a tendency to build too many alarms, or alarms with inappropriate limits. When a true incident occurs, an “alarm flood” is precipitated and the operator becomes unable to determine root cause and choose the correct path to resolution. Incidents traced to abnormal situations and the resulting alarm flood have resulted in over forty billion dollars in losses in the petrochemical industry alone (Campbell Brown, 1999). Measuring the number of “bad actors” or chattering alarms helps control engineers proactively manage and prioritize controller alarm performance.

- Interventions—process operators are responsible for the daily operation of the plant. Their principal means of effecting process change is to intervene in the operation of the MPC and regulatory controllers. Interventions include changing a controller’s setpoint, changing its mode from automatic to manual, directly changing the output to the valve, or changing an MPC’s constraint limits or cost function inputs. Operators spend their entire shift reacting to stimuli and making hundreds of interventions to the control system. These interventions can and do result in inappropriate variability transfer, often resulting in an easier to operate plant but one further from its economic optimum operating point. For instance, almost thirty percent of sampled PID controllers are in open loop, meaning the operator has intervened to remove any automatic control action. Some operating companies track and report operator interventions as an element of controller performance (Takada, 1998). The situation is equally acute in MPC, with as many as 30% of controllers inoperative and a similar number rendered effectively inoperative by the operator through clamped-down move limits and constraints.
- Configuration Changes—controller performance can be affected when a change is made in the feedback algorithm tuning, the transmitter, or the final control element. In one customer example (Desborough and Nordh, 1998), an environmental emissions team with a portable gas probe went from valve to valve, measuring for fugitive hydrocarbon emissions. Finding a leaky valve, they would tighten the actuator packing. Weeks later, the operator would complain to the control engineer about sluggishness and hysteresis (resulting in oscillations), and the control engineer would instruct the valve technician to loosen the actuator packing.

Most alarm, intervention, and configuration change events are recorded in the control system’s event log, and are available for analysis.

Consider a typical scenario: an operator on the night shift makes a change in a controller’s gain to improve the variability transfer performance while operating in maximum throughput mode (it’s cooler at night so there

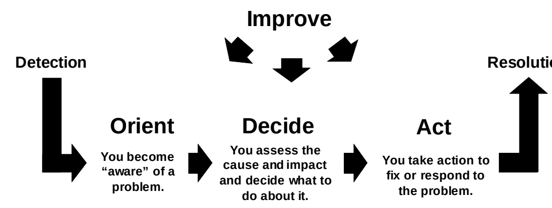

Figure 4: Decision support workflow.

are fewer cooling water temperature constraints). On the following day shift, the new operator, who has not been apprised of this tuning change and is now trying to operate the plant in energy conservation mode, acknowledges multiple alarms coming from the controller indicating high rate of change on the measured variable. He ultimately places the controller in manual so that its variability transfer problem is attenuated but in doing so sacrifices some energy efficiency. Through the remainder of his shift, he is forced to make multiple manual changes to the controller, which distracts him from his other duties. When the control engineer performs the troubleshooting activities surrounding why the day shift had difficulty running in energy conservation mode, five elements are involved: the energy conservation mode operating context, the variability transfer performance, the alarm performance, the operator intervention performance, and the configuration change management.

Without an understanding of how the various controller performance measures (variability transfer, alarms, and operator interventions) relate to the business KPI’s, the control engineer will not be able to focus their finite work effort on the most important problems, and instead will be forced to take subjective work direction from others who are more closely aligned with business performance.

Fighter pilots are taught to observe, orient, decide, and act—the so-called OODA Loop (Boyd, 1987). Similarly, the Six Sigma quality process teaches the DMAIC process improvement methodology: Define, Measure, Analyze, Improve and Control (Pyzdek, 2000). In oil refineries, paper mills, and other process industry facilities a similar workflow is followed by various stakeholders in controller performance (Figure 4). Managers, operators, process control engineers, and to a lesser extent maintenance technicians orient, decide, act, and improve controller performance:

- *Orient*—system-wide identification of specific problems, preferably automated “has the performance changed?”
- *Decide*—determine problem’s causes / effects through analysis of facts / further investigation and decide on resolution “what should I do about the performance change?”

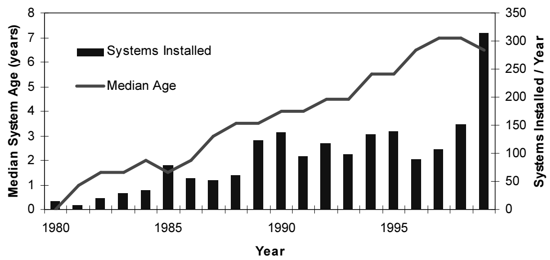

Figure 5: DCS installed systems and median age.

- *Act*—take action on problem through mitigation, investigation, or repair
- *Improve*—assess improvement in orient, decide and act processes

Although it is primarily the control engineer's job to orient, decide, and act on controller performance, often regulatory controls are not looked at unless there is a problem identified by the operator, or if it is a part of an MPC application. Control engineers are very busy with many responsibilities other than regulatory control.

Control Technology (Constraints)

In order to appreciate the issues surrounding practical industrial control performance monitoring, it is important to understand the system constraints present:

- Real time, high frequency time series data collection and automatic analysis is difficult and time consuming
- Legacy control systems weren't designed for performance monitoring hence many are not up to the task from a computing horsepower perspective
- Getting data from the legacy control system to a more powerful computing platform is limited by the available bandwidth
- Dynamic process models are unavailable for the vast majority of controllers, and would be prohibitively expensive to obtain
- The PID control algorithm dominates the continuous process industries

One of the biggest issues with practical controller performance assessment is data access and computing power. Based on a sampling of all US oil refinery and power plant distributed control systems, the median distributed control system (DCS) age is seven years and increasing (Figure 5) (Industrial Information Resources, 1999). Many plants have control systems which are fifteen years old.

The vast majority of distributed control systems operating in the world today were simply never designed to easily provide high frequency time series data (one sample per second) or perform complex calculations. Typically less than one thousand measurement parameters can be transferred per second to Windows-based computing platforms.

Dynamic process models are extremely expensive to obtain, either empirically or from first principles. Based on hundreds of Honeywell control projects, engineering costs typically range from \$250–\$1000 per single-input, single-output model. These costs include experimental design, plant testing, dynamic model identification, and model validation, but do not include software, hardware, or training. They also do not include the cost of process disruption as the plant is perturbed away from its economic operation conditions. About the only place the cost of dynamic modeling is ever warranted is during MPC implementation. Due to the significant costs involved, models exist for far less than one percent of all processes controlled by regulatory controllers. Even where these models have been created, they are typically very poorly documented or are out of date (models developed for MPC are the exception, as this is usually done as a well-documented project).

In a survey conducted by Honeywell (Desborough et al., 2000) of 11,600 regulatory controllers across eighteen facilities, the PID control algorithm was used almost exclusively. The site median for PID feedback control algorithm use was over 97% percent (Table 2).

There are at least three reasons for the predominance of the PID algorithm:

1. The PID algorithm works very well in the vast majority of applications. For the rare case of complex dynamics or significant time delays, other algorithms are occasionally used but it is more common to instead implement cascade control to facilitate dynamic decoupling.
2. The PID algorithm is easy to understand. A vast body of literature exists on PID implementation and tuning, and a number of software packages are available which facilitate PID tuning.
3. The PID algorithm is pre-programmed in every control system. Implementing a non-PID feedback control algorithm involves programming custom logic and could take as much as one hundred times the effort of implementing a PID algorithm, not counting the intangible lifecycle costs including documentation, support, and troubleshooting.

