Pneumatic Controls and

Commissioning: Analog Lessons for a Digital World

Pneumatic controls may be thought of as out of date, but their roots in existing buildings will remain for the forseeable future

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Before you dismiss this article thinking pneumatic controls are irrelevant in a modern building environment, consider that most buildings have some form of pneumatic control. In some instances, pneumatic controls are vestiges of older systems that will remain in place until the next renovation cycle, an event that may or may not occur in the foreseeable future (Photo A).

In other cases, they are the result of a cost-cutting process that traded direct digital control (DDC) of terminal units for first cost, the latter being the case in a mid-'90s building in which I did some retrocommissioning work.

An informal survey I have been conducting asks facility personnel how long they think it will be until pneumatic controls are phased out of their facility. Answers have ranged from 10 to 15 years to never. If you are dealing with existing buildings, most likely, you are dealing with pneumatic controls, especially if you are providing retrocommissioning services.

It is important to remember that despite the phasing out of pneumatic sensing and control, pneumatic actuation will continue to be specified and installed, specifically where large valves and dampers must be positioned quickly. This is especially true on campuses on which a compressed-air system already exists.

ANALOG TECHNOLOGY

Most of the HVAC processes and events the buildings industry deals with are analog, rather than digital. Seasons do not change instantly from summer to winter. Loads do not change instantly from minimum to maximum. Changes occur during a finite period of time and thermal inertia. Time lags and transportation delays can have a major impact on how an HVAC system responds to a change in environment or load.

Analog control processes—whether pneumatic, electric, or electronically based—mimic this behavior. These characteristics can be a boon to a workable control approach when contrasted with digital approaches. In other instances, they can sacrifice precision, efficiency, and maintainability, all of which can be enhanced by computer-based digital technologies. But in understanding the time-based rate of change associated with analog control processes and the related lags and inertia, one gains insight into the characteristics and complexities of HVAC processes that are being controlled. This insight can be an invaluable asset if you, as a commissioning provider, are trying to understand what is making a recalcitrant HVAC process tick (or not tick).

DIGITAL TECHNOLOGY

Understanding analog technology can be the

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Closed- and Open-Loop-Controller Response

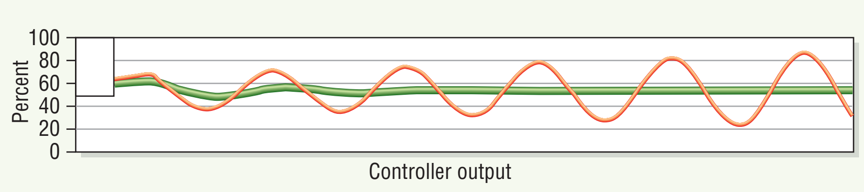
A well-tuned controller serving a closed-loop process will respond to a change and stabilize at the new condition (see figure). If a controller is too sensitive, a condition created by a narrowing of the proportional band or an increase in gain, it will become unstable. The trick in tuning a controller is to find gain settings that allow a controller to "capture" a set point, given the system dynamics. The dynamics include mechanical issues, such as the hysteresis of actuators and kinematics of their linkages; thermodynamic issues, such as the response of heat-transfer elements and sensors; and fluid-mechanics issues, such as transportation delays and the rate at which a disturbance propagates through a system. These issues, which are the result of a controller's output actions, feed back into a controller via its input. As a result, a controller responds and further impacts the process, thus the term "closed loop."

In contrast, an open-loop controller has no feedback from the process it is sensing. As a result, its output simply changes in direct relationship with changes in input to its sensing element. The relationship is established by the gain of a controller. High gains (narrow proportional bands) result in a controller in which output changes nearly instantaneously as the process variable it is sensing moves past a set point. As a result, a controller set up this way can be used to trigger actions in other systems when a specific condition exists.

