Successful DDC System Retrofits

By Mark Hydeman, P.E., Member ASHRAE

Over the past, decade my firm has assisted a variety of clients (both public and private) to retrofit existing pneumatic or hybrid pneumatic/legacy direct digital control (DDC) systems to state-of-the-art DDC. The scope of these projects usually is limited to the central equipment and lighting, excluding zone controls. Clients often are lured by dreams of energy efficiency, vendor independence, faster control response and intuitive Web-based interfaces that expose the inner workings of their buildings. Is it possible to meet such high expectations? The answer is a resounding "maybe."

Key Factors to Success

The success of a project is linked to several key factors:

- Setting realistic expectations for your client;
- Finding local control representation that is committed to doing a good job. A great contractor with a mediocre product is much better than a bad contractor with a state-of-the-art product;
- Writing a clear and detailed specification and ensuring the contractor holds to it; and
- Making sure that the contractor performs through a rigorous submittal review and formal performance verification process.

DDC retrofits are expensive. A central system upgrade runs roughly \$0.50/ft^2 (\$5/m^2) for HVAC systems and another \$0.50/ft^2 (\$5/m^2) for zone lighting con-

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trols.* Going to the zone level adds another $1,000 to $2,000 per zone (as much as $2/ft^2 [$22/m^2]). For that cost, tangible benefits must be shown to the owner. Typically, two major categories of issues drive owners to upgrade their control systems: operations and maintenance issues and expanded features.

Other issues that drive DDC upgrades include:

- Improved comfort;
- Outdated equipment;
- Limited parts availability;
- Poor support;
- System and control problems;
- Energy savings;
- Graphical interface;
- Web or remote interface;
- Graphical programming;
- Lighting controls;
- Tenant override and billing;
- Ability to expand to DDC at the zone level in the future;
- Trending (data access); and
- Alarming.

Although reducing energy costs as part of a DDC upgrade is possible, rarely are enough savings generated to justify the costs of the system. The retrofit has to provide the right amount of these qualitative benefits to make it worthwhile.

Retrofit Stages

A typical retrofit goes through six stages of planning and implementation.

Stage 1: Early Planning. In the early stages of the retrofit it is important to sit down with the owner (or manager) and building engineers to discuss what their goals are for the retrofit, the scope of the project and the long term plans for the facility. The purpose of these discussions is to develop the criteria and budget for the new control system. It is also important to identify if there are any operational deficiencies that should be addressed in addition to the controls upgrade. It is quite common to have mechanical upgrades lumped together with the controls retrofit such as adding variable speed drives to the cooling tower fans, repairing an air-side economizer or fixing ductwork to a rogue zone.

From the wish list of attributes, first separate them into sublists:

- Items that are part of the base bid;
- Items that should be included as additive or deductive alternates;
- Items that should be tabled for future retrofits; and
- Items that should not be considered.

This is an iterative process that requires both judgment and diplomacy. A typical plant operator will have a wish list that is larger than the owner's budget. Typically they will also have a stack of project proposals which may or may not be relevant to the owner's needs. It is the engineer's job to bring order to this constellation of competing desires and objectives.

In addition to operator and owner interviews it is also useful to review any consultant reports or proposals that the owner (or operator) has received. It is also very helpful to interview the existing control vendor about the operation of the existing system and any improvements that they have thought about. Except for cases where there have been problems with the existing vendor's performance, or their current products cannot meet the desired features, the existing vendor should be part of the bid list. In any event you should maintain a good relationship with the existing vendor because they can be a tremendous help in determining the scope of the existing control system.

You should locate copies of the following documentation, if possible:

- A current set of mechanical drawings that covers the equipment and systems that are part of the controls scope;
- A current set of control drawings;
- A list of the current DDC points (if applicable); and
- The current control sequences (sometimes these are on the drawings).

The first deliverable of the retrofit should be a narrative that describes the goals of the retrofit, details the scope of the project

*Note these costs depend on the complexity of the mechanical systems and the size of the individual lighting zones. Projects with complex systems such as ice-harvesters or individual lighting zones for each private office could run significantly higher.

and identifies any alternatives or unit prices that will be part of the bid package. You should also establish the project timeline and shortlist the vendors (three or four) that you recommend inviting to bid. This document is an important communication piece with the owner and operator. On getting their approval (after responding to any comments) you are ready to tackle the bid specification.

