

**ISSUES IN ON-LINE IMPLEMENTATION  
OF A CLOSED LOOP PERFORMANCE MONITORING SYSTEM****Claudio Scali<sup>(1)</sup>, Fabio Ulivari<sup>(1)</sup>, Antonio Farina<sup>(2)</sup>***(1) Laboratory of Chemical Process Control (CPCLab)**Department of Chemical Engineering (DICCISM)**University of Pisa, Italy**(2) ENI Refining & Marketing**Refinery of Livorno, Italy*

**Abstract:** The paper illustrates main features and implementation issues of a performance monitoring system which, on the basis of data recorded during normal operation, is able to detect the presence of anomalies, to investigate causes and to propose strategies of action. The off-line architecture of the system, successfully applied to industrial plant data, is briefly recalled. Continuous monitoring of a multi-loop refinery section finds hard constraints in heavy computation load and excessive traffic on the communication bus. A mixed structure, featuring on-line detection of anomalies, followed by research of their causes performed on an external computer, is studied. Effects of key factors as: sampling time, number of data, supervision time, loss of initial data, are analyzed and a supervision strategy, compatible with plant DCS characteristics, is proposed. © IFAC'06

**Keywords:** Performance monitoring, Control loops, Automatic recognition, Valves, Friction.

## 1. INTRODUCTION

The importance of closed-loop performance monitoring (CLPM), as a means of improving product quality and hence the overall economy of industrial plants, has recently led to a large interest in academic research and industrial applications (Huang and Shah, 1999).

The possibility of detecting the onset of anomalies and determining causes of performance deterioration in base control loops is certainly of vital importance, as the success of advanced control layers (Multivariable, Optimization) depends on the correct operation of them.

In industrial-scale processes, typically involving thousands of variables and hundreds of control loops, a monitoring system needs to operate automatically, leaving only key decisions to the operators. Furthermore, for a wider acceptability, it is desirable that the monitoring system operate on the basis of data made available from the data-acquisition system, without need of introducing additional perturbations in the plant. It is also highly desirable that process monitoring is able to account for various causes of performance deterioration, such as

incorrect design or tuning of controllers, anomalies and failures of sensors, presence of friction in actuators, external perturbations, and deteriorations in the process itself. Whatever the causes, the monitoring system should be able to detect them and to indicate actions to perform, ranging from retuning of controllers, to substitution of faulty sensors, compensation or maintenance of valves, or operations on upstream equipment.

A number of issues and problems still remain unresolved in the theory (e.g., significance and reliability of proposed performance indexes, their applicability in the case of multivariable control, simple and reliable technique for automatic detection of causes) and this explains efforts and research activity in the academy (Qin, 1998). Issues coming from applications seem less severe (e.g., the recommended degree of automation and interaction with the operator, off-line versus on-line architectures), but the success of a performance monitoring system depends strongly on them. In addition, there is a feedback from the field, in the sense that, depending on the characteristics of plant and control system, the most suitable architecture can

be chosen and customized according to operators' needs.

This paper focuses on implementation issues for on-line monitoring. In the first part the system architecture and the adopted techniques are briefly illustrated; in the second part constraints coming from available computation power and allowed data transfer traffic are faced and necessary changes in the system architecture to design a flexible supervision strategy, compatible with plant DCS, are analyzed.

## 2. FEATURES OF THE CLPM SYSTEM

Referring to Figure 1, available data from the acquisition system are: controlled variable (PV), set point (SP), controller output (OP); in addition also controller parameters and control ranges are known; in general the manipulated variable (MV) is not recorded.

Figure 2 provides a schematic illustration of the structure of the Closed Loop Performance Monitoring system.

The first module detects the onset of anomalies, i.e. is able to separate good performing loops from poor ones (oscillating, slow); tests are based on techniques firstly proposed by Hägglund (1995, 1999) and modified, during previous activity, in order to improve their efficiency (Ulivari et al., 2005). These modifications are briefly illustrated in the sequel.

