Commissioning Digital Control Systems for HVAC

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In the ten years since the introduction of DDC systems, the industry has experienced at least 3 generations of this equipment from each of the major manufacturers. Engineering of a state-of-the-art DDC system has become more of an effort at database and application software development than ever before and will require more effort on the part of HVAC design engineers to define points types and logical states. Due to widespread acceptance of these systems, owner's expectations have greatly increased. It is no longer acceptable to only provide air conditioning but rather total environmental control. Therefore at the installer end it is necessary to ensure the peak operation of the system and this is best accomplished through proper calibration and commissioning.

Field experience in the commissioning of both industrial and commercial control systems has pointed to the same needs in both ends of the spectrum. Excellent engineering documentation from the start of the project yields the best results at the end of the project. The controls installers have transaudient from mechanics to software developers with little understanding of the dynamics of increasingly complex HVAC systems. This points out the need for better documentation from the design engineer that conveys the controls intent in language that computer programmers understand.

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INTRODUCTION

This paper is the case study of the commissioning activities for a museum space located in Atlanta Georgia. The lessons learned at this facility can be applied to most facilities with Direct Digital Control Systems (DDC) with regard to how they should be commissioned and particularly to facilities with stringent environmental control requirements. This is particularly true for large central equipment such as chillers and built-up fan systems that consume large amounts of energy or places where environmental control parameters are stringent. The proper configuration of a DDC system can have tremendous impact on building energy usage.

The facility is a three-story structure located at a major university in Atlanta. The facility in this case study is an addition to the existing museum structure which was completed in 1993. The campus-wide DDC system was expanded to include this building and addition on the network. The museum is for Art and Archaeology and contains artifacts from Ancient America to Ancient Egypt, including mummies. The temperature and humidity criteria were given as follows: 72° F ± 2° F and 50% RH ± 5%. These tolerances were not to be spanned in 24 hours. In other words, if the humidity drifted 5% this could not occur in fewer than 24 hours. The owners' complaints of an unstable environment occurred from the outset. Wide fluctuations in both temperature and humidity, appearing at times not to follow the expected behavior of psychrometric principles, were recorded to be the case in almost all spaces. With irreplaceable artifacts in the space, the environmental extremes were intolerable.

The control strategy was conceived to control humidity and temperature but to save energy by avoiding reheat unless absolutely necessary. The selected units were single-zone variable air volume fan systems with steam reheat. The space temperature would modulate the fan volume by inlet vane control down to the minimum air flow before bringing on a modulating steam coil, thereby achieving dehumidification control without the energy penalty of an excessive amount of reheat. Room humidity would reset the cooling coil leaving air temperature downward to a low limit of 50° F if the humidity exceeded 50% RH and modulate a steam humidifier if room humidity drifted below 50% RH.

The initial commissioning methodology was basically a verification that all the control points were addressed correctly back to the controller. Temperature and humidity indications in the DDC system were compared to hand-held devices and checked for accuracy. This commissioning protocol is common for commercial facilities and is probably the most widely used method. As the problems persisted, a more rigorous methodology was implemented that was more documentation driven, in addition to being more functionally driven.

INDUSTRIAL PRACTICES IN COMMERCIAL FACILITIES

Industrial applications of control systems for critical areas such as clean room manufacturing or pharmaceutical process air systems, the check of the control system takes on a more methodical approach but causes problems to surface at the appropriate time to be solved. As a minimum critical transmitters and elements are calibrated on a bench against a standard traceable to the National Institute for Standards and Technology (NIST). Customary practice is for all transmitters and elements associated with critcal *systems* to be bench calibrated against NIST standards. This will cause calibration errors to surface prior to installation in the physical system.

After the control system cabling is terminated and the system is powered, a point-to-point check is made to ensure correct addressing and also to check for correct ranging and characterization. This is called loop shooting. A traceable instrument is used at the location of the sensor in the field and is put in place of the element or transmitter. In the case of an RTD temperature sensor a decade box is wired in place of the element. The decade box is dialed to settings that correspond to the low and high ends of the span as well as the center point in order to check linearity. If the control system is looking for a 0° F to 100° F element and a 20° F to 120° F element is in the field this problem will surface prior to start-up of the mechanical equipment. Quite often in commercial applications this step is omitted due to press of time and the installing technicians move on to loop tuning. It is impossible to tune a control loop where the sensors are improperly ranged or addressed. Many times a building experiences inexplicable problems only to find the problem is traceable to these root causes.