Stage 2: Development of a Bid Specification. The bid specification provides a basis for contractor pricing and details the performance requirements of the contractor and system. The bid specification also provides bid forms for comparing bids on an equivalent basis. Two resources exist for developing a solid bid specification. ASHRAE Guideline 13-2000, *Specifying Direct Digital Control Systems,* is a great resource for development of DDC specifications. In addition, an automated controls specification development system is available at www.ctrlspecbuilder.com. This automated system is based on ASHRAE Guideline 13 and built around the BACnet® protocol. It should be used with caution since it was developed by a specific manufacturer.

It is beyond the scope of this article to detail all of the requirements for a thorough bid specification. However, at minimum it should contain the following sections (see inset).

Bid Specification Checklist

- ☑ Project scope
- ☑ Proposals
- ☑ Submittal requirements
- ☑ Hardware and installation requirements
- ☑ Overall system performance criteria
- ☑ Software requirements
- ☑ Points lists
- ☑ Sequences of operation
- ☑ Training
- ☑ Commissioning (if applicable)
- ☑ Trending/performance verification
- ☑ Bid forms including alternates and unit prices

Our firm typically includes existing mechanical and/or control drawings in the bid package. However, we do not create new control schematics, control architecture or panel drawings as these are vendor specific and are done independently by the winning bidder. A thorough specification with oversight and review is sufficient to achieve a quality job.

This makes it essential to impress to the vendors, prior to the bid, your intention to hold them to the specification. The unfortunate truth is that most control systems are poorly specified leaving the contractor too much leeway to do as little as required. Making sure that vendors read the specification is a challenge as few engineers take the time to write a precise control specification. Far fewer take the time to hold the contractor to the specification.

At one site, an engineer had listed a flow meter in the points list and failed to call for its use in the sequences of operation. The result was that the client received (and paid for) an installed flow meter that was not wired to the control system and could not be trended or used in control sequences.

At another site, the contractor placed an outside air temperature sensor on the roof without a radiation shield. He had taken the time to hide it on the bottom side of a pipe. But, late in the afternoon the air-side economizers shut off because of false high temperature readings.

At a data center, a controls contractor installed a wet-bulb sensor in a system that used wet-bulb reset for the cooling towers. The sensor was so far out of calibration that the towers shut down because the wet-bulb reading was too high. They nearly lost control of the data center. Unfortunately, the controls industry is rife with stories such as these, and oversight is crucial. Controls are the Achilles' heel of our mechanical system's performance — one minor slip will waste energy and can cause systems to fail.

In a typical job, there are three opportunities to provide the required oversight: during submittal review; on job walkthroughs and during trend reviews. Each of these is talked about in the following sections.

Stage 3: Contractor Selection. As mentioned previously, the quality of the contractors and their relationship to the client is as important (if not more) than the system that they install. Contractors on the short list should be selected for their experience at similar projects, relationships (if any) that they have with the customer, for the depth of their local representation and for the product they represent.

Ideally, enough contractors are needed to provide price competition, but not so many as to make the process burdensome. Our firm typically selects three or four. As previously mentioned, we almost always include the existing contractor

Motivations to Retrofit

On several of our projects, a primary driver for the DDC retrofit was the desire for centralized, intelligent alarms. Modern DDC systems can provide text-based alarming via e-mail, phone or pager. Furthermore, the new systems can cascade critical alarms if they are not acknowledged within a preset time, allowing the system to automatically alert one individual after another until someone acknowledges the alarm.

In sharp contrast, several of our projects with legacy DDC systems cannot issue central alarms. To find out that a device is in alarm, the operator must page down through a text-based interface to the page that has the controller with the device in alarm. For facilities with critical equipment (such as data centers), this has been a primary motive to retrofit the controls.

Other examples include:

• A central plant serving 23 state buildings could no longer obtain parts for an outmoded DDC system that ran on an OS/2 platform.