The changeover controller in the sidebar "War Story: Don't Just Do Something, Stand There" was an open-loop controller. It sensed outdoor-air temperature and switched its output from minimum to maximum when outdoor-air temperature exceeded its set point. This signal triggered switching relays and other devices that caused the economizer cycle to be terminated, returning systems to minimum outdoor air.

Most of these devices would change state at a specific pressure and change back at the triggering pressure minus a deadband. For instance, a pneumatic switching relay with a changeover setting of 12 psi and a deadband of 3 psi would switch its ports one way when a triggering signal increased to 12 psi and return to its original state if or when a triggering signal reached 9 psi (12 psi – 3 psi = 9 psi). On a rising signal, nothing would happen until the input reached a triggering condition of 12 psi. Conversely, on a falling signal, nothing would happen until the signal dropped to 9 psi. If a signal rose to 10 psi before falling again, the relay would never change state.

If the proportional band for the changeover controller was not set to a narrow range, the output change from the controller would occur over a temperature range, rather than at a specific temperature. For instance, if the sensitivity of the controller was set for 0.2 psi per degree Fahrenheit (low end of available range equals wide proportional band/low gain/low sensitivity), the temperature would have to change 60 F to cause the output pressure to change 12 psi. In contrast, if the sensitivity of the controller were set for 3 psi per degree Fahrenheit (high end of available range equals narrow proportional band/ high gain/ high sensitivity), a 4-F change would be required to generate the required 12-psi signal. If the operators in the sidebar "War Story: Don't Just Do Something, Stand There" had used the manufacturer's recommended starting point for a proportional band of 1¼ psi per degree Fahrenheit, an approximately 10-F change would be required to create a 12-psig signal change. It would appear that the controller was not working properly in its open-loop/two-position application. The same setting in a closed-loop application would provide a stable response, although some improvements could reduce proportional offset by additional tuning.



Controller outputs for a stable (green line) and unstable (orange line) controller.

path to understanding digital technology. Analog control systems, particularly pneumatic control systems, are fabricated from discrete components based on electromechanical principles that yield the desired control logic and response through their functions in a relationship. A technician or designer working with discrete components can see and understand the integrated response of the system because they can see and work with the individual elements and their connections. Consider a simple control sequence in which a control valve is modulated by a controller sensing temperature in the discharge of the coil it serves. Modulation occurs when an associated system is operating. Otherwise, the valve is closed. Implementation in a pneumatic analog system might involve a controller with a sensing element that contains a refrigerant charge. A temperature change at a sensing element will cause a pressure change in a refrigerant charge contained in an element, which, in turn, might expand a bellows, moving a lever and repositioning a pneumatic relay. This causes a change in the device's output. The output can be "hard-piped" to another independent switching device that connects or blocks the signal to the valve, depending on the system operating status. This way, it can be modulated

War Story: Don't Just Do Something, Stand There

The old adage, "Don't just stand there, do something," often is invoked in situations in which taking quick action appears to be prudent. Unless you can act with confidence, the reverse may be more appropriate. An action taken without knowledge or consideration of potential outcomes often can lead to more problems than it solves.

My first inkling of this insight occurred during my first experience working with a control system of a large, existing high rise during the late 1970s. The company I worked for was retained by building management to help troubleshoot, solve operating problems, monitor utility consumption, and review system modifications when renovations occurred. One day, Bill, one of the firm principals, took me to the building to troubleshoot a problem while he attended a management meeting. The building was served by a large pneumatic control system that included a large engraved graphic control panel in the basement with a multitude of selector switches, set-point dials, and temperature indicators embedded in one-line graphic diagrams of the building systems, all of which purported to convey the building's operating status. However, the panels essentially were "cast in stone" because they were engraved in plastic laminate during the construction process and did not reflect any modifications. Bill advised during the drive to the site that the gauges' accuracy was questionable and one of the system graphics simply was wrong. I approached the troubleshooting session with a bit of anxiety, wondering what I would encounter.