After the loop shooting is complete then loop tuning and a qualification of the operational system can take place. All the major manufacturers of both commercial and industrial control systems have published procedures on how to accomplish loop tuning with their systems. Many also have personal computer based software that can accomplish this task by manually bumping the system to determine the time response of the loop and suggest tuning constants to be downloaded to the controllers. All critical spaces should have trends setup and recorded to determine the behavior of the system over time.

OWNER COMPLAINTS OF UNSTABLE CONTROL OF ENVIRONMENT

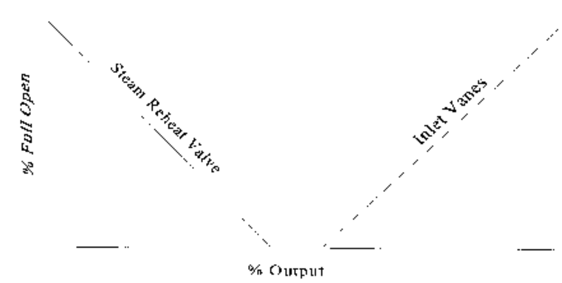
The owner placed several Hygrothermographs (chart recorders) in the space to make recordings of the temperature and humidity over a week long period of time. Figure 1. shows a sample of recordings from some of the worst areas during some of the most extreme weather. Several obvious solutions were arrived at during the course of the commissioning of the facility such as sealing the exterior of the building and closing smoke dampers at the top of the elevator hoist ways, but all these apparent solutions did not stand the test of time and only seemed to provide limited effect. Humidifiers running during the summer months, inability to dehumidify or humidify as needed and sudden temperature excursions to the warm side were persistent problems.

CONTROL STRATEGIES

The space temperature control scheme in graphical form is found in Figure 2.

Figure 1.

Figure 2.



The original control scheme called for the fan volume control signal to come from the room sensor and the cooling coil discharge temperature to be reset according to the room relative humidity. If the room temperature is too cold and the fan inlet vanes are shut, then the steam reheat coil will modulate to maintain the space condition. For humidification, the steam humidifier would modulate open if the space humidity dropped below 50% RH.

At first it was thought that humidity control with variable air volume was the cause of the instability. The sequence appeared difficult to tune since so many parameters were changing. The cooling coil loop was tuned at full air flow while the reheat coil loop was tuned at minimum air flow. The owner's maintenance personnel pointed this out and suggested that the fan inlet vane control be fixed at full air flow. However this was not an option due to the fact that the reheat coil capacity was sized for fan minimum flow and the small steam coil did not have the capacity to overcome the full capacity of the cooling coil in the dehumidifying mode. Adding to the problems was poor air distribution. Bar type grilles discharging from the ceiling straight downward offer little Coanda effect and in some cases were blowing directly on the space temperature sensors.

The owner's maintenance personnel under duress to solve the problems suggested that the proper operation should be to change the fan volume control point from the space to the return air temperature and the humidity control point from the space to the return air humidity. The theory was that the return air stream would represent a mixed room air condition and give a better indication of actual space conditions.

The return air on the top floor and was observed to pick up as much as 9° F of temperature rise due to conduction during the summer months between the room and the air handling unit as it traveled through the attic ductwork without insulation. The relative humidity sensor in the return duct reported a drop in relative humidity due to the temperature rise and would attempt to modulate open the humidifier control valve in the summer time. The supply duct relative humidity high limit set at 95% RH would shut the humidifier valve after a short time and the cycle would begin all over again. This is an obvious energy waste -attempting to humidify in the summer months in addition to inducing additional control instability.

These changes were made under duress to ''do something.'' Too many times the sequence of operation is modified in response to an observed problem since it is assumed that all of the instruments are calibrated at the factory therefore not requiring anything further than installation and wiring back to the appropriate panel. Anytime multiple entities are competing for control in a software development project there is the question ''who is in control'' and the control system reflects this ambiguity. To make matters worse the owner's maintenance staff was responsible for advocating and making the changes to the software in response to the user's complaints. Two lessons are learned here:

(1) One entity needs to remain in control of the commissioning effort and that person needs to make a comprehensive commissioning plan that all parties adhere to.

(2) Clear communication of the control strategy and a complete transfer of information to all interested parties is required.

The owner's maintenance personnel did not fully understand the system and assumed the responsibility of making changes prematurely. Oftentimes changes were made from the existing host computer over the campus network while the commissioning team was at the site working on the problems.