To detect oscillations (Hägglund, 1995), the integral of absolute error (IAE) is computed for every half-cycle and compared with a limit value  $IAE_{lim}$ :

$$IAE = \int_{t_i}^{t_{i+1}} |e(t)| \cdot dt \quad (1)$$

$$IAE_{lim} = f(a, \tau_I) \quad (2)$$

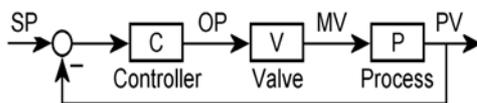


Fig. 1. The reference scheme.

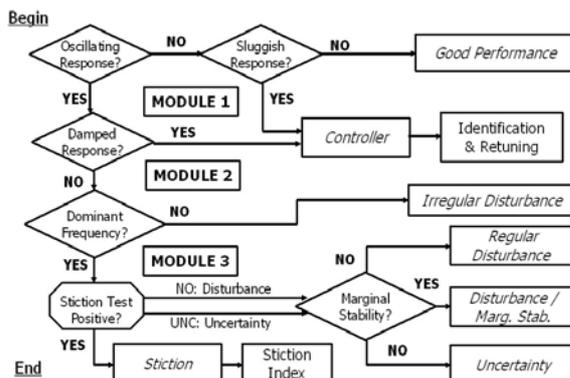


Fig. 2. Architecture of the CLPM system.

Where:  $t_i$  and  $t_{i+1}$  are two consecutive zero crossing of error  $e = SP - PV$ ,  $a$  is a parameter that must be chosen (suggested value: 1%) and  $\tau_I$  is the controller integral time constant. An oscillation is considered significant when the value of IAE exceeds  $IAE_{lim}$ . If the number  $N$  of detected oscillations exceeds a fixed value  $N_{lim}$  (for instance  $N_{lim}=10$ ), during a supervision time  $T_{sup}$ , the oscillation is considered persistent. The suggested value of  $T_{sup}$  (Hägglund, 1995), depends on the loop ultimate period and can be correlated to the controller integral time constant  $\tau_I$  ( $T_{sup} \approx 50 \tau_I$ ). This is certainly reasonable when the main objective of the analysis is to detect tuning problems. In presence of stiction the frequency of oscillations can change largely, according to stiction characteristics while keeping a constant tuning.

This is shown in Figure 3 where simulation results, obtained by adopting the data driven model proposed by Choudury et al. (2005), are reported. Similar results are given by the analytical model proposed by Karnhopp (1985).

Therefore, for stiction detection purposes, it is more convenient to use a mobile supervision window  $T_{sup}$ , constantly updated on the basis of duration of last anomalous half-cycle.

For every anomalous half-cycle, the two zero-crossing times  $T_1$  and  $T_0$  are defined (Figure 4) and the supervision time is updated as:

$$T_{sup} = T_1 + \beta(T_1 - T_0) \quad (3)$$

The parameter  $\beta$  is generally taken equal to 1.1. In the case of half-cycles not complete before  $T_{sup}$ , the analysis is extended to the end of the cycle.

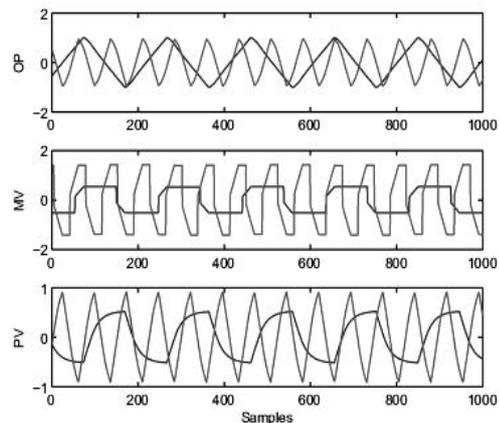


Fig. 3. Different trends of OP, MV and PV with stiction parameters (constant tuning).