Upon arrival, I was introduced to the lead operating engineer, who took me down to the control room. He started pointing at various gauges and switches on the graphics panel. He launched into a rapid-fire explanation of how the systems had gone "haywire," causing the systems to be "starving for air" some of the time, but perfectly happy on other occasions.

Feeling slightly overwhelmed, I asked if there had been any particular event or change that had occurred around the time the problem arose. The lead operating engineer's response was: "Absolutely. It was right after we calibrated all of the controls as recommended by your company." At that point in my career, I was enough of an engineer to know that, properly executed, a recommendation to calibrate a control system had to be a good thing in the big picture. However, I was enough of a mechanic to believe the, "If it ain't broke, don't fix it," adage and to have my own doubts about engineers (myself included).

I proceeded to ask if the building staff noticed the problem immediately after working on any particular device. I followed the lead operator as he headed for the elevator. On the way to the 20th-floor mechanical room, he showed me control drawings for the building, installation and operation instructions for a number of pneumatic control devices, and a cover letter from my company recommending a calibration effort. He also explained that the systems no longer would go off the economizer cycle automatically when it was hot outside. The staff manually had to change over the systems. This presented a problem on multiple fronts. If staff members were involved with something else in the morning, and the outdoor temperature increased more rapidly than they had anticipated, they were caught off guard, triggering complaints from building occupants. If it was not cool enough to go back off of the economizer in the evening before they went home, someone had to stay late, come in early, or both to make sure outdoor air was being used for cooling when possible to help control energy costs. All of this was costing the lead operator and his partner sleep and causing aggravation.

When we got off of the elevator, we walked into the biggest machine room I had ever seen. The lead operator led me through a maze of pipes and ducts to an innocuous-looking controller on the wall. He pulled out a screwdriver and said, "Watch this." He then rapped the cover of the controller with the handle of the screwdriver, at which point confusion ensued. Switching relays clicked, control air hissed out of controller ports, dampers and valves moved, pump and fan sounds changed, and pipes, ducts, and pneumatic lines vibrated as water and air rushed through.

The lead operator stood there calmly, unperturbed by it all.

"See what I mean?" he said. "Those units were on 100-percent outdoor air and shouldn't have been. Before you guys told us to calibrate all of this stuff, that never happened. We've followed these instructions to the letter. The only way we can get the systems to change over is to do what I just did or open the controller and make a big change in the set point. If I want these units to change over at 72 F, then I should be able to set this controller at that setting and have it happen. What do you suggest I do?"

At that point, there were a lot of questions running through my mind, including:

- How could one little controller cause all of that to happen? Actually, I knew the answer, and it seemed pretty alarming. To make all of that happen, that one little controller had to be connected to all of that stuff.
- How was I going to trace the connections among one controller and all the other systems to figure out where the

when the system it serves is in operation. When the system is off, the switching device blocks the signal and causes the valve to revert to its normal position. A relay logic circuit, which is a collection of discrete contacts and coils connected with wires, controls the switching device.

In contrast, a digital control system can—and often will—contain all of the control processes described inside a "black box," the workings of which are evident only to someone with a compuproblem was? Compared with everything else I had seen, these systems were huge. The fact that the basement panel was connected to them, meaning there were 20 floors of tubing and wire between it and each element it controlled, only made things more overwhelming.

These questions, along with the system changeover activities, had pretty much shoved my anxiety level over the edge. In my somewhat panic-stricken state, I found myself contemplating three different responses to the operator's challenge:

• Run. This primitive reaction probably was not feasible, as I was not sure how to get out of the mechanical room.

• Do something. Part of me felt I needed to do something to show that the calibration was not a bad recommendation. But, overwhelmed by what I had experienced and lacking any knowledge of the controller that was the alleged source of the problem, I did not have a clue what to do.

• Do nothing. This was the course of action I chose. As it turned out, it was the best strategy. Checking my watch, I was relieved to discover that the principal's meeting was over, meaning I would not have time to dig into the problem any more that day. I made arrangements to return two days later, which would give me time to calm down, do some research, and work out a solution.

