DIAGNOSING AND SOLVING COMMON CONTROL LOOP PROBLEMS

ABSTRACT

A substantial percentage of industrial control loops perform poorly. This decreases product quality, lowers profitability, and makes processes difficult to operate. A few types of problems are commonly responsible for degraded loop performance. To improve control loop performance, problems need to be accurately diagnosed and the correct steps taken for solving them. This paper describes the most common problems affecting control loop performance and how to identify and solve them.

INTRODUCTION

Studies show a surprisingly large percentage of industrial control loops perform poorly. Ender [1] and Bialkowski [2] referred to several studies in two papers published in 1993. The reported loop performance can be summarized as follows:

- More than 30% of controllers remain in manual.
- More than 30% of loops actually increase variability over manual control due to poor tuning.
- 15% of loops have design problems.
- 30% of loops have equipment problems.
- Fewer than 20% of installed control loops perform well.

Based on performance assessments done on thousands of control loops, Desborough and Miller [3, 4] confirmed control loop performance was on average still this bad in 2001. In 2008, VanDoren [5] reported the following breakdown of loop performance:

- 36% were in open loop
- 10% had poor performance
- 22% had fair performance
- 16% performed acceptably
- 16% performed excellently

Common Causes of Poor Control Loop Performance

The author audited several hundreds of poorly performing control loops at 15 processing sites to establish the root causes of degraded control performance [6]. The study revealed loops with poor performance typically had the following common problems:

- Poor controller tuning (77%)
- Incorrect valve size or trim (51%)
- Valve hysteresis (27%)
- Valve stiction (26%)
- Nonlinear process characteristic (18%)
- Large external disturbances (18%)
- Incorrect control strategy (15%)

Note, the individual percentages add up to more than 100%, indicating the worst performing loops typically had more than one problem. The remainder of this paper will look more closely at diagnosing and correcting these problems.

OSCILLATIONS

Oscillations are a frequently observed symptom of poor control performance. The inherent feedback in a control loop can cause oscillatory behavior under the conditions discussed below. In addition to feedback in the control loop, many process designs include circular flows of mass or heat, which can also provide mechanical feedback and cause oscillations.

Control loop oscillations can have several causes. It could be due to incorrect controller tuning, control valve stiction, external cyclic process disturbances, or cycles introduced through the setpoint. Level control loops can also cycle due to control valve hysteresis.

Control loop performance assessment software can automatically detect and diagnose control loop oscillations using various techniques [7]. In some cases manual diagnosis or verification might be required. Manually finding the root cause of cycling can be done quite effectively through the diagnostic steps below.

Oscillations Due to a Cyclic Setpoint

The first cause of loop oscillations to test for would be a cyclic controller setpoint. This problem can be determined by visually inspecting a time trend of the controller's setpoint. If the setpoint is not visually cycling, this cause can be ruled out.

A cyclic setpoint is most often due to incorrect tuning settings in a higher-level controller. This controller should be tuned to correct this problem. Setpoint cycling in a cascade control arrangement can also be due to excessive interaction between the primary and secondary controllers. This cause can be verified by comparing the integral-action settings of both controllers. They should differ by at least a factor of five to minimize cyclic interaction. The same applies for the derivative settings, if used.

Oscillations Due to a Cyclic Disturbance or Control Valve Positioner

If the oscillations are not setpoint-driven, the next step would be to determine if they are generated within the loop itself or by a cyclic external disturbance. To test this, a time trend of the process variable behavior with the controller in manual can be inspected visually. If cycling is present while the controller is in manual, it could be caused by an oscillating control valve positioner or by a cyclic external disturbance.

An oscillating positioner can easily be confirmed by inspecting the device in operation while the controller is in manual mode. Cyclic valve stem movement should be visible and periodic air releases from the positioner audible.

Finding the root cause of a cyclic disturbance requires the engineer to look at factors outside the loop. Knowledge of the process and control system design and the use of plant-wide oscillation analysis software can help pinpoint the root cause of the cycling. The process may have to be physically inspected for unmeasured disturbances such as steam traps.

Oscillations Due to Overaggressive Tuning

If the oscillations are not induced through the setpoint or an external disturbance, they must be generated from within the loop. It is assumed an oscillating positioner was eliminated in the previous step. The next step would be to discriminate between overly aggressive tuning and valve problems as the cause of the cycle.

Valve or damper problems can obviously be ruled out if the controller output is not connected to such a device, for example, the primary controller in a cascade control arrangement. In this case, tuning should be suspected, as previously stated.