COMMISSIONING METHODOLOGY

It was decided to recommission the building after approximately two years of out-of-limit temperature and humidity were experienced by the facility. The plan was to take a fresh approach and commission the control system from the ground up. After two years had passed, the user had not accepted the building and tension was experienced by the team members. The design engineer was maintaining that they were not at fault and it must be the installation causing the problems. The contractor was pointing to design deficiencies and interference from the owner's staff. The owner was withholding retainage from both the contractor and engineer since the user had not accepted the building.

The approach to recommission the system was aimed at recertifying the control system in order to gain confidence in the system and remove that variable. As mentioned previously, proper control system commissioning is a two-step process:

(1) Calibrate each sensor against a known standard.

(2) Check the throughput of the system by using traceable instrumentation.

The first step is normally undertaken on a bench, but due to the fact that the system was already installed and functioning it was decided to calibrate a hand-held device and compare that to the element reading. The same hand-held temperature sensor that was used during the initial commissioning effort two years previous was placed in an ice bath and calibrated to 32° F. It was found to be nearly three degrees out of calibration and now the root of the problem was starting to surface.

The throughput checking activity used two devices: a decade box and a loop calibrator with a 4-20mA simulator. The decade box was accurate to as much as 0.2% with the loop calibrator accuracy to within 0.03% of full scale. The decade box is used to simulate the input to the system from an RTD temperature element. For example, a 100Ω platinum RTD would have a 100Ω resistance at 75° F. At 20° F it would have a resistance of 92Ω and at 120° F it would have a resistance 118Ω. A mix of 100Ω and 1000 Ω element were installed. When the elements were disconnected from the system and the decade box placed in line and set to the appropriate values, all of the points tested reported from 1° F to 3° F from standard. The 100Ω elements used ‘‘factory calibrated’’ transmitters in a current loop and the 1000Ω elements were wired straight to the control panels as a voltage loop. In the case of the 1000Ω elements the offset was attributed to wiring resistance of 1Ω to 3Ω between the element and the control panel where the resistance is measured by virtue of voltage drop. If the decade box resistance was changed by as little as 2Ω, the corresponding temperature would change by between 2° F and 3° F. Therefore if the resistance of the wiring and terminations between the element and control panel was as much as 2Ω, the point would be off by as much as 3° F. This was a major contributor to the system’s inability to effectively achieve dehumidification. The sequence called for a low limit for the cooling coil leaving air temperature of 50° F which will be able to dehumidify if the space is to be 72° F and 50% RH (dewpoint of 52.5° F). The control system was controlling to 50° F but, due to the temperature sensors being out of calibration, the coil discharge temperature was 53° F and therefore the space was never able to dehumidify properly.

The calibration of the humidity sensors was also a problem. The loop calibrator has a setting that will display the percentage of 4-20mA. For example if the humidity sensor is showing 50% RH, the loop current should be 12mA (½ of the span $+$ the zero or $8+4=12$). The loop calibrator will show 50% at 12mA, 25% at 8mA, 75% at 16mA and so forth. The humidity sensors were calibrated to a sling psychrometer and the zero and span adjusted to show the same percentage of loop current on the loop calibrator as determined by the sling psychrometer. The most notable aspect of all the humidity sensors was the inability to hold calibration for more than 24 hours. All of the sensors were the standard product of the manufacturer of the control system. There are several manufacturers of space humidity sensors that will guarantee the stability of their products over time. This is a major contributor to the inability to hold space conditions long-term.

The selection of instrumentation is critical to an installation where long-term stability and tight control is paramount. In a situation where the control system is competitively bid it is the responsibility of the design engineer to specify the performance characteristics of the instrumentation. For this facility the design engineer merely specified a tolerance of ± 5% RH for humidity sensors as an example. The instrument installed would hold ± 5% for several hours. Many of the sensors selected by the control vendor had very wide ranges. Some temperature sensors had ranges as much as −40° F to 240° F and attempting to control a space to ± 2° F (0.7% of span) is impossible.

The industrial model is for the actual make and model number of the instrument is specified by the design engineer and include this information as part of a functional specification. The commercial model is to use a performance specification typically used for a wide range of facilities (office buildings, hotels, etc.). The difference between performance specifications and functional specifications is the level of detail and direction given to the control system vendor/installer. As an example a functional specification will include information for how graphic screens will be constructed and what colors will be used for each process and change of logic state. Functional specifications will also include direction for the structuring of software such as partitioning of controllers. An example of controller partitioning that can be applied to commercial applications is to require that the supply air temperature loop only use lines 1000 to 1999 and the humidity control loop only use lines 2000 to 2999 in a particular panel. This allows for modifications to software to occur without requiring renumbering of the code. A benefit of controller partitioning in industrial applications is to control the order in which controllers are scanned by the CPU—not typically necessary in commercial applications.