Commercially available multivariable model predictive controllers are implemented almost exclusively as constraint-pushing optimizers (see Sorensen and Cutler, 1998; Anderson et al., 1998; Hardin et al., 1995, for a representative sample). They tend to act more like dynamic optimizers than multivariable regulatory

	1st decile	average	median	9th decile
Feedback Control—PID	94.7%	97.3%	97.7%	99.7%
Feedback Control—non-PID	0.0%	1.7%	0.6%	4.8%
non- Feedback Control	0.0%	1.0%	0.6%	3.1%

Table 2: Use of PID in continuous manufacturing facilities world-wide.

People	Control Engineers spend a great deal of their time troubleshooting problems
	Control Engineers don't spend much time on regulatory control performance
	Instrument technicians don't use computers for passive data analysis
Process	Many problems with controller performance are due to external process problems
	MPC problems are usually caused by operability instead of model mismatch / tuning
	Problems are resolved via tuning only a small proportion of the time
	Operators are the control engineer's most important source of information
	Different groups have conflicting objectives which impact control performance, e.g. tighter valve packing reduces hydrocarbon emissions but increases stiction.
Tools	Information needed for diagnosis: • High frequency trend data • Process insight and other non-quantitative data
	Past internal attempts to develop a PCMS have failed

Table 3: Voice of the customer summary.

controllers and are rarely square. This has very important implications for control performance monitoring, as metrics commonly associated with controller performance such as minimum variance have virtually no relevance for a controller whose objective is not regulation, but constrained optimization. There are a surprisingly high number of these controllers operating so tightly constrained that the optimizer is ineffective and the system is essentially open-loop. In the experience of many users (Desborough and Nordh, 1998), performance of these controllers has more to do with the way the operator sets the various MV and CV constraints than the degree of MV / CV variability and variability transfer. This suggests a need for improved user interfaces, training, and diagnostics for operators so they won't constrain the controller so tightly.

Workforce (Final Control Element)

In April 1998, Honeywell visited eight customer sites around the world asking "What are the past, current, and future needs of those persons responsible for maintaining controllers in continuous process industry facilities such as pulp mills, oil refineries, and ethylene plants?" Over twenty managers, control engineers, and instrument technicians were interviewed. The "Voice of the Customer" (VOC) methodology (Burchill and Hepner Brodie, 1997) was followed. The VOC trip resulted in over 900 "voices" from customers. These were categorized and organized into a spreadsheet from which product requirements were identified (Desborough and Nordh, 1998). These are summarized in Table 3.

The most important and often heard requirements were to a) make the technology simple and easy to use, b) allow the user to find information quickly and easily, and c) be simple to setup and maintain.

Further, it was identified that the user interface should:

- incorporate time series trends to assist in the diagnosis of problems
- present a prioritized list of controllers that are not meeting performance criteria
- present information in a "push" fashion, for example a problem could be highlighted in an email to the control engineer, versus the engineering having to sort through additional reports.

In the fall of 1998, Honeywell sent out a 200 question survey and received approximately 35 responses from control engineers. In summary the following PCMS requirements were identified:

- Easy configuration
- PC platform
- Single page summaries
- Time series trends

- Client-server architecture
- Cost-effective
- Standard data formats
- PID instead of MPC performance monitoring initially
- On-demand analysis

Some additional results from the VOC trip and customer survey will now be discussed. Control engineers, operators, instrument technicians, and managers are usually co-located in the plant and have a good relationship. They have shared objectives of ensuring the safe and economic operation of the facility. Quite often these objectives are explicitly set through KPI's. As well, KPI's are often used directly as inputs to individual compensation.

A controller is a capital asset, and as with any capital asset it has a well-documented lifecycle within an organization starting with its purchase and ending with its disposal. The control engineer is involved with virtually every aspect of the controller's lifecycle. Delivery of the controller to a usable state is facilitated through HAZOP and engineering design, plant testing, model identification, commissioning, and operator training activities carried out by the control engineer. The current undergraduate control curriculum addresses some but not all of these activities—notable exceptions are troubleshooting, spectral analysis, statistics, and experimental design. Operators are the primary users of controllers. During a controller's useful life, the process control engineer plays a supporting role through the monitoring, diagnosis, and resolution of performance problems. Controllers are commissioned very infrequently, usually only during major plant expansions or during new plant construction. The control engineer thus spends the majority of their time monitoring and maintaining controllers and other applications resident on the DCS.

Control engineers have formal and on-the-job education in process control. Typically they divide their time between regulatory control troubleshooting and advanced control. They also maintain the alarm system used by operators. Their typical responsibilities are listed in Table 4 (Desborough et al., 2000). Informally, they can act as focal points for instrumentation, IT, operations, and process engineering. Their daily tasks are widely varied, generally consisting of meetings, troubleshooting, and new development. They use DCS engineering tools, multivariable control design tools, and standard office software such as Microsoft Word and Excel. They interact primarily with operators. Control engineers have survived decades of downsizing and outsourcing. They want to be rewarded by interesting work and are often frustrated by mundane operator-initiated troubleshooting tasks. MPC implementation and support are considered high-valued control engineer activities. Tuning skills required to maintain regulatory control are not perceived as unique or tremendously valuable. Control engineers are goal driven and usually have a very good understanding of the business and process objectives of the facility. Control engineers are the implementers and in many cases the maintainers of the controllers, but they are not the end users of the controllers that they implement—the operators are. It is important to note that many plants don't have a dedicated control engineer.

Operators are the users of the controllers. They are responsible for the day-to-day safe and economic operation of the facility. Operators control the plant, usually by changing modes or setpoints of regulatory and MPC controllers or giving instructions to outside operators, and they act as a focal point for anything which might affect the plant. They have a practical understanding of process operation, sometimes supplemented by formal education such as a two year technology certificate from a trade college. Operators interact with other operators, maintenance technicians, process engineers, and control engineers, typically via face-to-face discussions, but also via log books or other reporting mechanisms.

Instrument technicians are usually very responsive to the needs of operators and control engineers and spend most of their time maintaining the electronic and mechanical elements of the controller. Often they do not have access to PCs where they are doing their work (in the field). Their focus tends to be on the resolution rather than the identification of instrument problems. They are very task driven and only the best technicians have an understanding of the business and process objectives impacted by their work.

Managers are concerned with the economic operation of the facility. They have a wide range of experience, but are typically promoted from operations, maintenance, or engineering. They are responsible for making sure the people and groups within the facility work in a manner consistent with business objectives. They read reports and attend meetings. They use a variety of communication and office tools. They interact with control engineers, operators, and maintenance technicians.

Current Facilities (Plant)

Unlike a head position controller on a computer hard disk, where the same control algorithm and tuning parameters can be reused in thousands of identical units, every process in the continuous process industries is in some way unique and as a result every controller implementation is a custom activity. Nominally identical paper machines or ethylene furnaces will have subtly different dynamics, operating objectives, feedstocks, or product grades, requiring each controller to be individually commissioned and tuned to suit the particular business context. As a result there are few economies of scale.

	1st decile	average	median	9th decile
PID feedback control	152	332	289	576
non-PID feedback control	0	3.9	5.3	22.0
non-feedback control	0	2.5	2.0	7.7
Calculations / other	31	70	59	184
APC	1.5	6.3	5.0	13.5

Table 4: Control engineer responsibilities.

	1st decile	average	median	9th decile
Composition	0%	2%	3%	6%
Flow	22%	39%	37%	46%
Level	12%	20%	19%	30%
Pressure	16%	20%	20%	26%
Temperature	14%	19%	17%	36%

Table 5: Regulatory control measurement types.

Higher performance algorithms are rejected in lieu of the PID algorithm, which for reasons outlined in Section 5 is easier to implement and support.