If the controller output drives a mechanical control element, the shape of time trends of the oscillating controller output and process variable should be visually inspected to differentiate between control valve stiction and overly aggressive tuning as the cause of cycling. If the oscillation is caused by tuning, the process variable will tend to cycle in the shape of a sine wave. The amplitude of the cycle will normally grow until the process variable, controller output, or both become bounded by physical or programmatic limits.

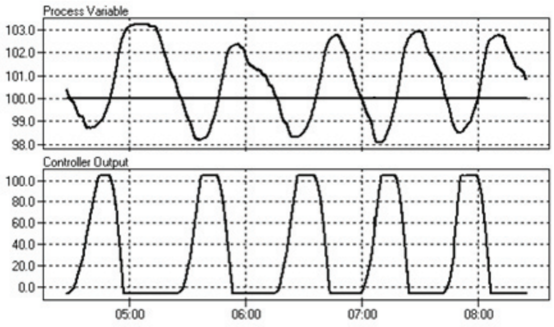

Figure 1. Controller cycling due to tuning - the controller output saturates at its upper and lower limits

Overaggressive tuning refers to excessively high static or dynamic gains in the controller. This can be the result of setting the controller gain too high, integral time too short, or derivative time too long. If the control loop cycling is due to overaggressive tuning, the controller should be properly tuned to correct this problem. See the section on tuning further down in this document.

Oscillations Due to Control Valve Stiction

Another common cause of cycling in control loops is control valve or damper stiction. Stiction is short for Static Friction. It means once the valve position becomes stationary, it tends to stick in that position. Then more force is required to induce valve movement than to sustain the movement. This has the undesirable effect of once the static friction is overcome, the valve breaks free and overshoots the desired position.

If the cycling is caused by stiction, the controller output's cycle often resembles a saw-tooth wave, while the process variable may look like a square wave or irregular sine. This is referred to as a "stick-slip cycle".

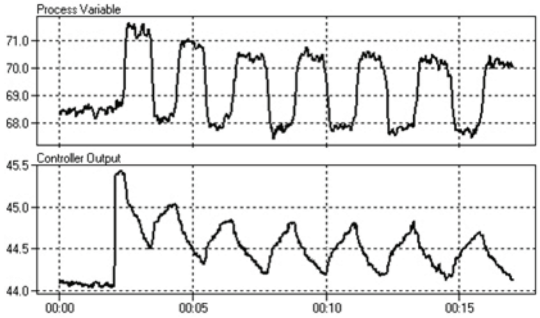

Figure 2. After a setpoint change the control loop cycles due to control valve stiction

Stiction can also be detected by placing the controller in manual and periodically making small (0.5%) step changes in the controller output. A time trend of the process variable can then be inspected to see if the valve responds to every step made in controller output or only to every few steps. The latter will indicate a sticky control valve.

Stiction might be caused by an over-tight valve stem seal, sticky valve internals, an undersized actuator, or a sticky positioner. It can sometimes be solved by lubricating the valve stem while stroking its position between limits. Most often, stiction can only be solved by servicing the control valve and/or its positioner.

The author has found in some cases, lengthening the integral time setting of the controller (or using a lower integral gain depending on the integral unit of measure) can reduce the tendency of a control loop to cycle due to stiction. This is possibly due to mechanical vibrations in the pipes and structures causing a slow creep in control valve position to balance the excessive force or torque coming from the actuator. However, detuning the controller will lead to sub-optimal and sluggish control loop performance and is therefore not the recommended solution, but a temporary suppression of the cycle at best.

CONTROL VALVE PROBLEMS

Four control valve problems commonly affecting control loop performance are stiction, hysteresis, incorrect valve sizing and incorrect valve trim. Unless eliminated, these problems can make controller tuning almost impossible. Control valve stiction was already discussed above. The other problems are discussed below.

Hysteresis

A valve with hysteresis behaves as if there is a dead band between the control signal and the valve position. Every time the controller output changes direction, the dead band first has to be traversed before the valve physically starts moving. Hysteresis may be caused by play in mechanical linkages, excessive friction in the valve, an undersized actuator, or a defective positioner. Many variable-frequency drives have a built-in, adjustable hysteresis function that will have the same effect as a mechanical dead band.

Hysteresis can affect control performance in three possible ways. First, because of the dead-band, the process variable cannot be controlled very precisely under the influence of disturbances. A loop with hysteresis will display almost the same symptoms as sluggish controller tuning.