On the ride back to the office, Bill asked me what I had found out. I filled him in on my experience. With a bit of a smile, he said, "Sounds like the proportional band on the changeover controller needs to be narrowed down." Because I didn't know exactly what proportional band was, let alone why narrowing it down would fix this seemingly insurmountable problem, I continued to ask questions. What I learned was:

• A process by which a change in a system is detected and the controller "in charge" of the process reacts is a closed-loop process. A process by which a change in the system cannot be seen by the controller "in charge" is an open-loop process.

• Proportional control means a controller's output is proportional to the difference between the set point and the actual condition under control in an HVAC process. This difference often is called "error" or "proportional offset" and is an inherent characteristic of a proportional-control system. The proportional band of the controller is the input span over which the output of the controller is proportional to the difference between the set point and process variable. A proportional band of 10 F means a 10-F change in input would be needed to cause controller output to go full span (typically defined as 3 to 15 psig for standard HVAC pneumatic control systems). A narrow proportional band means a controller will respond quickly to any difference between what it wants and what actually is going on. This is a good thing, unless the controller is so responsive that it overreacts. If it overreacts, the system is unstable. The goal of tuning a controller is to get it to react to a difference between what it wants and what actually is going on as quickly as possible, but not so quickly that the system becomes unstable.

• What I had encountered was an open-loop controller. It sensed outdoor-air temperature, but its actions would not affect the outdoor air temperature. It was intended to send a changeover signal to the systems, causing them to return to minimum outdoor air when the ambient temperature made the economizer operation undesirable from an energy standpoint. For it to work properly, it needed to have a narrow proportional band (see the sidebar "Closed- and Open-Loop-Controller Response"). Because the operators probably were not well-versed in proportional-controller theory and had been handed the manufacturer's calibration instructions as a guideline, they probably had set the proportional band to the nominal starting point recommended by the manufacturer. While this setting typically would provide a good starting point for a tuning process, in an open-loop situation, it caused the output to change gradually as the outdoor temperature increased. As a result, the controller appeared dysfunctional. Making a large set-point change would have solved the problem, but, from the operators' standpoint, made the controller appear not to have been calibrated. If conditions were such that the controller was close to generating the signal necessary to trigger the changeover response, rapping the controller with a heavy object would jiggle things enough to make the output change and trigger the system changeover.

• All of the noise was normal. The mode change triggered by the changeover signal represented a step-change input to the control systems that had the potential to cascade through the other control loops in each air-handling unit. The changeover signal also could trigger instabilities elsewhere if any of the systems became unstable. The fact that the upset occurred and then went away was an indication of the stability of the building systems and was the reason the lead operator was unperturbed. He knew from experience that things would calm down.

The knowledge gained from my experience in the building that day, Bill's coaching, and some subsequent studying allowed me to return to the building as scheduled, work with the operating staff to adjust the controller's proportional band, and solve the problem. The effort was the beginning of a lengthy relationship with the building and its operating team as we worked to solve problems with the building's pneumatic control system and HVAC equipment.

ter interface and knowledge of the programming language. Yet, the desired outcome and narrative description of a control sequence will be identical.

The best way to understand control systems may be to learn how to design, install, and maintain a pneumatic control system and then apply those concepts to current digital systems. This approach is exactly how many industry experts learned to deal with DDC. When they started their careers, DDC technology did not exist in the buildings industry and only was beginning to make inroads in the process-control industry. Analog control systems, particularly pneumatic analog control systems, simply were the technology used.

As DDC matured and made its way into the buildings industry, experts used their knowledge gained by working with pneumatic control systems to exploit advantages represented by digital technology, where fundamentals still applied. In many cases, similarities between the two technologies' functions allow "cross-training." Interestingly enough, the reverse also is true. If you understand digital technology and suddenly find yourself confronted with analog technology, you can use fundamentals as a foundation for understanding new territory.