Another reason the PID algorithm is so commonplace is that the vast majority of process measurements have fast dynamics with minimal process delay. One exception is composition control, which is often based on measurements from a slow analyzer with long delay such as a gas chromatograph. Table 5 shows a distribution of regulatory control measurement types from a sample of over ten thousand controllers at eighteen sites in multiple process industries (Desborough et al., 2000).

In the authors' experience, non-minimum phase processes are seldom encountered, usually on less than one in a hundred loops (typically boiler water level control or cold-hydrocarbon fed exothermic reactors). Even in a boiler where the boiler water level is subject to shrink-swell non-minimum phase behavior, the level controller is but one of the controllers required to operate the boiler effectively, and the other controllers do not exhibit non-minimum phase behavior.

Changes in Industry (Disturbances)

There are several profound changes that are expected to influence control performance expectations and challenge industry's ability to meet those expectations. The trend of tighter environmental regulations will continue, as evidence of the effect of CO2 emissions on climate grows (Meszler, 1999), creating new constraints layered on new economic objectives. As stated by the American Petroleum Institute (1999), "The petroleum industry of the future will be environmentally sound, energy-efficient, safe and simpler to operate. It will be completely automated, operate with minimal inventory, and use processes that are fundamentally understood." There will be higher expectations on control systems to reduce process variability that influence emissions and waste.

Fewer new plants are being built to meet increasing demand. For example, no new refineries were built in United States in the 1990's while capacity increased by 120,000 b/d in 1999 alone (Chang, 1999). The number of refineries in United States has actually decreased since the 1980's (American Petroleum Institute, 2000). Even the time between shutdowns is being challenged by developments in heat transfer fouling mitigation (Panchal and Ehr-Ping, 1998).

Competitive pressures, mergers and acquisitions have had the effect of increasing the responsibilities of each control engineer. The total number of engineers employed in the United States has been in decline since 1987 (`http://stats.bls.gov/oco/ocos027.htm`). Several sites that the authors communicate with are reporting skill shortages to meet the demand of maintaining MPC and regulatory control applications (Desborough and Nordh, 1998). To have any impact on industry, controller performance monitoring must be automated and intuitive to the average Bachelor's level engineer.

Instrumentation technology advancements will have a positive impact on variability and reliability. As instruments and valve positioners fail they are generally replaced with digital or smart devices that improve precision of control and provide self-diagnostic information.

One other important trend in the area of data access is the move to OPC (OLE for Process Control), an open standard for data access. OPC will make data access ubiquitous. All major control vendors have developed OPC support for their legacy systems and industrial users are aggressively moving to OPC (Studebaker, 1999).

Process Control Monitoring System (Controller)

The high-level goal of a Process Control Monitoring System (PCMS) is to provide plant control engineers with enhanced capabilities to identify problems for many controllers while minimizing additional effort or expense. By combining the computer's ability to rapidly gather and analyze large quantities of data with the control engineer's abilities to recognize patterns and understand complex relationships, controller performance can be improved while simultaneously freeing the control engineer to spend more time on high-valued activities.

A PCMS collects data, computes metrics, and presents these metrics in a form suitable for the user to take the appropriate action. Results from the Honeywell VOC trip and survey indicate that users seek the answers to two fundamental questions:

1. Has the controller performance changed?
2. What should I do about the performance change?

A PCMS must facilitate the orient-decide-act-improve workflow for business, operational, engineering, and maintenance stakeholders. It must include a mechanism for computing metrics and a framework for guiding users through appropriate diagnostic actions so they can choose the proper course of action. It should track changes in configuration and operations context.

Metrics

A metric is defined as a standard measure to assess performance. Controller performance metrics fall into three broad domains:

- Business metrics—is the controller meeting its business objectives? Examples include LP objective function for an MPC / optimizer, and product quality variation. These metrics help to indicate if the controller is meeting its business objectives.
- Operational metrics—is the controller being used effectively by the operator? Examples include uptime / service factor, and MV limit constraint shadow costs. These metrics help to indicate if the operator is interacting with the controller in a way that helps to fulfill the business objectives.
- Engineering metrics—is the controller meeting its engineering objectives? Examples include dynamic model accuracy and minimum variance benchmarks. These metrics help to diagnose engineering deficiencies within the controller.

Different users, because of their roles and responsibilities, have different metrics needs (Table 6). A PCMS must be able to meet the needs of each type of user, with a special emphasis on the control engineer.

According to Trimble (2000), there are two types of metrics:

- performance metrics—high-level measures of overall performance, usually focused on the effect of the asset's performance on the wider system or business. Business metrics and operational metrics tend to fall into this category. Performance metrics are primarily used to orient the user to the presence of a problem. It is preferable for these metrics to be computed and presented automatically so as not to burden users with additional tasks.

- diagnostic metrics—measures which indicate why performance is unacceptable, usually focused on the asset's internal workings. Engineering metrics tend to fall into this category. Diagnostic metrics help the user decide which action to take once a problem has been identified. These metrics quite often involve interactive data visualization, invasive testing, or other manual activities.

It was identified in Section 5 (Constraints) that the vast majority of controllers lack any kind of process model. Also, most control systems are poor providers of time series data and event data, making collection difficult and time consuming, and therefore expensive. Metrics that require special data may be extremely expensive to compute (Table 7).

Any metric that requires any kind of model or data which is difficult to obtain must have an informational benefit well in excess of the cost of model creation (invasive plant tests, model identification, documentation, etc) and collection of special data.

There are a number of criteria to consider when defining controller performance metrics. Trimble (2000) asserts that metrics must be SMART (Specific, Measurable, Actionable, Relevant, and Timely). Caplice and Sheffi (1994) similarly propose the following metric criteria: validity, robustness, usefulness, integration, economy, compatibility, level of detail, and behavioral soundness, which are described further in Table 8.

Metric Presentation

Due to the wide scope of responsibility for the control engineer and other stakeholders, it is important to collect and present metrics across a wide breadth of responsibility at the appropriate analysis depth, ranging from overall facility performance metrics to individual valve diagnostic metrics. A single metric with a narrow or shallow scope will not help users answer the basic questions posed at the beginning of this section and summarized in Table 9. Instead, a PCMS must contain an appropriate balance of detailed individual controller diagnostic metrics and overall performance metrics within a presentation environment which allows user to overview, zoom and filter, and finally obtain details on demand.

User	Business Metrics	Operational Metrics	Engineering Metrics
Manager	60%	30%	10%
Operator	10%	80%	10%
Control Engineer	10%	30%	60%

Table 6: Metrics needs by user.

Data Type	Comment
high frequency time series data	shorter than 5 second sampling period
event data	alarms, operator interventions, controller configuration changes
invasive process testing	designed experiments to obtain dynamic models
manually-entered data	configuration or economic data
continuous data collection	an automobile's odometer is only useful if it is collecting data all of the time

Table 7: Special data types.

Criterion	Description
Validity	The metric accurately captures the events and activities being measured and controls for any exogenous factors.
Robustness	The metric is interpreted similarly by all users, is comparable across time, location and organizations, and is repeatable.
Usefulness	The metric is readily understandable by the decision maker and provides a guide for action to be taken.
Integration	The metric includes all relevant aspects of the process and promotes coordination across functions and divisions.
Economy	The benefits of using the metric outweighs the costs of data collection, analysis, and reporting.
Compatibility	The metric is compatible with the existing information, material and cash flow systems in the organization.
Level of Detail	The metric provides a sufficient degree of granularity or aggregation for the user.
Behavioral Soundness	The metric minimizes incentives for counter-productive acts or game-playing and is presented in a useful form.

Table 8: Metrics criteria.