Many engineers believe that since digital control is ‘‘precise’’ that the controllers can do almost anything. If the controller has 12 bit resolution for the analog to digital convertor that means that the 4-20mA signal will be converted to a number between 0 and 4095 ($2^{12}-1$). A change of 0.7% of span is a change of approximately 28 ‘‘ticks’’ (4095×0.007). A ‘‘tick’’ is defined as a change of a digital register by one count (i.e. 111111111111 to 111111111110). This represents the full tolerance of the space condition. A control action must take place well before the space reaches the extreme of the specified tolerance. If the controller is set up to take initial control action such as move an inlet vane damper slightly over 15% of the room tolerance (i.e. space condition of 72.3° F versus setpoint of 72° F) then the system will be required to take action after approximately 4 ticks. The input can easily bounce 4 ticks without a true change of room condition during a brief sample period of just a few seconds. If the sensor span used is narrower for example 40° F to 90° F then the analog to digital convertor tolerance for ±2° F is 164 ticks and the 15% change threshold becomes 25 ticks for a resolution increase of over 6 fold. It was argued by the control system installer that the controller will ‘‘settle out’’ at the setpoint. The previous discussion about the number of ticks for control action threshold and input noise or bounce demonstrates that digital controllers settling out only has an opportunity to occur if the load *never* changes. Reality is that lights turn on and off and museum occupancies fluctuate during the day as tour groups come through. The only way to make the controls appear stable is to decrease the authority or gain of the controller. This will change the previous 15% change threshold to 195% to achieve the same performance with a small span sensor and positioner. Therefore the 0.3° F change is now a 3.9° F change to achieve a response from the control system. This will cause the vane actuator to experience a longer period of time without movement (stability of the output) but the space will experience wide swings in temperature over longer periods of time.

If the controller is modulating an inlet vane damper with a 3—8 psi spring actuator with a sensor span of 280° F and range of 5 lb is 5/280 or 0.018 (1.8%). This means that the valve will go from full open to full closed over 1.8% of the input range of 280° F. This is not good control resolution for a space that must be maintained at $\pm$ 2° F. If a positioner is used on the actuator and the input signal to the positioner from the control system is 3-15 psi to achieve the 3–8 psi valve range then full open to full closed range is (15psi–3psi)/(90° F—40° F) or 24% of the input span. Now the control resolution has increased over 13 fold (24%/1.8%) from the original selection by coupling the actuator positioner with the 40° F to 90° F space sensor.

The output characterization is just as important as the input range of the sensors. For the 3–8 psi range example given previously, it was found by reviewing the software that all outputs were ranged from 0–20 psi. The reason for this was to assure full open or full closure at the extreme ends of the range. The DDC system will work in terms of percentage outputs. In this example, if the controller is placing an output at 25%, then 5 psi will be output to the valve. If the spring range is 3–8 psi then the valve will be 40% open. The controller must sense sufficient offset from the setpoint for a sufficient amount of time (integral term) before another correction is made. When faced with unstable control, technicians will usually try to ‘‘slow down’’ a loop by decreasing the authority of the controller. This will only exaggerate the problem if the outputs are not properly characterized. This results in a much wider drift in space conditions over a longer period of time.

Valves cannot be properly characterized by placing the cataloged spring range in the software. The valve must be placed at a given percentage open manually from the control system using either a lap top computer or preferably the front end. The stem travel is then observed physically in the field with the system pumps running. Usually the percentages are 0%, 10%, 50%, 90% and 100%. The reason for the 10% and 90% is to make sure that the valve will ‘‘bump’’ with a small change in output off of the fully closed or fully open condition. Many times the valve’s final calibration with the system pumps running will be very different from the cataloged spring rating. One such chilled water valve was cataloged at 9–13 psi and the final calibration came in at 5–14 psi. This is common industrial practice and is performed during the loop shooting phase of the commissioning.