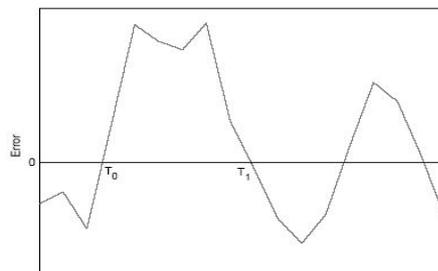


Fig. 4. Zero-crossing time for a half-cycle.

To detect slow responses, an Idle Index is proposed (Hägglund, 1999); this parameter is a function of time periods when the correlation between OP and PV signal increments is positive or negative. In the package, to avoid sensitivity to plant noise, also slow responses are identified on the basis of *IAE*, calculating when the error of a single deviation become too large, that is greater than an assigned limit value  $L_{min}$  (for instance  $L_{min}=10$ ):

$$\frac{IAE}{IAE_{lim}} > L_{min} \quad (4)$$

The second module investigates the frequency behaviour of oscillating loops; if a damping response is detected, then the controller is indicated as cause of poor performance (as well as for the case of slow response). In this case a procedure for identification of process and disturbance dynamics and controller retuning (Rossi et al., 2003) is started; the performance improvement with the new tuning is shown to the operator who takes the final decision of changing controller settings.

The dominant frequency of the oscillation is also evaluated and not regular disturbances are isolated.

Oscillating signals are sent to the third module which allows to detect the presence of stiction in actuators, distinguishing this phenomenon from the presence of disturbances or from marginal stability conditions. The presence of stiction can be hidden by variations of process parameters and by stiction characteristics and a region of uncertainty may remain, where no decision can be taken (Rossi and Scali, 2004).

For this reason, different techniques recently proposed in literature, are applied in sequence, in order to reduce the number of uncertain cases. Among them: the Cross-Correlation (Horch, 1999), the Bicoherence (Choudury et al., 2004), the Relay technique (Rossi and Scali, 2005).

A stiction index is also evaluated in order to quantify its extent and to permit scheduling of valve maintenance from few analysis repeated in time.

A direct comparison of MV(OP) plots is also shown to the operator, for cases when MV is available (for instance in flow control), thus confirming/excluding the presence of stiction.

The efficiency of the CLPM system, firstly analyzed by intensive simulations, has been validated in several applications to industrial data, obtained from refineries and petrochemical plants. In particular, in Rossi et al. (2003), problems of frequent retuning of temperature controllers for a polymerization reactor undergoing surface fouling are reported. In Rossi et al. (2005), monitoring of refinery loops, mainly affected by valve stiction, is successfully carried out.

To conclude, off-line applications to industrial data have confirmed several positive features of the system: (a) complete automation of the procedure (after calibration of few parameters on the plant), (b) no perturbations need to be introduced in the plant, (c) open architecture (with easy adoption of new or updated techniques), and (d) flexibility to incorporate operator's knowledge.

About point (c), techniques for automatic recognition of the presence of stiction when MV is available, as proposed by Yamashita (2006), are currently under experimentation.

### 3. ON-LINE IMPLEMENTATION

Off-line applications are limited to “*una tantum*” analysis of closed loop performance (for instance before deciding the adoption of advanced control) or to periodic check (for instance to evaluate the current status of friction in valves and to schedule maintenance operation). Evident advantages would be given by a continuous on-line monitoring of plant loops. Taking into account the heavy computation load required for assessment of causes of anomalies, this operation must be done in an external computer. Therefore a mixed structure, partly on-line and partly off-line is proposed.

The detection of onset of anomalies can be performed on-line, in order to discriminate good performing loops directly on DCS and limiting data acquisition to bad ones. In fact, the proposed indexes require few parameters and bring a limited increase of the computation load, as they consist only in few program lines (summation and comparison with constant values).

This is in agreement with Hägglund (2002), who proposes a DCS implementation of detection indexes, describing an application oriented only to detection of anomalies, with indications to operators (flashing alarms), without automatic detection of causes.