	Has the controller performance changed?	What should I do about the performance change?
Workflow:	Orient	Decide / Act
Information level:	Overview First	Details on Demand
Metric type:	Performance Metrics	Diagnostic Metrics
Data gathering	Automatic	Human-Facilitated
Result presentation:	Automatic Push	Manual Pull
Invasiveness	Non-invasive	Invasive
Breadth:	Wide	Narrow
Depth:	Shallow	Deep
Focus:	Broaden Focus	Narrow Focus

Table 9: Basic process control monitoring questions.

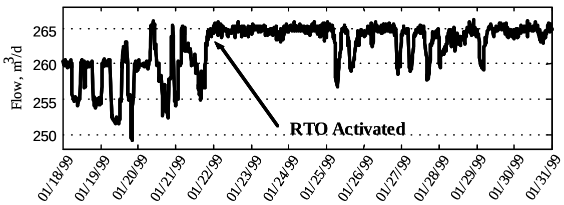

Figure 6: Hydrocracker unit throughput in response to control improvements.

Case Studies

BP Grangemouth Refinery, Scotland

Grangemouth Refinery is an integrated 210,000 BPD refinery complex. The hydrocracking unit of the refinery consists of four reactors: two series-flow reactors which hydrotreat the fresh feed, a first stage hydrocracking reactor which converts part of the feed, and a second stage hydrocracking reactor which receives feed from the fractionator bottoms/mild vacuum column (unconverted oil). The second stage reactor completes the conversion of feed to lighter material by cracking unconverted oil in the recycle feed stream. The hydrocracking reaction is highly exothermic. Both safety and throughput depend on tight temperature control to meet and push constraints.

A first generation MPC and a feed maximizing optimizer that were implemented in 1994 were upgraded to current technology in 1998. As is common in such upgrades, no new step tests or modeling were performed. During 1998 the feed source and product mix objectives shifted and a temperature oscillation manifested itself in the second stage reactor bed outlet temperatures. This cycle propagated throughout the entire recycle controller and ultimately to the main fractionator, mild vacuum column and the second stage reactor. Because of this cycle in reactor temperatures, the reactor weighted average bed temperature MPC was often fully constrained and thus could not achieve its objective. The feed maximizer could not run safely under these conditions, resulting in significant lost opportunity.

A complete step test and controller redesign were undesired due to the cost, workload of on-site staff, and the length of time required for a redesign. A vendor consultant, who is an expert on hydrocracking processes and MPC applications, examined active constraints, operating data, and MPC tuning closely. A restricted bump test was conducted to update a small fraction of the MPC models. A systematic controller assessment of the unit was also conducted that showed four key PID controllers were poorly tuned (Fedenczuk et al., 1998). In addition to PID tuning and updating a few models, several changes were made to temperature constraints and profiles. Figure 6 shows the increased throughput of the unit when the feed maximizer was enabled.

This is a typical MPC maintenance problem—complex and multifaceted, requiring a holistic diagnostic approach. Problems that are more subtle are often more difficult to diagnose. Reducing reliance on a human expert requires quantitative assessment of model adequacy, MPC constraints, MPC tuning, and alignment of MPC objectives with process objectives.

Engen Petroleum Durban Refinery

Engen Petroleum Durban refinery is a medium scale (nominal 100,000 BPD) refinery in South Africa. The only opportunity to service most control valves is during shutdowns, which are planned every two or three years. While it is important to correctly identify poor performing control valves that need maintenance, it is both expensive and time consuming to invasively test all control valves. To this end, a comparative test of a commercial non-invasive controller performance service and invasive valve tests was performed.

Results of non-invasive tests and invasive valve tests of seven problem controllers are listed in Table 10. Valve stick—slip is defined as the resolution in actual stem travel. Dead band is defined as the minimum change in the valve input signal before the stem will move. Non-invasive tests were based on qualitative pattern analysis of the process variable and controller output time series data in normal closed loop operation by a human expert. The Entech control valve dynamic specification (valve stick—slip plus deadband) cites a value of one percent as the threshold for nominal control valves (EnTech, 1998). Using this criterion, all valves in Table 10 fail the test and should be maintained. However, the validated problem resolution suggests that only three of the seven valves actually had a valve-limiting performance problem.

In the non-invasive assessment, only the valve stick-slip and dead band relevant to closed loop performance is significant, which proved to be more reliable in this comparison. Dependence on a human expert is however a strong condition that will be influenced by individual biases and experience.

New Research Directions

Many issues still need to be addressed before a reliable, comprehensive PCMS can be developed that meets the needs of the industrial user. The extent of industrial controller monitoring adoption will be strongly influenced by closing the gaps between the industrial user needs and the current state of the art (subject to the constraints already discussed).

First, general recommendations for performance metrics and diagnostic metrics will be given, covering a diverse set of new research directions. Next, a much smaller subset of the most important research directions will be addressed in greater detail.

Loop	Controller Behavior Problem	Non-invasive Valve Analysis	Invasive Test		Problem Resolution	Resolution Consistent With:	
			stick-slip	dead band		non-invasive test	invasive test
1	Oscillating	severe stiction	1.40%	2.33%	Valve	yes	yes
2	Low σ^2, not oscillating	valve OK	1.80%	1.39%	Tuning	yes	no
3	Oscillating	moderate stiction	0.40%	2.33%	Valve	yes	yes
4	Saw-tooth pattern	moderate stiction	0.50%	0.57%	Valve / Tuning	yes	yes
5	High σ^2, not oscillating	valve OK	1.50%	0.40%	Tuning	yes	no
6	Oscillating	valve OK	1.20%	0.30%	Tuning	yes	no
7	High σ^2, not oscillating	valve OK	0.30%	1.75%	Tuning	yes	no

Table 10: Comparison of invasive and non-invasive valve analysis.

General Research Directions

Performance Metrics. Performance metrics are designed to broaden rather than narrow the user's current focus, and help them orient to the presence of problems on controllers they wouldn't otherwise be examining. They are high-level measures of overall performance, usually focused on the effect of the asset's performance on the wider system or business. In general they require minimal user configuration effort. They are based on available data and their computation can be performed automatically. Their presentation should be automatic and intuitive to the average user. Performance metrics should ultimately help the user shift their current work activities to a more important area. A summary of recommended performance metric research directions is presented in Table 11.

Diagnostic Metrics. Diagnostic metrics are designed to narrow the user's current focus, and help them to decide which action to take to resolve a problem on a specific asset. They are often detailed measures of performance, usually focused on the asset's internal workings or inputs. They may require user configuration effort and quite often have a cost associated with them, either in terms of user effort or process disruption. They often require new data to be gathered, and computations and analysis usually require human intervention. Their presentation requires user interaction. Diagnostic metrics should ultimately help the user select the proper action to resolve a specific asset's problem. A summary of recommended diagnostic metric research directions is presented in Table 12.

Specific Research Directions

Knowledge Capture and Continuous Improvement. There is a need to establish a knowledge infrastructure founded on consistent models and representations of controller performance, much analogous to the financial community's standardized set of accounting metrics and practices:

- Benchmarking standards (facility-wide, MPC, regulatory control, valve)
- Alarm, operator intervention, and variability transfer performance tracking
- Probabilistic categorization of performance faults
- Normalization and scaling (for comparison to other controllers and protection of proprietary data)
- Weibull analysis—equipment failure; what drives controllers to fail and can this be generalized / predicted? (e.g. is there a relationship between positioner life and degree of oscillation?)
- Rigorous actuator nonlinear modeling

Automated Non-invasive Control Valve Stick-Slip Detection. Control valve problems account for about one third of the 32% of controllers classified as "poor" or "fair" in the industrial survey (Miller, 2000). Faults in control valves are often intermittent and are often misdiagnosed with simple minimum variance ratios and spectral analysis. An abundance of literature exists for invasive analysis of control valve performance that requires stroking the valve when either in-service or out-of-service (Fitzgerald, 1988, 1990; Ancrum, 1996a,b; Boyle, 1996; Wallen, 1997; Sharif and Grosvenor, 1998). With invasive tests, the amount of change in signal required to move the valve stem (stick) and the amount it moves when stem friction is overcome (slip) is easily quantified. However, except for the cross-correlation work of Horch (1998), no non-invasive methods have appeared in the literature. It is neither cost-effective nor practical to detect valve faults using invasive approaches across an entire site. A passive method that can reliably and automatically classify valve performance in closed loop is a desperately needed component in the orientation phase.

