Applying Artificial Intelligence to Modern Building Controls

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Synopsis

Computer based building control systems have the potential to do much more than monitor, control and gather data. The addition of some well placed sensors and custom software can raise a system's "IQ". Intelligent controls can keep Owners apprised of the real time health of equipment components. System owners who are more informed with real time knowledge are able to make more pragmatic and proactive maintenance and operating decisions.

This paper describes an innovative, proven concept that enhances the usefulness of existing DDC and PLC-based controls. Intelligent, knowledge based control systems help insure that systems consistently operate at design conditions. The payout comes by improving performance and reducing energy, maintenance and operating costs.

About the Author

Mike Birchak is a registered professional engineer in Ohio, Kentucky and Michigan and is listed with the NCEES national registry. A graduate of Carnegie Mellon University (MS in Mechanical Engineering), Mr. Birchak worked for the Procter & Gamble Company for 10 years prior to entering private practice. He started The Industrial Solutions Group (ISG) in 1987. ISG has an international practice – having become recognized as a leader in the development of innovative energy, productivity and reliability improvement ideas for industry. Mr. Birchak is a member of NSPE, ASHRAE and AFE. He has served as President of the Engineers' Foundation of Ohio (EFO) and as director of the OSPE.

Current Control Systems Aren't 'Green' Enough

Operating at Design?

The concept presented in this paper started with a simple observation. Utility and HVAC systems rarely operate as designed. It's not what one would expect when you consider how many systems there are, how long the basic technologies have been around, and how many resources are applied to delivering quality systems. Owners often commit millions of dollars to make tenants comfortable. Engineers then spend countless hours evaluating applications, developing concepts, and designing components that are as cost effective as possible. Then, quality construction and start-up teams build the system and make it operational. All these efforts are checked and adjusted – often through independent commissioning efforts. Despite all of these efforts and resources, a year or two after turnover, we frequently find that the performance has slipped – energy costs are higher than expected and various temperatures and humidities are out of limits.

It's not just a perception. More than ever before, we know it happens. We can, and do, measure it. Modern control systems faithfully tabulate, record and document the performance changes on a minute by minute basis. CD's and hard drives fill up with data. Yet, systems just don't 'stay commissioned' forever. Retro-commissioning is a noble attempt by our industry to return buildings to 'green' design conditions. But, does retro-commissioning provide any assurance that the performance won't begin backsliding soon after the report is accepted?

Poor Assumptions -- Adequate Owner Ability and Resources?

So, what's going on here? More importantly, what can be done about it?

Our experience indicates that this 'spiral of underperformance' is enabled by a couple of poor assumptions that most delivery team members bring to the project. In a nutshell, designers overestimate the ability and availability of the Owner's resources. Through the course of dozens (or hundreds) of projects, engineers become expert in the systems they design. Just as a professional ball player is often not a good instructor for the beginning player, engineers often overlook the difficult realities building owners face when striving for peak building performance with limited resources.

Owners readily admit to limited staffing – both in number and capability. Gone are the days (if indeed they ever existed) when a skilled technician could dedicate significant time to resolving a persistent problem. Rather, there's always an urgency to resolve the problem at hand. It's very difficult even for the most capable of organizations to avoid the tendency to go into a fire fighting/jury rigging mode at times. The result is as predictable as it is inevitable: performance declines.

Clearly, commissioning and retro-commissioning are important services that are part of the answer. The key question is: can we do more? The answer is: Yes. We can do two things. First, we can be realistic and understand that the Owner's team is unlikely to be staffed with full-time engineers focusing all their attention on keeping systems at design conditions. Second, we can step up our game with intelligent control systems that make it easier for System Owners to do the right thing.

Hardware Development -- Ahead of Software Development

The State of Hardware Development

Hardware continues to give designers more options. Hardware is more powerful, faster and less costly each year. Virtually all building mechanical systems are now installed with electronic controls and building management systems. Central DDC or PLC systems make sense for even the smallest of systems. And, the continually decreasing cost and increasing capability of workstations, hard-drives, etc. has dramatically reduced the cost of collecting and storing data over long periods of time.