In more details, the original technique for oscillation detection required 11 parameters, while the modified technique needs 5 more parameters:  $T_0$ ,  $T_1$ ,  $\beta$  (already defined), plus  $T_{sup-old}$  (observation time at previous step) and  $\Delta T_{old}$ , duration of previous half-cycle. No additional parameters are required for detection of slow responses.

Some further considerations are worth for a complete picture of problems and possible solutions, as illustrated in the sequel.

1. Data acquisition with small sampling time and their transfer to the external computer where the CLPM systems performs a check of loops conditions would generate a too intense traffic, with consequent overload on the communication bus. A drastic reduction of amount of acquired data can be obtained by increasing the sampling time from the present applications value ( $T_s=10$  seconds), to the value of the DCS archive (typically,  $T_s=60$  seconds); in this case, the CLPM system would analyze the same amount of data already acquired for the DCS archive, without any additional traffic. Not surprisingly, that will bring a deterioration in information on loops status: a quantitative evaluation of this phenomenon and its effect on the quality of results in the plant under current analysis can be interesting.

2. A consistent saving of traffic can be obtained by acquiring only data belonging to anomalous loops to detect causes, without transferring data of good performing loops (in general, in previous off-line applications, they represent about 50% of total). A possible problem may arise from the fact that, as data acquisition starts once the anomaly is detected, there is a loss of data corresponding to the first time interval (where anomaly is detected): it can be of interest to evaluate its effect on the efficiency of the monitoring system.

3. In addition, a continuous supervision of all plant loops could be not necessary and could be limited to some of them, with time windows and strategies to be decided, according to tasks and priorities assigned to the CLPM system. Possible solutions to be investigated are illustrated below.

The first two points will be investigated in the sequel and then considerations about the third point (supervision strategy) will follow.

### 3.1 Effect of sampling time on results.

A total of 38 loops, referring to data coming from refinery plants and already used in off-line analysis, have been investigated and results are reported in Table 1.

The first row contains original verdicts obtained with a sampling time  $T_s=10$  seconds (considered the right one); in rows 2 and 3 contain indications with  $T_s=30$  and 60 seconds: the first number indicates loops maintaining the original verdict, while the second number indicates loops having different verdicts in the original classification.

It can be noted that increasing the sampling time the number of good performing loops remains almost constant: for  $T_s=60$  seconds, 1 missed alarm appears. The number of loops tagged as affected by stiction decreases from 18 to 14 to 12. The number of Uncertain verdicts and Irregular Disturbance increases.

As expected, data sampled at the same rate as the DCS archive cannot be used, because the deterioration of information with the increase of the sampling time affects the quality of the analysis.

Smaller sampling times (less than 10 seconds) would increase the accuracy in signal reconstruction, but the consequent improvement in the quality of analysis results does not seem to justify the more intense traffic generated, as shown by a specific experimentation (with  $T_s=1$  second) on a fewer number of loops.

**Table 1 Influence of Sampling Time**  
(total of 38 loops)

$T_s$ [s]	Good Perf.	Stic.	Unc.	Slow Resp.	Irr. Dist.
10	13	18	4	1	2
30	11	14	4+5	1	2+1
60	10+1	12	3+8	1	2+1

**Table 2 Influence of loss of initial data**  
(total of 24 loops)

Data	Stiction	Uncertain	Irregular Disturbance
All	18	4	2
No Initial	17+3	3	0+1

### 3.2 Effect of loss of initial data on results.

For this evaluation, 24 oscillating loops in the previous set of 38 (18 tagged as Stiction, 4 as Uncertain and 2 as Irregular Disturbance), have been analyzed. From the global set, initial data, corresponding to the first appearance of the anomaly, have been eliminated.

From Table 2, it can be seen that the number of Stiction loops increases, passing from 18 to 20 (including 3 False Alarm), Uncertain loops change from 4 to 3, Irregular Disturbances from 2 to 1. Thus, the loss of initial data seems to cause less severe errors in stiction detection; this can be explained by considering that the stiction phenomenon, once started, continues to show up for long times, with persistent oscillations (the extent will increase after days or weeks).