Second, a level control loop will continuously oscillate after a setpoint change in the presence of hysteresis. This is as a result of the overshoot (discussed earlier), combined with the control loop's inability to immediately do an effective reversal of the excessive control action due to the dead band.

Finally, control loop instability can occur if controller tuning is attempted without consideration of hysteresis. During a tuning test on a loop with hysteresis, part of the controller output change can be absorbed by the dead band and result in less valve movement. The process gain would seem to be less than it actually is. As a result, the controller gain could be set too high. This problem may go unnoticed in the presence of minor disturbances or if small setpoint changes are made. However, once a significantly large setpoint change or disturbance occurs, the effect of the hysteresis will be small in comparison with the controller output change and the control loop will be at a high risk of becoming unstable.

Hysteresis can be detected from process data by computer software or by manually doing a hysteresis test. For the manual test, the controller output is changed in increments of about 5% and the process is given time to settle out after each step. Two steps are made in one direction, and a final step is made in the opposite direction. The process variable should line out at the same level after the first and final steps. If not, hysteresis is present in the control loop.

Hysteresis can be reduced substantially by adding a positioner to a control [8]. If a valve already has a positioner, the control valve and/or positioner need to be serviced.

Improper Valve Sizing

Valves should be sized to obtain full flow at around 75% of travel, depending on the valve style. If control valves are oversized it results in a high process gain, meaning the same change in controller output will have a larger effect on the process. A high process gain by itself is not a problem (the controller gain can be set low to compensate for it), but if the control valve has any positioning deficiency like stiction or hysteresis, the effect of the deficiency is amplified by the process gain. Increasing the size of control valves directly reduces the quality of control.

Less common than oversized control valves are undersized ones. In the latter case, the controller output will often reach its upper limit with the valve fully open, but still the process can not be brought to setpoint. Note, this could also be a limitation of the process, especially if the process variable shows no significant change above 90% of controller output.

Oversized and undersized valves can be detected automatically with control loop performance assessment software or historical process data can be manually inspected. Incorrectly sized control valves should be replaced with properly sized valves. Before undersized control valves are replaced, the engineer should ensure it is in fact the valve causing the bottleneck in flow and not something else in the process

After changing a control valve with a differently sized one, the controller should be retuned to match the new process gain.

Nonlinear Valve Characteristic

The relationship between the valve position (or percentage valve travel between closed and open positions) and its CV (or flow rate, under a constant pressure differential) is called its inherent characteristic curve. Most valves come with one of three distinct characteristic curves: quick opening, linear, and equal percentage [8].

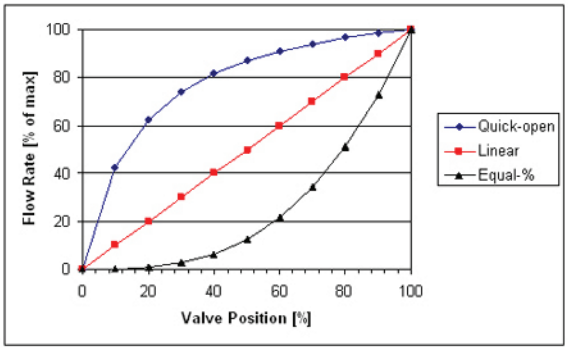

Figure 3. Valve characteristic curves

A valve's characteristic curve is determined under laboratory conditions with a constant pressure differential across it. However, once it is installed in a process, the characteristic curve can be significantly distorted by the process' own characteristics. The new relationship between flow and valve position is called the valve's installed characteristic.

For the majority of control applications, it is important to have the installed characteristic curve be as linear as possible. If it is not, the process gain will vary with valve position and the tuning settings will not work optimally across the full valve travel.

The installed characteristic of a control valve can be obtained by recording the flow rate at various valve positions and plotting these on a curve. The degree of nonlinearity can be determined by dividing the steepest gradient on the plot by the shallowest. Some loop diagnostic and tuning software packages can help with calculating the degree of nonlinearity of a control valve.

If the degree of nonlinearity of the installed characteristic of a control valve is more than two, controller tuning issues can be expected. The loop will tend to be more unstable at the steepest gradient on the installed characteristic curve and more sluggish at the flattest gradient.