• An owner-occupied campus for a high-tech company needed centralized alarming and integrated demand shed signals.

• At a multi-tenant high-rise, the motivation was centralized alarming together with the desire to track and bill tenants for after-hours usage.

unless a compelling reason exists to exclude them.

The content of the bid proposals should be detailed in the bid specification. A typical project has the following elements: bid forms; construction schedule; system architecture; sample trend file; sample programming file; resumes of key personnel; service contract details; and exceptions (if any).

Upon receipt of bids, we typically interview each contractor still in the running and have them walk us through the job describing the proposed system architecture, how it serves the scope of the current project, and how it can be expanded in the future (if required). In some cases, we ask them to mock up one or more sequences and demonstrate their software interface and programming.

In our projects, bids typically are evaluated using a matrix that includes scores for a variety of hard and soft factors. These include price, depth of representation in the local area, experience with similar facilities, experience of the individuals assigned to this project, ease of use of their software and other criteria preselected with the owner. *Table 1* shows part of an example matrix comparing two bids. The leftmost column has the criteria previously discussed. The second column is the weight (importance) associated with the criteria. We always make these weights add up to 100 because it forces the team (owner and engineer) to prioritize the items that really matter.

Each vendor's bid is evaluated in two columns. The first describes how the vendor performed under the criteria. The second is the score on a scale of 1 to 10 (10 is the best of the contractors for that criteria). The final score for each contractor is the sum of the weights times the individual contractor's rank for all of the criteria. For example, Vendor 1 got 10 (rank) times 15 (weight) or 150 points for the first criteria. The vendor with the highest score wins.

Stage 4: Submittal Review. As mentioned at the beginning, submittal review, construction administration and performance verification are key components of quality assurance for a control project. The items to look for in control submittals include:

- Review of the control hardware;
- Review of the control system drawings, device list and architecture; and
- Review of the control programming prior to installation in the controllers.

The control hardware includes: the controllers; the operator's workstation; control devices like valves and dampers; sensors; transducers; transmitters; gateways (if necessary); lighting panels (if part of the retrofit); and network devices like routers and hubs. Items to look for include thermostat features, (such as display setpoint adjustment and after hours button), sensor accuracy, radiation shields on the OSA sensors, controller

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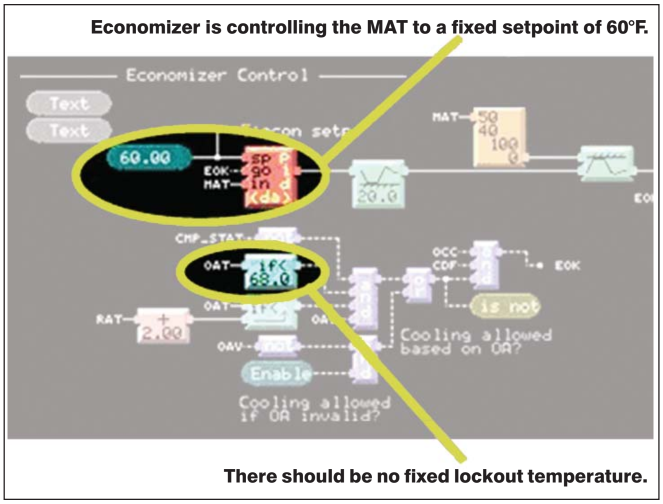

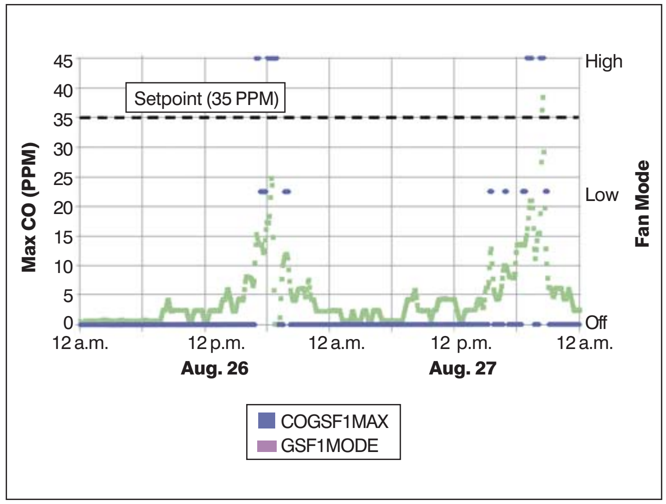

Figure 1 (left): Control programming for air-side economizer. Figure 2 (right): Trend review of garage exhaust fan.