Scope	Research Direction
Facility-wide	1. Behavior clustering (common oscillations) 2. Automated model-free causal analysis 3. Performance change detection (changes from target, past history, industry norm) 4. Control performance analysis for specific processes: • sheet-forming processes (e.g. paper machine cross-direction / machine direction control) • processes with tight heat / material integration (e.g. ethylene plants) • processes with high degrees of government regulation (e.g. biotech, food and beverage, nuclear power, pharmaceuticals industries) 5. Business impact analysis of controller performance
MPC	1. Constraint and objective function representation 2. Operability (by operating shift, mode, grade, and objective)
Regulatory Control	1. Alarm, operator intervention, configuration, and variability transfer performance representation 2. Performance categorization based on measurement type / control objective (especially level control)
Valves	1. Non-invasive automated actuator stick-slip detection with only PV, SP, OP data

Table 11: Research Directions for performance metrics.

A valve technician usually carries out invasive valve analyses with an objective of comparing the open loop valve performance with the manufacturer's specifications. This is a valve-centric view of performance. The authors have noted several instances where the invasive analysis conflicts with a graphical analysis of the closed-loop time series. Quite often the valve is operating within its specification but still causes a significant stick-slip behavior in the process variable.

Several motivating examples are now given to illustrate a few validated patterns of control valve problems. The first example (Figure 7) shows an obvious valve-induced oscillation that is approximately symmetrical. The PV versus OP plot is characterized by a rectangular pattern tilted to the left. According to Horch (1998), valve-induced oscillations have a zero cross-correlation at zero lag while tuning-induced oscillations produce a minimum or maximum at zero lag. This first example has a cross-correlation of nearly zero at zero lag.

The second example (Figure 8) has an asymmetrical time series confounded by significant setpoint changes. A rectangular pattern tilted to the left with a shifting centroid can be seen in the PV versus OP plot. Here the cross-correlation is about half way between zero and the minimum, which is inconclusive.

In the third example (Figure 9), a large filter constant was applied in the DCS in an attempt to compensate for the valve behavior. The resulting pattern in the PV versus OP plot shows a wedge-shaped object tilted to the left. The cross-correlation is again inconclusive.

In the fourth and final example (Figure 10), an intermittent valve stick-slip can be seen where the slip is of different magnitudes. The patterns in the PV versus OP plot are still rectangular objects tilted to the left. Cross-correlation fails to identify this as a valve problem because the time series is not repeating. In each of these examples the trained human eye can quickly verify the existence of valve stick-slip.

Performance-Impact Prioritization. A controller is implemented with the objective of changing the final control element to ultimately achieve a business objective. Specifically, it causes the final control element to move from its current value to a value it wouldn't have otherwise pursued. By the same token, a PCMS (controller) has the same effect on the workforce (final control element)—causing the workforce to change their current set of work activities from what they otherwise would have done. The work activities of the control engineer should be prioritized based on making changes to the worst-performing controllers which have the greatest impact on business objectives.

Prioritizing controller repair activities based on performance alone could result in an economically unimpor-

Scope	Research Direction
Facility-wide	1. Multivariable time series-based model-free root cause analysis (e.g. subspace methods) 2. Time series feature extraction and pattern matching aligned along specific tuning and actuator failure modes using visual query language (VQL) techniques such as dynamic time warping (DTW) (Kassidas et al., 1998) 3. Causality analysis between infrequently collected data (e.g. lab samples, KPIs) and frequently collected data
MPC	1. Constraint handling ability 2. Identification of individual model(s) contributing to overall MPC instability using for example subspace methods, singular value analysis, or relative gain array (RGA) and its extensions 3. Dynamic model quality analysis (precision and accuracy, linearity, etc) 4. Inferred property bias, updating, and dynamic compensation problem diagnosis
Regulatory Control	1. Constraint handling (SISO MV saturation) 2. Oscillation characterization (waveforms, PV-OP bivariate analysis) 3. Identification of obvious tuning problems • Tight tuning causing oscillation • Loose tuning causing sluggishness • Inappropriate gain / integral / derivative values • Inappropriate PV filtering 4. Loop pairing analysis
Valves	1. Leveraging of new diagnostic information which is becoming available from smart valves 2. Trim wear detection 3. Low flow controllability characterization 4. Air supply problem detection

Table 12: Research Directions for diagnostic metrics.

tant controller being repaired before a better performing but economically important controller. Likewise prioritization based solely on impact will tend to narrow the focus to the small subset of controllers known (or rather perceived) to be economically important, which then receive attention whether their performance is poor or not. For example, a twenty-four inch gas flow service with a butterfly valve on an ethylene plant refrigeration system will have vastly different performance characteristics and business impact than a two-inch liquid flow service with a cage valve on a boiler condensate return line, yet if the repairs are prioritized based on performance measures alone, economic improvements may not be realized. If the objective of a PCMS is to change the priority of the control engineer's activities, then that priority should be based on metrics which consider both performance and impact.

Today, assessing controller impact requires expert knowledge of the process as well as qualitative experience with the controller's impact and interactions with other controllers and key business objectives. Only by understanding the actual role of each controller relative to unit and site objectives can controller impact be set. There is great benefit in simply combining today's available performance metrics with controller impact assessment. More work is needed, however, in the area of automatic detection of causal relationships between business objectives and individual controller performance so that performance-impact prioritization can be performed automatically.

Performance-impact prioritization is an important research area. Examples of possible applications include estimation of benefits or loss due to poor performance, shutdown planning, HAZOP assessments, and equipment reliability assessment.

Multivariate Assessment. Most multivariable control performance assessment research has focused on variability transfer performance (Harris et al., 1996; Huang and Shah, 1996, 1997). Multivariable variability