### 3.3 A possible supervision strategy.

In theory, detection indexes could be able to perform a continuous supervision of all plant loops; Hagglund (2002), reports an application including over 90% of total loops; however, depending on the number of loops and on capacity of the DCS, it is quite reasonable to expect some limitations.

In the case under study, the system is a Honeywell TDC3000 with HPM's and Basic Controllers and is in charge of about 600 control loops over a total of 13 thousands of configured variables.

Actual constraints on the computation load and on traffic of the communication bus between DCS and external computer do not allow a supervision of a number of loops ( $N_{loop}$ ) larger than  $10 \div 15$  at the same time.

The following supervision strategy can be proposed:

- A fixed number of loops ( $N_{loop} < N_{tot}$ , total) is maintained under observation for a fixed time ( $T_{obs}$ ), considered sufficient to detect the anomaly onset,
- The generic  $N_i$  loop not showing anomaly in  $T_{obs}$  is tagged as Good Performing loop; for this loop monitoring lasts up to  $T_{end} = T_{obs}$ ,
- The generic  $N_j$  loop showing anomaly in  $T_{obs}$  is tagged as Bad Performing loop; for this loop, at time  $T_{det}$  (when anomaly appears) data acquisition starts for a total number of  $N_{sam}$  data ( $T_{acq} = N_{sam} * T_s$ ) and ends at time  $T_{end} = T_{det} + T_{acq}$ ,
- At the end of the cycle, lasting  $T_{end} = T_{obs}$  (for GP loops) and  $T_{end} = T_{det} + T_{acq}$  (for BP loops), monitoring of loops belonging to a new set starts.

Adopting this strategy, all plant loops ( $N_{tot}$ ) are monitored in a time equal to  $T_{plant}$ . A quantitative evaluation of these factors have been performed referring to a subset of data of the same plant, already available from previous analysis.

By analyzing Table 3, it is evident that the number of verdicts changing with a decrease of the number of data ( $N_{sam}$ ) increases: a value of  $N_{sam}=700$ , corresponding to an acquisition time of  $T_{acq}=N_{sam}*T_s=7000$  seconds ( $\approx 2$  hours), can be considered sufficient to obtain reliable results about causes detection.

**Table 3 Influence of number of analyzed data (total of 24 loops)**

$N_{sam}$	Modified verdict
800	2
700	3
600	3
500	4
400	5
300	5
200	14
100	18

**Table 4 Time of occurrence of anomalies (total of 24 loops)**

N° Loop	$T_{det}$	N° Loop	$T_{det}$
1	44'	13	5h 1'
2	35'	14	24'
3	34'	15	2h 59'
4	36'	16	11'
5	2h 58'	17	20'
6	1h 31'	18	36'
7	15'	19	57'
8	12'	20	32'
9	10'	21	25'
10	10'	22	4h 1'
11	18'	23	5h 53'
12	7h 11'	24	1h 4'

From Table 4, the time of occurrence of anomalies ( $T_{det}$ ), is always less than 8 hours for all loops and then a value of  $T_{obs}=8h$  can be safely proposed. In more details:  $T_{det}$  shows to be less than 30 minutes for 9 loops, 60 minutes for 16 loops, 120 minutes for 18 loops and 240 minutes for 21 loops; therefore the choice of  $T_{obs}=8h$  is largely conservative and could be reduced to 4h.

At this point, an estimation of the total time required to supervise the complete plant ( $T_{plant}$ ) can be done. Assuming a total number of plant loops  $N_{tot}=50$ , and a number of loops under supervision at the same time  $N_{loop}=10$ , the total time depends on the total monitoring time  $T_{end}$  and is easily computed as:  
 $T_{plant} = (N_{tot}/N_{loop}) * T_{end} = 5 * T_{end}$

The duration of a supervision cycle for each loop is estimated under different hypotheses regarding the

occurrence of anomalies (more significant parameters are illustrated in Figure 5).