A/D resolution (bits), controller memory and backup power, feedback controls on the actuators, valve CVs, damper blade types and seals and actuator shutoff ratings.

The engineer should spend a fair amount of time reviewing the control drawings, device list and system architecture. Walk through each system to ensure all of the desired points and devices are properly identified. In the panel drawings, ensure each controlled device and signal (such as pump variable speed drive and pressure sensor) are wired to the same controller.

In the system architecture drawing, ensure that a reasonable number of high-level controllers† are provided to limit the number of low-level controllers per communication branch (most systems can address up to 250 controllers, but 100 or less are usually recommended to prevent network overload). This is also the first time to see the point naming convention proposed by the contractor. At minimum, each point needs to be identified by part of the system and the device to which it is tied.

Also, if the DDC system is interlocked with a fire/life safety control system, make sure these interlocks are clearly documented on the drawings. Similarly, the drawings need to show existing pneumatic actuators and devices (like signal selectors) that are tied to the DDC system. All of the information needed to troubleshoot the DDC system must be on a single set of drawings.

Our firm always reviews the control programming before it is installed in the field. In every case where we reviewed the programming, we caught problems or determined a cleaner way to write the code. *Figure 1* shows an example section of code for an air-side economizer on a built-up DX unit. As highlighted on this screen capture, three problems were noted:

1. The economizer was not controlled to the unit discharge supply air temperature (SAT) but the economizer mixed air temperature (MAT). Because of this the economizer could not be sequenced with the compressors as the first stage of cooling (a requirement of ANSI/ASHRAE/IESNA Standard 90.1-2001).

2. The economizer setpoint was to be the reset supply air temperature setpoint for the DX unit. As shown in this figure it was fixed at 60°F (16°C).

3. The economizer high limit control was supposed to compare the return air dry-bulb temperature against the outside air dry-bulb temperature. The block circled caused the economizer to be disabled (at minimum position) whenever the outside air temperature was above 68°F (20°C).

Differences between the control logic and sequences are common due to a number of issues including inexperience of the control technician, inability to understand the sequences as written, failure to read the sequences carefully and the control contractor finding a better way of solving the problem. Reviewing the programming ensures that the logic is properly executed and presents the opportunity of learning new ways of solving the problem. In addition to catching errors in logic, reviewing the programming also allows functional issues to be caught such as setpoints that are hardwired as attributes of programming blocks and, therefore, not easily accessible from the user interface.

Where the contractor uses a graphical programming package such as the one shown in *Figure 1,* some aspects of the program may be hidden from view as they are set as attributes to a control block. Examples include delays on make-or-break. equations in programmable blocks and averaging of an input signal. In general, we ask the contractor to provide a copy of the programming software to facilitate our review of their program.

Stage 5: Construction Administration. During the construction phase of the project, it is important to perform spot checks and limited functional tests. Examples of spot checks include verifying the accuracy of a sensor's reading in the energy management control system (EMCS) using a calibrated reference; checking the gains on the PI loops to make sure that they have been tuned (i.e., they are not all the same); review of the physi-

† Primary or advanced application specific controllers that typically communicate peer to peer on high speed backbones like ARCNET or Ethernet.