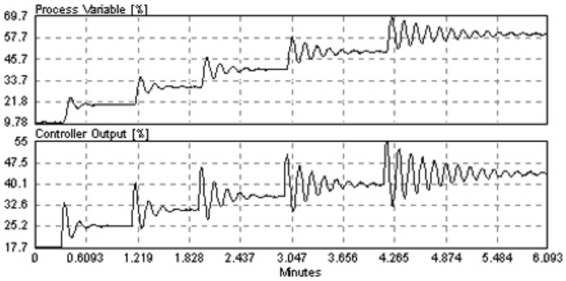

Figure 4. Different control loop responses due to a nonlinear installed characteristic of the control valve

Some digital valve positioners can be programmed with its own characteristic curve to linearize a nonlinear installed characteristic. Alternatively, a linearization curve can be programmed in the process controller. The obvious, but more costly solution, is to replace the control valve with one having the correct characteristic.

Improper Controller Tuning

As shown before, many poorly performing control loops have incorrect tuning settings. Improper controller tuning can cause poor control performance in three ways:

- Sluggish response to setpoint changes or slow recovery after disturbances.
- Overshooting past setpoint.
- Cycling in process variable and controller output.

These problems are easily identified by inspecting a time trend of a control loop's setpoint, process variable and controller output. Oscillations have been discussed previously; overshoot and sluggishness are discussed below.

Overshoot

Overshoot of the process variable past setpoint after a disturbance or setpoint change is mostly the result of the controller's gain being too high and/or integral time too short (integral gain too high). This results in too much controller action, which in turn causes the process variable to overshoot its setpoint.

Overshoot could indicate the control loop is running very close to its stability limits, which is a serious condition because the control loop can easily become unstable if the process characteristics change slightly. The controller should be properly tuned as described below to correct overshoot.

If the overshoot happens only on setpoint changes, they could be slowed down by using a ramp function or a first-order filter. Alternatively, the Internal Model Control (IMC) tuning methods [9] can be applied. IMC tuning virtually guarantees no overshoot on setpoint changes.

Special consideration for level loops

Under steady load conditions, a level control loop does not require integral action to reach a new setpoint. However, having integral action present anyway causes overshoot following the setpoint change. This is normal behavior for a level loop and impossible to eliminate through retuning the controller.

Sluggish control

Sluggish control makes itself evident in large offsets and relatively long recovery times following disturbances and in an uncharacteristically long time for a control loop to reach a new setpoint.

The speed of response of a control loop is limited, mostly by the dead time in the control loop [10]. For this reason, the speed of loop response should always be compared to an achievable value. For example, if a flow control loop reaches a new setpoint in 30 seconds, while a temperature loop takes 15 minutes, it cannot be said the flow loop performs better than the temperature loop without accounting for the underlying process dynamics.

Groundbreaking research by Harris and Desborough [11] makes it possible for computer software to identify sluggish control loops automatically, while requiring prior knowledge only of the process dead time. Their technique compares actual loop performance to minimum variance control.

Proper Controller Tuning Method

Retuning is required to improve the performance of a sluggish controller. The philosophy behind controller tuning is essentially setting the controller's P, I, and D actions to work in harmony with the process characteristics. Proper controller tuning is done by using the static and dynamic characteristics of the process (gain, dead time, and lag) to set those of the controller (gain, integral, and derivative).

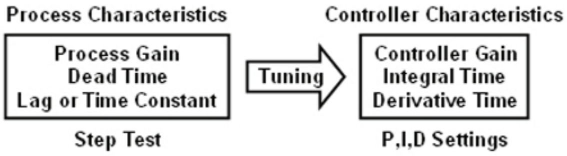

Figure 5. Controller Tuning Philosophy

Hence, before a controller can be tuned, it is necessary to establish the dynamic characteristics of the process. This is done through a "step test" by making small step changes to the controller output (or setpoint) and analyzing the response of the process to obtain the process gain, dead time, and time constant.

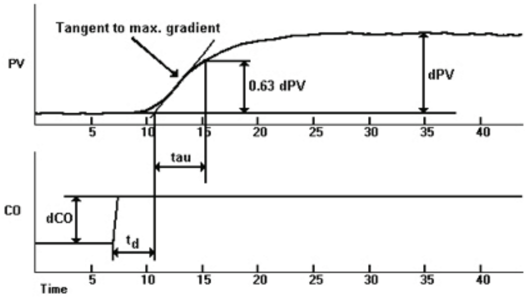

Figure 6. Determining process characteristics from manual measurements on step test plot

Once the process characteristics are available, the controller tuning constants can be calculated by plugging the former into a set of tuning equations. Various sets of tuning equations have been developed, each with its own objectives or advantages [12].