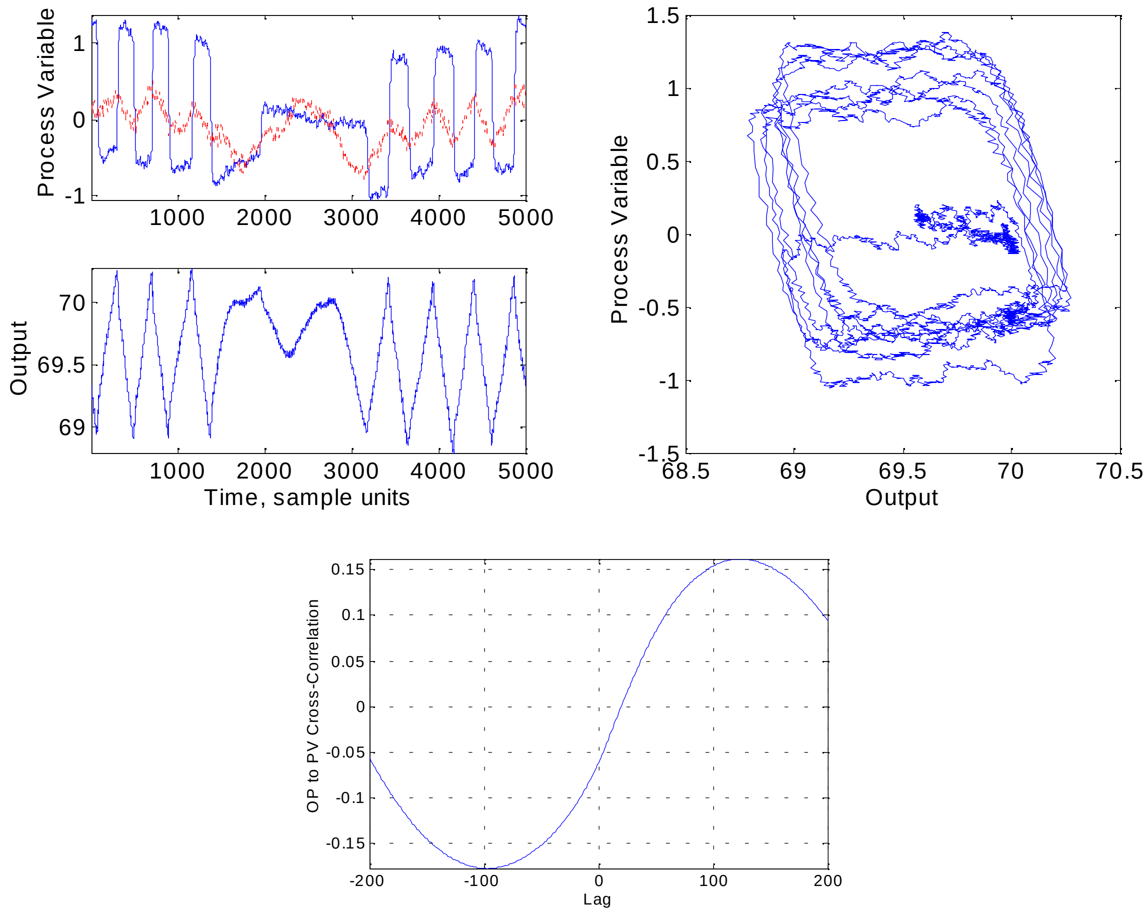

Figure 7: Control valve example 1.

transfer has turned out to be a complex subject and has not found its way to mainstream commercial controller monitoring applications. As stated in Section 5 (Constraints), most model predictive controllers are implemented as constraint-pushing optimizers. Regulation becomes an issue when the controller is fully unconstrained, which is rarely if ever the case. An area that has not been studied in much detail is multivariable control assessment in the context of economic optimization subject to constraints. Operators and engineers need better metrics to identify and diagnose MPC controllers that are failing to meet economic objectives in a safe manner (i.e. by satisfying mechanical and operability constraints). The primary methods at the operator's disposal to improve the economics of the controller are to change 1) the constraint limits and 2) the active set of controlled and manipulated variables. Performance and diagnostic metrics which help the operator decide when to make these changes would be of great value. The primary methods at the control engineer's disposal to improve the economics and dynamic operability of the controller are to change 1) the controller aggressiveness through tuning and 2) one or more of the dynamic models in the control matrix. Performance and diagnostic metrics which help the control engineer decide when to make these changes would be of great value.

Non-regulatory Objectives and Integrating Processes. About two thirds of level controllers have a surge attenuation objective. Failure to recognize the true objective of level controllers is common, often resulting in overly-aggressive tuning that propagates process variability downstream of the surge vessel. Most of the metrics available are either not appropriate or limited to non-integrating processes. In the authors' experience, there is currently a disproportionate fraction of assessment error in level control compared with other measurement types. Even if the operating objective and context of the controller is known, automated assessment of level controllers is challenging. In most facilities, vessel geometry is only documented on P&ID's, PFD's, or paper specification sheets—if at all. The effort of obtaining this information is non-trivial. A

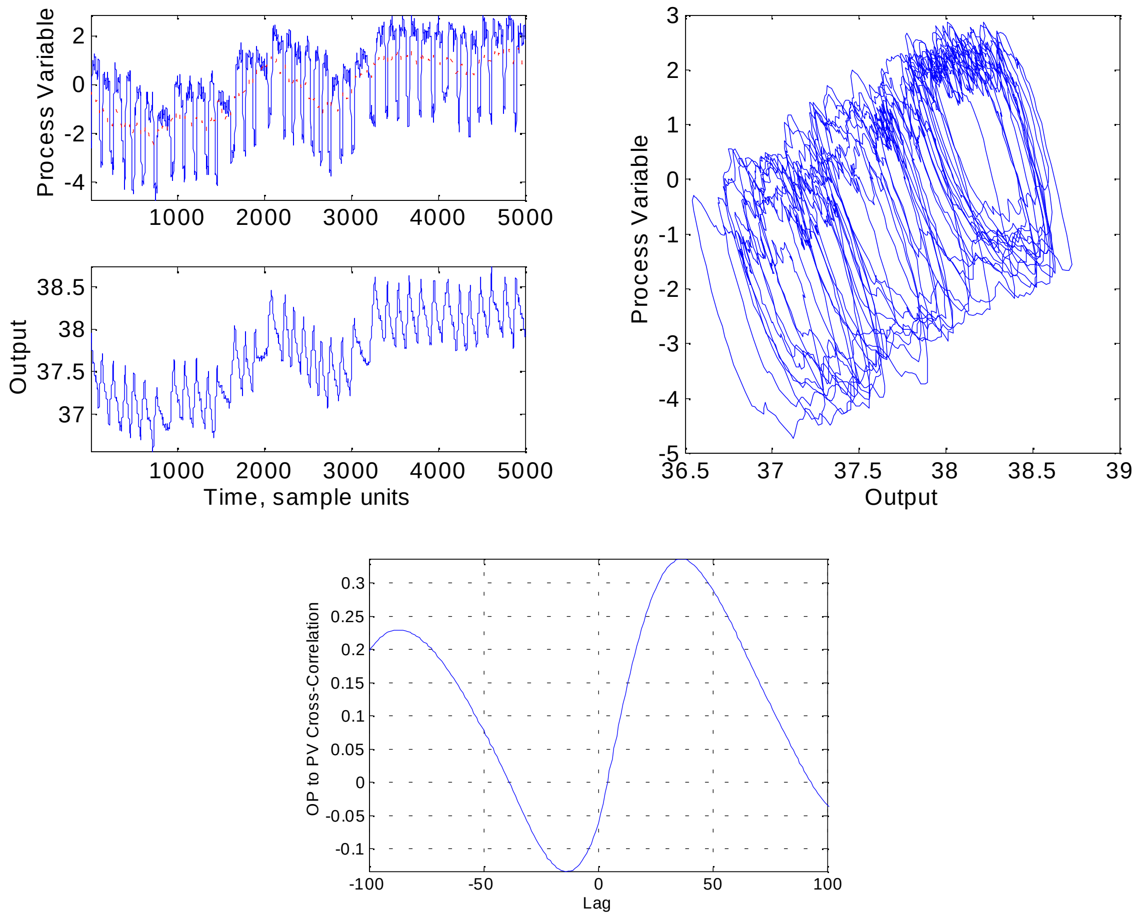

Figure 8: Control valve example 2.

level performance assessment solution that does not require a model or vessel geometry is far more likely to be adopted in industry. Research that specifically assesses level controllers and non-regulatory objectives is therefore of practical value.

Valve faults in level controllers are also very difficult to diagnose because the process is generally integrating. The same time series and PV versus OP patterns that clearly show valve problems for flow and pressure controllers are unclear in level processes (Figures 11 and 12).

Summary and Conclusions

Studies have shown that only about one third of industrial controllers provide an acceptable level of performance (Ender, 1993; Bialkowski, 1993). Furthermore, this performance has not improved in the past seven years (Miller, 2000), even though many academic performance measures have been developed in that time (Harris et al., 1999).

Over the past three years the authors have gathered input from hundreds of industrial practitioners of controller performance assessment and in many cases have directly observed their work practices and current Process Control Monitoring Systems. The authors have also developed a successful commercial PCMS designed to address the needs identified by industrial practitioners (Loop Scout™).