PHOTOS A1 and A2. One-pipe pneumatic technology encountered on a recent retrocommissioning project. The one-pipe pneumatic transmitter (left) and receiver controller (right) serve the central systems in a lab building on a large college campus.

The following sections highlight a few lessons I learned while working with pneumatic control systems.

FUNDAMENTALS

Despite significant changes in the control of HVAC processes over the last 15 to 20 years, the processes themselves and the physics underlying them are the same. For example:

• Varying flow in a pipe or duct frequently requires that the pressure driving the flow be varied, despite how it is controlled.

• The discharge temperature required from a cooling coil providing sensible cooling and dehumidification is set by the required space condition and the sensible-heat ratio, regardless of how it is controlled.

While newer technologies may allow us to optimize required control strategies and perform them with more precision and speed, the fundamental requirements of the control strategies are about the same. Competent mechanical designers have lamented their loss of control over the quality and performance of HVAC systems as reliance on pneumatic/analog technologies has shifted to digital, computer-based technologies. Because they do not understand newer control technologies and are confounded by the "black-box" concept, they feel they are at the mercy of control contractors in terms of obtaining a satisfactory HVAC system.

The reality is that a satisfactory HVAC system can be obtained if proper components are selected, installed, and operated in a manner that meets fundamental physical requirements of the process. The control system has a lot to do with achieving success, but will not perform if HVAC fundamentals have been misapplied. A lack of familiarity with DDC systems does not close the door on control of an HVAC system's quality and performance. The key to success involves a two-pronged approach:

1) Communicate HVAC process requirements clearly and in detail so they can be implemented properly by control specialists familiar with current technology.

2) Include requisites for a commissioning process to verify that an installed system's performance matches your requirements. Complement this verification with training of the operating staff to ensure performance continues.

DIRECT DIGITAL CONTROLS

Younger control technicians who are intimately familiar with DDC technology sometimes are confounded by the pneumatic controls they are forced to deal with. The operating principles behind many DDC technologies are not that different from those behind pneumatics. If you understand one, you likely can get up to speed on the other pretty quickly. Figure 1 is a common example. Proportional-control theory (see the sidebar "Closed- and Open-Loop-Controller Response") is another. While DDC has opened the door to proportional-control alternatives, the proportional-control algorithm or one of its variations still is very common. Many problems encountered with DDC systems have roots in system instability and frequently can be solved by applying proportional-control theory and tuning techniques.

The presentation of control information for some digital systems is similar to the presentation of information for pneumatic control systems. Many manufacturers offer a graphic programming language option or as a method for setting up their system's software. If you compare a pneumatic control drawing to a DDC program implemented in a graphic programming language, you will discover they are quite similar. Again, if