REPORT ORGANIZATION

The field methods and protocols are important to the overall commissioning effort. However, no job is complete until the paper work is through. This is where the database is indispensable. All of the physical Input/Output (I/O) points were placed in a Microsoft Foxpro database. There are several XBase database applications available on the commercial market such as dBASE V and Foxpro. An XBASE application is chosen since the software can relate multiple tables as well as provide powerful programming capability in a DOS or Windows environment. As an example the characteristics of the instrumentation are stored in a table where there is a record for each unique model number. Another table or file contains the point names and addresses where a particular sensor is used multiple times. Through programming the instrument characteristics can be downloaded from the instrument table or file to the point definition table related through the model numbers. In this manner characteristics of each sensor and controlled device were input and commissioning forms preprinted prior to the field checkout of the installed system. After the data were gathered, the field readings were placed in the database and a correction report generated. The database can also be used as an ongoing maintenance tool for the life of the building whereby problem areas can be diagnosed by comparing the present loop readings to the previously recorded values and either eliminating or confirming calibration as a source of the trouble. An example of the report is found in Figure 3.

This is an excerpt from the final report given to the owner. The reading taken in December 1994 was off by approximately 0.5° F but the error was nearly twice the allowable error of 0.055%. The database is an excellent tool for reporting deficiencies and storing historical data for later retrieval.

CONCLUSIONS

Since so many problems are traceable to the misapplication of instruments, it is the responsibility of the design engineer to specify the quality of the devices, just as the quality of the chillers and air handling units are specified. It is not enough to say that all temperature sensors will be accurate to $\pm$0.25° F without a commensurate specification on the range of input and stability over time. The concepts of con-

Figure 3.

Point Name	Description	System		Manufacturers Tolerance		Electronics Tolerance		Initial Reading Dec 94	Final Reading Jan 96	
								Reading At Mid-Point of Span		
RAC-1T	ZONE 1 TEMP	AHU-01					Expected Value	76.61	76.81	DEG F
			±	0.0025	±	0.0030	Measured Value	80.63	75.90	DEG F
							Initial Error	-0.0074	0.0001	
			Allowable Error		±	0.0055	Adjusted Error	0.0104	0.0031	

The **Point Name** is the name given to the I/O point in the control system

The **Description** is the point function

The **System** is the air handling unit associated with that point

The **Manufacturer's Tolerance** is the tolerance or accuracy of the device stated by the manufacturer expressed as a percentage of the range.

The **Electronics Tolerance** is the tolerance of the control panel ability to sense a signal.

The **Expected Value** is the value expected to be displayed by the system when a given resistance is applied at the sensor location.

The **Measured Value** is the value actually recorded by the system when the resistance was applied.

The **Initial Error** is the error that is the difference between the Measured and Expected Value divided by the range of the sensor.

The **Adjusted Error** is the value arrived at by adding the electronics tolerance to the absolute value of the initial error.

The **Allowable Error** is the value of the sum of the manufacturer's tolerance and the system tolerance. The point is considered to be in proper throughput calibration if the adjusted error is within the allowable error.

trollability and resolution of control are too often not understood. The use of standard performance-based specifications, which in theory can be applied to facilities as diverse as office buildings to clean rooms with minor editing, has created many of these problems. If a control company is savvy enough to realize the issues and the requirements at hand and puts the required devices in the proposal that can produce tight control, they will lose the bid to the company that does not recognize the application and blindly follows the project specifications. The result is a failed project. In Georgia it is required for engineers to practice in their areas of expertise. For industrial process control this requirement is routinely enforced. However in the commercial market the systems usually do not customarily involve explosion hazards and other potential life threatening situations and the enforcement of the requirement for ''expertise'' is not viewed as an absolute necessity.

It is equally important for the contractor to be in charge of the commissioning effort and present an organized approach that all parties buy-in. In this fashion, when things do not go as planned, there is a clear line of responsibility for the final product without undue influence on the outcome. It is impossible to diagnose a control problem if more than one thing is changed at a time. With multiple parties in the mix this will happen.

Controls commissioning has become a key industry issue. Control systems have become increasingly complex in the commercial arena and more susceptible than ever to program errors, misapplication of devices, interface with other subsystems, design errors, system effects and operator errors. If the time is not taken to properly commission these systems the system will not have the robustness to survive more than a few months in this ''harsh'' environment. Commissioning responsibility needs to include a check of the software, hardware, location of devices and panels, HVAC systems design and control strategy, preparation of documentation and training of the users. This requires commissioning to start during the design phase of the project. Commissioning is best done by either the design engineer if he is qualified and understands how the system is to function or the installing contractor with the same caveats. If a project is competitively bid and the contractor is responsible for the commissioning, then commissioning must start during the submittal/shop drawing phase of the project.

The database is the key component to organizing the approach and keeping records throughout the commissioning process as well as diagnosing the problems that arise. The database can also transition to an effective maintenance tool for the life of the facility.