The current landscape of industrial process control contains some key considerations for developers of Process Control Monitoring Systems:

- Practicing control engineers desire a PCMS which is simple to setup, maintain, and use, and allows information to be found quickly and easily;
- Real time, high frequency time series data collection and automatic analysis is difficult and time consuming;
- Legacy control systems weren't designed for performance monitoring hence many are not up to the task from a computing horsepower perspective;
- Getting data from the legacy control system to a more powerful computing platform is limited by the

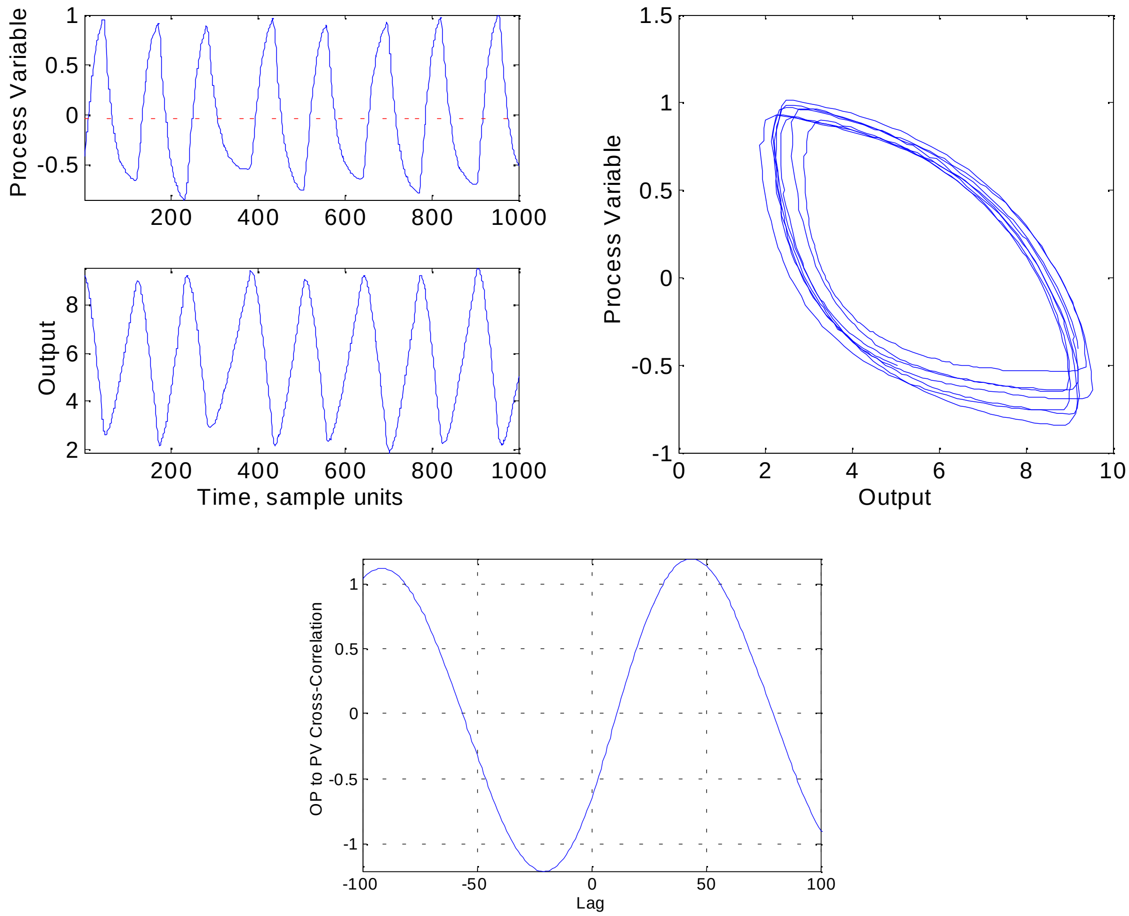

Figure 9: Control valve example 3.

available bandwidth;

- Dynamic process models are unavailable for the vast majority of controllers, and would be prohibitively expensive to obtain;
- Every process in the continuous process industries is in some way unique and as a result higher-performance algorithms are rejected in lieu of the PID algorithm which is easier to implement and support, and as a result is used 97% of the time;
- MPC is usually implemented with the objective of constraint-pushing optimization rather than multivariable regulation;
- MPC performance problems are usually caused by the way the controllers are operated;
- Typical MPC maintenance problems are complex and multifaceted, requiring a holistic diagnostic approach, often relying on process insight and other tacit knowledge.

Although there has been a great deal of academic work in the area of controller performance assessment (see Harris et al., 1999, and the references contained therein), there is still a great deal of work to be done. In particular, the following areas deserve special emphasis and consideration:

- A PCMS must facilitate the orient-decide-act-improve workflow for business, operational, engineering, and maintenance stakeholders, but especially the process control engineer;
- Of the four phases of the orient-decide-act-improve workflow, orientation has received the least amount of research attention but is actually the most important to the industrial process control engineer;
- A passive method that can reliably and automatically classify valve performance in closed loop is a desperately needed component in the orientation phase;
- More work is needed in the area of automatic detection of causal relationships between business objectives and individual controller performance so that performance-impact prioritization can be performed automatically;

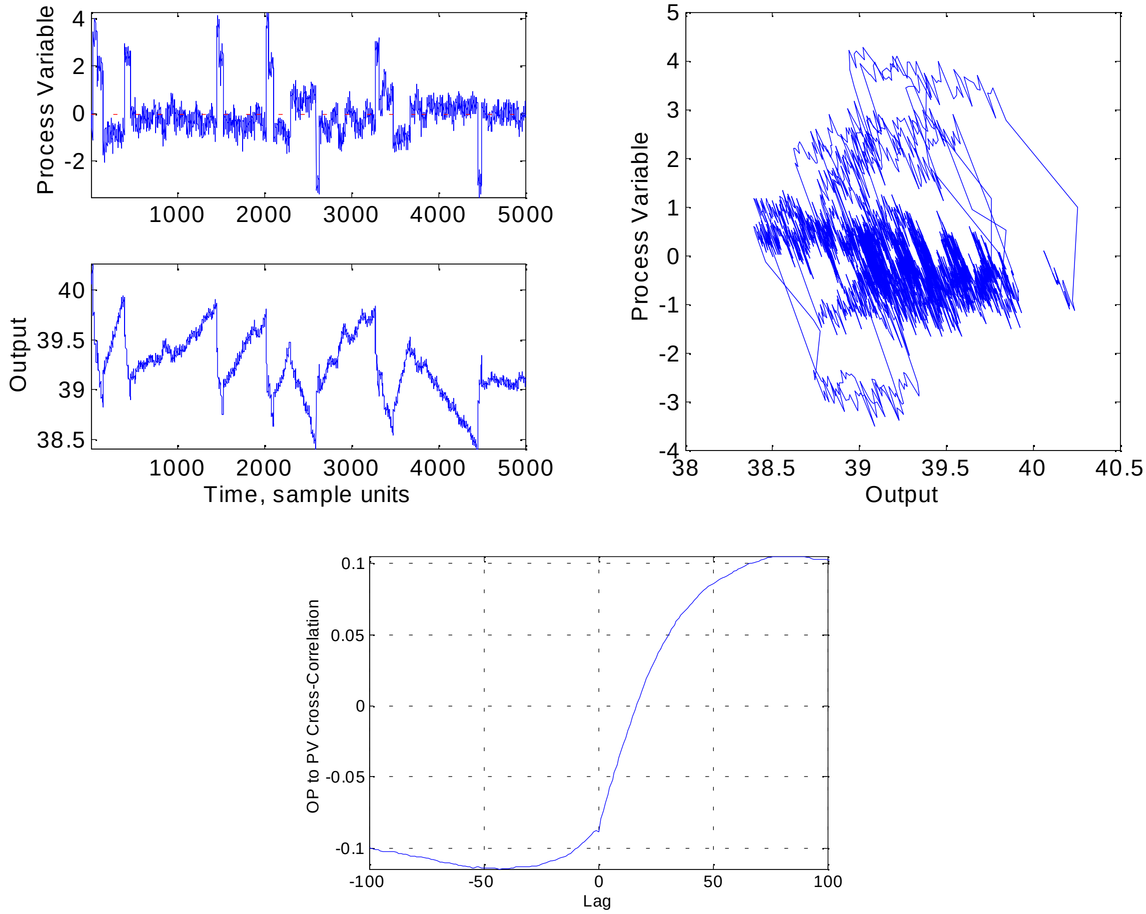

Figure 10: Control valve example 4.