Item	Weight	Vendor 1	Rank	Vendor 2	Rank
First Costs (Base Price and Alt. 1, 2, & 3)	15	$XXX. This includes permits and anticipated overtime. They still exclude "premium costs associated with any mandatory overtime effort."	10	$YYY. This also includes permits and anticipated overtime. This does not include the ~$ZZZ for the subrogation clause in the contract.	8
Schedule (Base Price and Alt. 1, 2, & 3)	14	Can complete the work by Dec. 31, 2002 if we start on or about Sept. 9.	10	Can complete the work by Dec. 31, 2002 if we start on or about Sept. 9.	10
First Costs Lighting With Construction in 2004 (Alt. 4)	10	$XXX plus escalation for parts and labor for installation in 2004.	10	$YYY plus escalation for parts and labor. They are renegotiating with their union in June 2003 and are willing to stipulate the labor escalation based on the ratio of present and renegotiated labor rates.	9
Interoperability	1	Not Applicable, Proprietary System	0	Being a BACnet® system allows for third-party lighting controllers to be integrated into the interface. This provides the option to bid in 2004 for competitive pricing.	10
Training	8	Unknown	10	They have courses both in town and at the factory. They will provide PDF course materials for free.	10
Reliability	10	The programming is distributed.	10	The programming is distributed.	10
Service	5	They did not offer any service contracts as they feel that this is unnecessary. They will provide replacement parts at XX% of list price.	5	They provided a long-term service agreement for three years. Parts will be provided at YY% of list price.	7
Future Expansion (e.g., addition of DDC to the Zone Level)	7	Would require addition of an Ethernet backbone and several global controllers.	9	Would require additional global controllers.	10

Table 1: Example of a contractor selection matrix used in scoring competing vendors for a retrofit project.

cal installation for compliance with the specification and codes (e.g., access clearances in front of variable speed drives); and slope and offset for analog points (indicating that they have indeed been calibrated).

Functional tests allow you to test reaction of the control system to events that you might not pick up in the performance review that follows. Important ones include: manually shutting down a controller or piece of equipment and watching the system's response; testing critical alarms by simulating contact closure; pushing the system to extremes of heating or cooling by overriding setpoints; and powering down the system to check its recovery.

Stage 6: Performance Verification. Our specifications call for the contractor to provide two weeks of one-minute trend data on all points (real and virtual) for review by the engineer. To limit our costs we further stipulate that we will only perform one review and that subsequent reviews will be back-billed to the contractor out of their retention. This second clause can generally only be done on private projects where the owner is willing to make this requirement part of the contract.

The purpose of this trend review is to certify that the system is operating as designed. It has been extremely useful in catching a range of performance failures that weren't apparent from the previous stages of review. In addition the act of trending so much data provides a valuable test for the network architecture demonstrating a worst case scenario for network traffic.

Three issues need to be addressed to successfully perform this test:

1. The contactor has to understand what is being asked for up front. It will impact their costs including the network architecture, the time that they need to allot for programming, and the quality of work that they will have to perform. We discuss this aspect of the specification in detail during the pre-bid conference.

2. The data needs to be formatted in a manner that is easy for the engineer to use. Most systems have a range of data formats that are available for storing and exporting trends. These are very system specific.

3. The engineer needs software for managing and analyzing the data. Although standard spreadsheet and database products can be used for this work, it is recommended that engineers use more advanced tools if they plan to do this work regularly. The report by Friedman and Piette[1] provides a comparative review of several commercial and publicly developed products. As an alternative you can use the EMCS software directly to review the trends although typically this will limit you to time series data and may severely limit the number of points that you can view in one graph.

We recommend reviewing using following steps:

1. Review gross statistics on the trended points. At a minimum look at the maximum value, minimum value, average value, number of valid points of data, earliest date and time stamp, and latest date and time stamp. Looking at this data quickly shows if points are fixed (never changing), missing from the trends (either in whole or part) or out of range.

2. Testing each of the control sequences one at a time. *Figures 2* and *3* (described in detail below) present some sample trend reviews.

3. Writing a report that documents any deficiencies and outlines the scope of subsequent trend reviews if required.

Figure 2 depicts an example trend review of a garage exhaust fan. The fan is controlled by a two-speed motor and has a setpoint of 35 ppm of CO. The CO concentration measured is depicted as green dots using the y-axis on the left side of the graph. The speed of the exhaust fan is shown as blue dots using the y-axis on the right side of the graph. The x-axis shows the date and time.

On the two days shown on the graph, the CO levels are well below setpoint until approximately 6 p.m. when employees are leaving the building. On both days the exhaust fan ramps up the first stage (low speed) to limit the CO level to 20 ppm and the second stage (high speed) to limit the CO level to 35 ppm. As seen in this graph the system appears to be operating as designed.