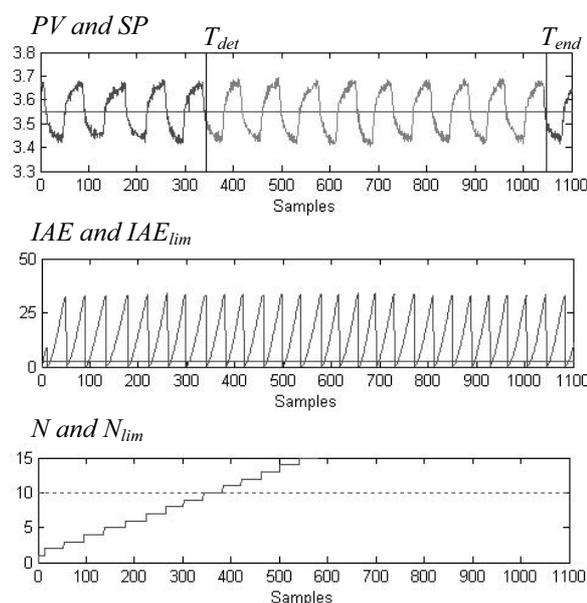
For instance:

*Hypothesis #1.* All loops are tagged as Bad Performing and show the first occurrence of anomalies at the end of the observation period:  $T_{det}=T_{obs}=8h$ ;  $T_{end}=T_{det}+T_{acq}=10h$   
 $\rightarrow T_{plant}=5 * T_{end}=50h$ .

*Hypothesis #2.* All loops are tagged as Good Performing; in this case:  $T_{end}=T_{obs}=8h$ ;  
 $\rightarrow T_{plant}=5 * T_{end}=40h$ .

*Hypothesis #3.* All BP loops, with average value of  $T_{det}=4h$ ;  $T_{end}=T_{det}+T_{acq}=6h$   
 $\rightarrow T_{plant}=5 * T_{end}=30h$ .

Clearly the first and second hypothesis are very conservative; the third one seems more appropriate.



**Fig. 5. Main parameters in the analysis of an anomalous loop.**

A more realistic scenario should take into account the fact that the situation of each individual loop will be different: therefore the supervision of loops where anomalies shows up at short time (Table 4) will end in much shorter times, thus allowing a faster supervision of the whole plant.

Some conclusive remarks can be drawn:

- Supervision times are considered quite acceptable in the plant under analysis;
- The proposed strategy has large flexibility in order to take into account results from first analysis and to incorporate operator experience or specific needs; for instance:
  - Loop priority and frequency in the monitoring procedure can be changed according to causes indicated from off-line analysis;
  - GP loops maintain high priority in order to detect as soon as possible the onset of an anomaly;
  - Loops affected by stiction can be monitored with larger period (and lower priority), by

considering the slow evolution of this phenomenon; in the case of valve without bypass, the monitoring can be also suspended up to time of the first plant shut down.

#### 4. CONCLUSIONS

The Closed Loop Performance Monitoring system presented in this paper has the global objective of detecting anomalies and tracing back also causes, in order to indicate more appropriate actions to perform. For these reasons, constraints on the computation load and excessive traffic on the communication bus, force to split the two tasks.

Indexes to detect the onset of anomalous responses can be implemented on the DCS, while the more demanding analysis of causes must be hosted on an external computer.

The analysis of loops data of the refinery plant under study has allowed an evaluation of the effect of key factors as: sampling time, loss of initial data, time of occurrence of anomalies, number of data and duration of acquisition period.

The proposed supervision strategy, which allows a monitoring of a subset of total control loops of the plant at the same time, is fully compatible with the present DCS characteristics.

Under different hypotheses about the occurrence of anomalies in the plant, the time required for a complete supervision of all plant loops is considered quite acceptable.

Finally, the proposed strategy has large flexibility in order to incorporate operator experience and to modify priorities and supervision time of each loop, taking into account results from off-line analysis.

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