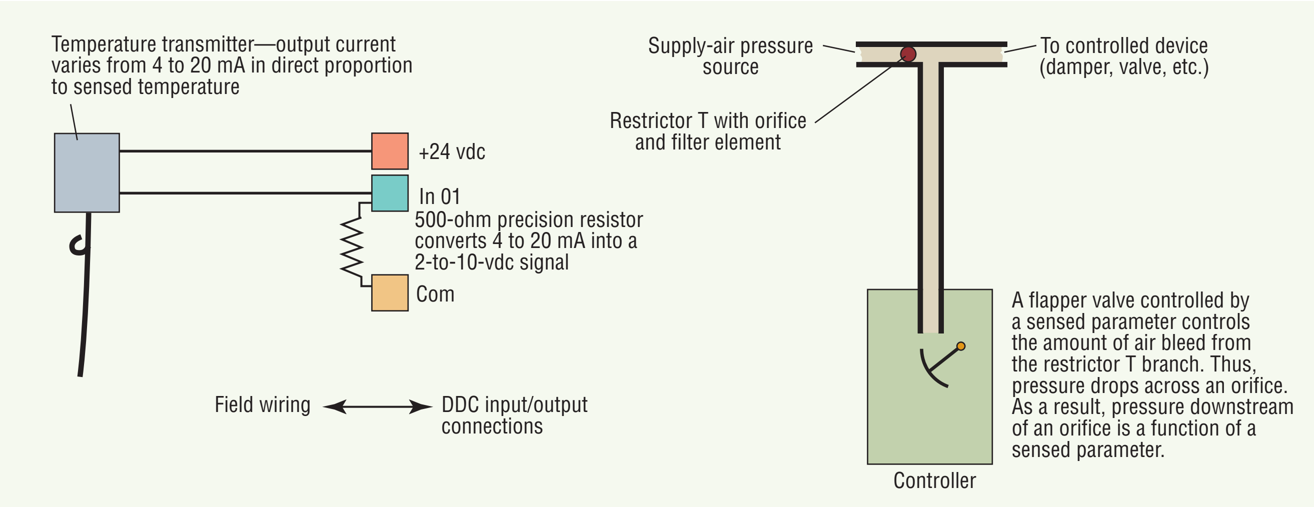


FIGURE 1. Left to right: 4-to-20-mA transmitter operation vs. pneumatic transmitter operation. Both approaches create a signal by passing a flow through a resistance. The pneumatic device advances airflow through a restrictor, while the electronic device passes current flow through a resistor. In both cases, the operating theory is based on fundamental physical principles, not computer technology.

you can interpret one, you can interpret the other.

PROBLEMS AND SOLUTIONS

A problem that seems extremely complicated and affects several different components may have a simple solution that can be implemented at one location, solving the problem everywhere.

HVAC systems always have been integrated and interactive assemblies. The increasing predominance of variable-flow technologies, driven by a desire to conserve energy, tends to compound the interactive nature. Frequently, an interactive response of an HVAC system that is in trouble can make a problem seem overwhelming and intimidating. The accompanying war story is an example. When I was first exposed to a changeover problem demonstrated by the lead operator, I was overwhelmed by the buildingwide reaction. What I failed to appreciate was the fact that his action at one point in the system triggered all of the problems. Focusing attention on that one point in the system solved the dilemma.

It can be easy to dive into the complexity and get lost, missing an obvious answer right under your nose. Take a few minutes to be sure you understand the technology you are dealing with before diving in. A pause often saves time in the long run. Don't just do something, stand there.

WE ALL HAVE SOMETHING TO LEARN

Throughout my career, I have benefited immeasurably from mentors providing me with challenging problems to solve and taking the time to explain things to me when I was stuck. Of course, for that to work, you have to be willing to admit you do not know something, recognize you may have made a mistake, and ask questions. These things are not easy, but generally are well worth the effort.

WE ALL HAVE SOMETHING TO TEACH

In the sidebar "War Story: Don't Just Do Something, Stand There," the problem was solved when I took what I learned back to the building and worked with the operators to solve the problem. In the course of this effort, they learned from my experiences with proportional control, while I learned how to apply engineering theory in an operating building without causing problems, something that is not as easy as it may sound. The insights gained while working with a building's operating staff are invaluable tools, delivering better systems that are configured to deal with day-to-day operating realities.

TEAMWORK

It takes a team effort to provide a lasting solution to many problems. In the sidebar "War Story: Don't Just Do Something, Stand There," Bill needed me to be his eyes and ears in the field, freeing him to deal with other issues. I needed his insight and knowledge to interpret and correct the things I was seeing. The operators in the high-rise needed what I learned to help them solve their problem and correctly implement engineering recommendations from my company. I needed their knowledge of the building to implement the solution I identified. My company and the operators' management needed the problem to be solved to allow efficiency improvements associated with calibration efforts to be realized.

The bottom line is that most problems lend themselves to a team solution, especially when dealing with high technology and the specialization that goes along with it. Learning to be a team player can be a valuable asset when commissioning buildings and their control systems, regardless of the type of technology employed.

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