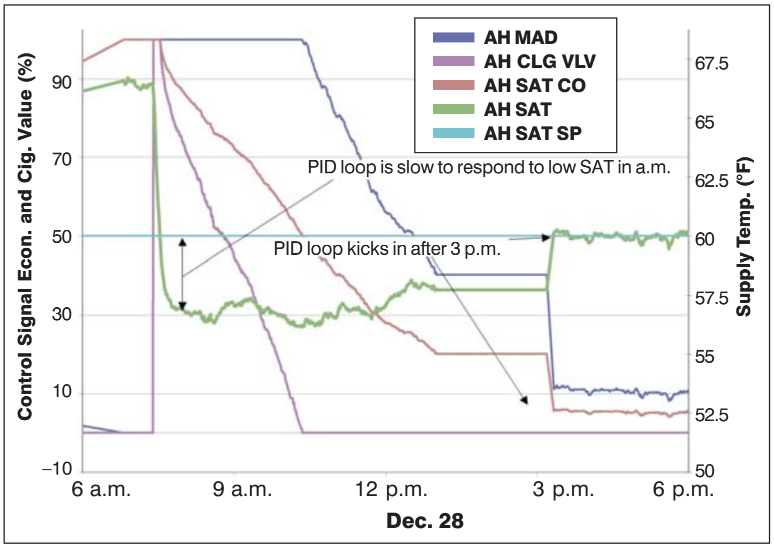

Figure 3: Trend review of air-handling unit cooling loop.

Figure 3 shows the cooling loop of an air-handling unit (AHU) with an air-side economizer and chilled water valve. This graph shows the following points:

- AH MAD: The economizer damper signal (left axis);
- AH CLG VLV: The position of the cooling valve (left axis);
- AH SAT CO: The output of the PI loop that is used to stage the economizer and cooling valve (left axis);
- AH SAT: The supply air temperature leaving the cooling coil (right axis); and
- AH SAT SP (right axis): The control setpoint for the AHU supply air temperature.

As shown in this figure, the PI loop is slow to respond to the fact that the actual leaving supply air temperature is well below the setpoint. For most of the day, the supply air temperature is ~ 3°F (~1.7°C) below the setpoint of 60°F (16°C). At about 3 p.m. it appears to regain control. This was fixed by adjusting the tuning parameters of the PI loop. Between 1 p.m. and 3 p.m., data was lost in the trend reviews. In reality, it can be inferred that the signals smoothly ramp down between the 1 p.m. and 3 p.m. readings.

Lessons Learned

The DDC retrofit process discussed here is somewhat burdensome and will cost more in engineering and contractor fees than more traditional processes. However, it has some concrete benefits in terms of long-term operating costs and performance. If the contractor understands the process upfront, they spend more time making the system perform as designed and they usually have one of their best technicians on the job. If they don't, the project can go through many rounds of performance review that will impact the contractor's profit.

In our experience, contractors rise to the challenge and provide high quality systems if provided with the incentives to do so. Furthermore, most contractors appreciate the time we have spent reviewing their work before it is installed in the field. Mistakes we find protect them from expensive troubleshooting and reprogramming later.

It is important to keep the atmosphere collaborative and not combative. Focusing on the owner's need for a timely system that works and the contractor's need to make money and keep the owner happy will lead to a happy conclusion for all.

Author's Note

This article describes one firm's perspective on a process to successfully upgrade an existing control system with state-of-the-art DDC. The design-build process described here has been tested and proven to work, but it is by no means the only way to design and implement a successful controls upgrade. Although the process described here is for a retrofit project, many of the techniques and issues also apply to new construction.

This article is a summary of the material presented in ASHRAE Learning Institute's professional development seminar on Direct Digital Control Retrofits: From Project Planning Through Performance Verification. The author, Mark Hydeman, is coauthor of this seminar.

References

1. Friedman, H. and M.A. Piette. 2001. *Comparative Guide to Emerging Diagnostic Tools for Large Commercial HVAC Systems*. LBNL No. 48629, Lawrence Berkeley National Laboratory, www.peci.org/papers/diagtools.pdf.

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