Software makes the identification of process characteristics and the calculation of the controller settings very simple and error-free, as well as provides simulations of predicted loop response and robustness. Using a software application to optimize controller performance significantly improves accuracy and saves time.

Software can also simulate loop response and provides quick fine-tuning capabilities. Note, once a control loop is properly tuned, robustness and speed-of-response are in a trade-off. The loop cannot be made faster and more robust at the same time.

Once new tuning settings are obtained, they should be entered into the controller and a setpoint change should be made to verify the expected behavior. Then the loop performance should be monitored over several hours or days to ensure the desired performance objectives are met.

NONLINEAR PROCESS CHARACTERISTICS

Nonlinear behavior in a process makes its control difficult. With a standard controller on a nonlinear process, optimal controller response can be obtained only at one operating point. The loop could be quite unstable or sluggish under all other conditions. If the degree of nonlinearity (highest gain divided by lowest gain) is greater than 2, control problems are likely to arise. This is also true for varying lag and dead time. If process characteristics change with changing operating conditions, we say the process is nonlinear.

Nonlinear Characteristic Curve

Even in the absence of a control valve, a process has a certain relationship between control action and process variable, called the process characteristic curve. An example would be the process controlled by the primary control loop in a cascade control arrangement.

The process characteristic could be nonlinear, which causes the process gain to differ based on controller output. For example, the heat transfer in a heat exchanger is dependent on the temperature differential between the heating and heated fluids. As the process fluid's exit temperature setpoint becomes closer to the heating/cooling fluid's entry temperature, the control loop will have a far lower gain compared to when the temperatures are far apart.

The characteristic curve can be plotted from process variable measurements taken at different controller output levels. Once the characteristic curve is established, its inverse can be programmed in the control system to linearize the control loop.

Gain scheduling can also be applied by programmatically loading different controller gains into the controller based on its output.

Other Nonlinear Process Characteristics

In some cases, process dead time and lag also change with varying operating conditions. For example, the dead time between a feeder and mass meter on a conveyor belt will change with the speed of the belt.

It is quite possible for process gain, dead time, and time constant to vary when some process operating condition is changed. In this case, step tests should be done under different operating conditions and controller tuning settings calculated for each condition. These PID settings should then be programmatically loaded into the controller, based on the operating condition.

IMPROVING CONTROL LOOP PERFORMANCE WITH ADVANCED CONTROL STRATEGIES

Even after the hardware is fixed and the control loops are properly tuned, the performance of some control loops may still not meet desired specifications. Feedback control loops have inherent performance limits that cannot be exceeded regardless how well they are tuned. Processes could be interactive, nonlinear, and inherently slow, which also limits what a single controller can do.

In cases like these, the control performance can likely be improved by implementing a more complex control strategy. These advanced control strategies include cascade, feedforward and ratio control, gain scheduling, decoupling, and ultimately, model predictive control. The two most commonly applied advanced control strategies are described below.

Feedforward Control

Process disturbances outside the control loop can affect its process variable, thereby impacting performance negatively. Regardless of how tightly a feedback control loop is tuned, it can only initiate a control action after the process variable has deviated from setpoint. If the process has long dead time or large lags, it could take an even longer time to eliminate the effect of a disturbance. “Straight-line” control is never possible with feedback control if disturbances are present.

However, if external disturbances can be measured and if they have a predictable effect on a control loop’s process variable, a technique called feedforward control can be implemented.

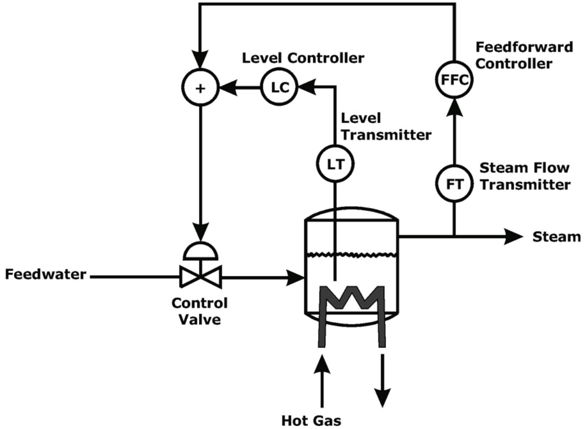

Figure 7. Feedforward control added to feedback control

With feedforward control, the effect of a disturbance is negated by applying a counteracting control action as soon as the disturbance is detected. Ideally, the disturbance and control action will cancel each other out and the process variable will remain unaffected.