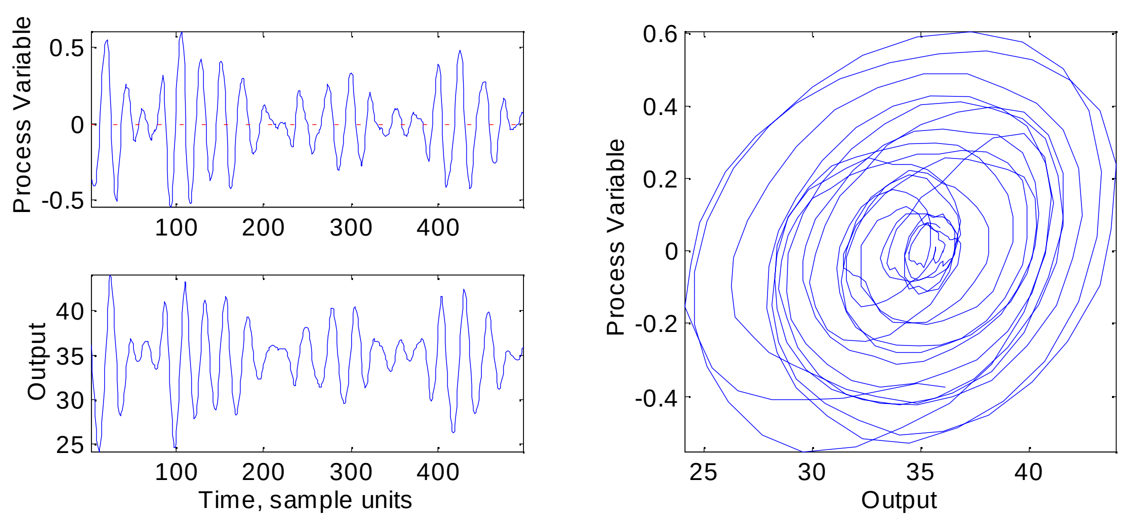

Figure 11: Level control example 1.

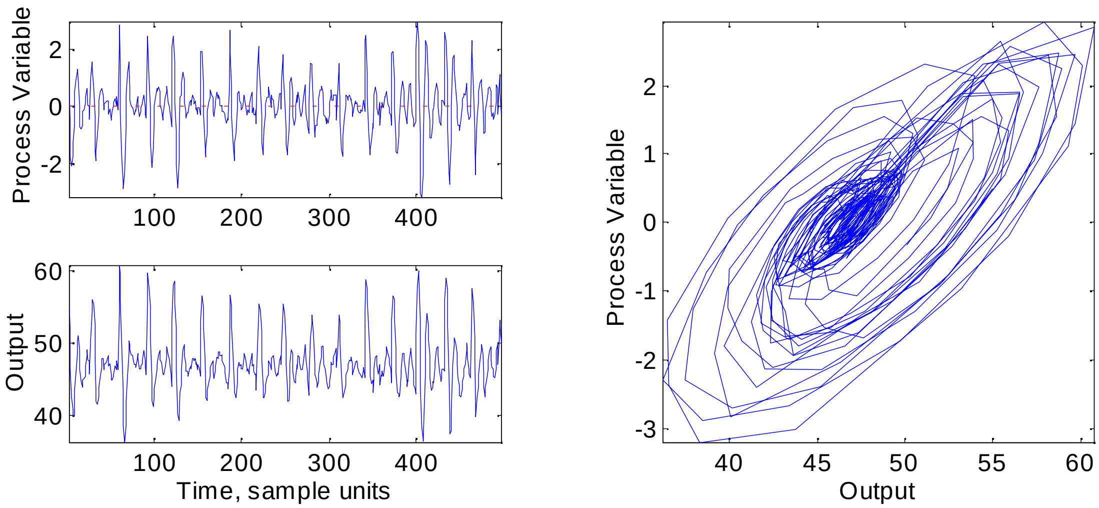

Figure 12: Level control example 4.

- Operators and engineers need better metrics to identify and diagnose MPC controllers that are failing to meet economic objectives in a safe manner (i.e. by satisfying mechanical and operability constraints);
- Research that specifically assesses level controllers and other controllers with non-regulatory objectives is required.

In summary, the industrial process control engineer is in an unenviable position. There will always be more work for them to do than time available to do it; time is their most precious resource. Process Control Monitoring Systems which automatically orient engineers to the likely location of the most economically important controller problems and then facilitate diagnosis and resolution of that controller's problems will play a vital role in increasing their effectiveness and hence their facility's effectiveness.

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Glossary

DCS distributed control system

DTW dynamic time warping (Kassidas et al., 1998)

HAZOP Hazard and Operability Assessment

KPI key performance indicator

LP linear program

MV manipulated variable

MPC model predictive control

OLE object linking and embedding

OPC OLE for Process Control

OP output of controlled variable; signal sent to final control element (e.g. valve)

parameter an instance of a measurement associated with a point, e.g. TC101.PV or a configured attribute of that point, e.g. TC101.GAIN

PCMS Process Control Monitoring System

point database entity containing associated information about a controller, e.g. TC101

PFD process flow diagram

PID proportional, integral, derivative control algorithm

P&ID process and instrumentation diagram

PV process value of controlled variable—typically expressed in engineering units, e.g. kg/hr

RTO real time optimization

SP setpoint of controlled variable—typically expressed in engineering units, e.g. kg/hr

tagname see point

VOC voice of the customer

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Appendix

Energy Savings from Improved Controller Performance

1. 1994 United States energy consumption statistics:

SIC code	Industry	Trillion BTU/yr	Number of Facilities
26	Paper and Allied Products	2665	584
28	Chemicals and Allied Products	5328	2994
2911	Petroleum Refining	6263	246
33	Primary Metal Industries	2462	1453
	Total	16718	5277

   Source: US DOE, 1994 `http://www.eia.doe.gov/emeu/mecs/mecs94/consumption/mecs5.html`
   A conservative estimate is that these industries in 1999 consumed 15×10^9 MBTUs of energy.

2. In 1996, on a dollars-per-million-Btu basis, petroleum was the most expensive fossil fuel ($3.16), natural gas was second ($2.64), and coal was least expensive ($1.29).
   Source: `http://www.eia.doe.gov/neic/infosheets96/Infosheet96.html`
   A conservative estimate is that energy in 1999 cost $2/MBTU.

3. It is very common to quote energy savings of 1–4% through implementation of advanced control and other process control technologies
   Source: `http://www.foxboro.com/industries/gas/`
   A conservative estimate is that improvement of existing controllers through enhanced Process Control Monitoring Systems could reduce energy costs in the process industries by 1%.

4. **Process Industry Energy Savings**
   = Energy Consumption × Energy Cost × Energy Savings from Improved Control
   = 15E9 MBTU/yr × $2/MBTU × 1%
   = **300 Million Dollars per Year**