Cascade Control

Similar to the way in which flow loops control better if its control valve is fitted with a positioner, slower level and temperature loops control better if their underlying process flows are controlled with a secondary flow controller.

For example, consider a level control loop on a large tank, of which the controller output goes to a control valve directly. Now consider the valve has hysteresis or stiction. These defects will cause the tank level to oscillate continuously due to reasons discussed previously. The cycle will have a long period due to the slow dynamics of the large tank. The underlying flow will also cycle and this may propagate to upstream or downstream processes, depending on the design.

Now consider the level control loop is provided with an inner flow control loop. If the control valve had only hysteresis, the cycling will cease because hysteresis does not cause cycling in a flow control loop. If the valve had stiction, the flow loop will cycle, but the period of the cycle will be so short it will have virtually no effect on the level of the large tank. The effect of the fast cycle on the upstream or downstream processes could also be attenuated to undetectable levels.

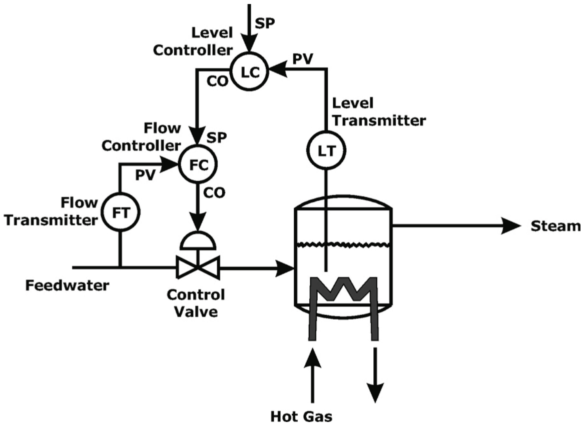

Figure 8. Cascade control

In the same way, flow rate disturbances due to pressure fluctuations will be detected and eliminated by the new flow control loop before the level is affected. By using cascade control, we add an inner control loop to deal with control problems in a fast and effective manner, shielding the primary process of its existence.

One main criterion for successfully applying cascade control is the dynamics of the inner or secondary control loop must be significantly faster than those of the outer or primary control loop. The secondary control loop should have a settling time at least five times shorter than the primary control loop. If this criterion is not met, the secondary control loop will not effectively improve control performance and interaction between the two loops can be come a problem.

Tuning of cascade loops should address the inner loop first, and once it has been optimized, it is placed in cascade control mode after which the outer loop is tuned.

WORK PROCESS FOR IMPROVING CONTROL LOOP PERFORMANCE

Optimizing control loops and sustaining long-term performance can be done very effectively by implementing this seven-step approach developed by PAS, Inc.:

1. First, a process control philosophy is developed to provide guidelines for consistency in implementation and optimization of control loops.
2. Then computer software is used to collect process data, analyze the performance of all loops, and rank the loops according to importance and performance.
3. The next step is to diagnose the problems of the bad-acting control loops. This is initially done by the performance assessment software, but certain problems require human expertise for proper diagnosis. Once diagnoses are obtained, problems are addressed accordingly.
4. Control loops with hardware problems should have these problems addressed before tuning can be done effectively.
5. Controllers with poor tuning are then step tested and new tuning settings calculated, implemented, and performance verified.
6. If performance is still not adequate, advanced control strategies can be implemented.
7. Once the loops have been optimized, the final step of periodic monitoring and reporting is used to ensure any further performance problems are identified and addressed early.

To learn more about the 7 steps, please visit www.pas.com to download the white paper.

SUMMARY

Several studies have shown average control loop performance is very poor. While many engineers look to controller tuning as the solution for improving control loop performance, this paper highlighted several scenarios where tuning is not the best solution and provided techniques for diagnosing and fixing the actual problems.

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ABOUT PAS

PAS is a leading supplier of software products and consulting services to the process industries worldwide and has been delivering value to customers since 1993. Solutions offered include Alarm Management, Automation Configuration Management, Knowledge Management, and Control Loop Performance Management.

PAS offers a comprehensive suite of products and services to support our customers' control performance improvement initiatives through the seven steps above. These include software for monitoring and improving loop performance, process control training, and consulting and optimization services.

More information is at www.pas.com.