The State of Software Development

Software has also improved by leaps and bounds. Low cost technician interfaces and data tracking software is cost effective and readily available. Products that track, graph, record and store data abound. So, where's the opportunity?

Well – existing software products fall short in an important way. Today's Data Acquisition Systems (DAS) do an excellent job of gathering and tracking 'data'. They don't, however, do as well at providing the Owner with advance 'knowledge' that components or subsystems are not performing at design. In many cases, DAS provide much of the data needed to solve a problem. Unfortunately, virtually all systems have an important data point or two missing that is needed to fully identify and diagnose a problem. Most control systems often simply automate the same kind of data that System Owners manually collected 20 years ago on their 'rounds sheets'.

Adding Intelligent Control

Today's technology allows us to do better. With some careful thought and reasonable investment, it's now possible to go beyond 'data collection and presentation' to 'knowledge gathering and notification'. The easiest way to define what is meant by intelligent control is to provide some examples. Below, are some critical operating questions that a typical System Owner would currently find difficult to answer.

'Gas Mileage' Checks

Most diligent car owners check their 'gas mileage' every time they fill up. A variety of potential problems can initially show up as poor gas mileage: dirty air filter, fouled spark plugs, poor driving habits, low tire inflation and any number of engine problems.

If gas mileage slips – you are now 'alert' to the fact that some additional maintenance may be in order. If you fail to act, you'll continue to spend more on fuel. Even worse, you know a lurking problem will likely become more severe and eventually strand you on the side of the road. Below are similar 'gas mileage' questions the typical HVAC and utility System Owner should be empowered to easily answer:

- At the current loading and outside air conditions, is my chiller efficiency (kW/Ton) matching design?
- Are my pumps currently operating at design efficiency?
- Are the heat transfer coefficients of each of my coils meeting design parameters?
- Are the chiller evaporator(s) and condenser(s) meeting design?

The above list isn't comprehensive. There are many additional important questions. The point is, if such basic checks are important for a $20,000 car, doesn't it make sense to have such answers for a million dollar HVAC system at the Owner's fingertips?

Operational/Reliability Checks

In addition to 'gas mileage' checks, there are a number of operational checks that are not currently readily available to system owners. Examples include:

- Are critical instruments (temperature, pressure, etc.) properly calibrated?
- Are air dampers bringing in the right amount of outside air?
- Are the variable speed drives operating at the proper speeds?
- Are pumps operating on their 'curves'?
- Is this bypass valve or damper 'leaking' through?

If a System Owner were notified in real time of any variances with design – corrective action could be taken before the system strays far from design.

System Requirements

Knowing Where You Are

Some 'homework' is needed before embarking on the tasks required to raise the "IQ" of your existing control system. You need to start by determining the baseline from which to proceed. This means assembling some (hopefully existing) documentation, including: Process and Instrumentation Diagrams, System Network Architecture Drawings, and Mechanical and Control Systems Specifications.

Knowing Where You Want to Go

Intelligence costs money, but ignorance costs more. There is a point of diminishing returns, however. After understanding the baseline, some technical and financial analysis must be conducted to optimize the path forward to Intelligent Control. Do you want to

comprehensively upgrade the control system or incrementally convert selected sub-systems? If so, which sub-systems? The investment in intelligent control may not payout quickly enough on very small equipment.
Some Intelligent Control system organizational and interface decisions are also needed:

- Should the new data be integrally displayed with existing operator interface screens or should a separate set of screens be developed?
- How will Intelligent Control alerts be generated and communicated?
- How will the new data be organized for storage and retrieval?
- What types of trending and graphs are desired?

The development of a Functional Specification answers such questions. It defines where you want to go and provides a concise document to guide you there.

Hardware Requirements

The building's existing central control system is an important building block of an Intelligent Control system. Even so, two types of additional hardware may be required: 1) field instrumentation, and 2) HMI (Human Machine Interface). Many systems already have a robust HMI and additional investment is not required. Most systems, however, are a little short on instrumentation.

Adding intelligence requires on-line access to all key data. Existing systems may have 80 to 90% of the information needed. The remaining 10 to 20% will also need to be collected electronically. For example, many systems have manual pressure or temperature gauges to help System Owners understand how components are operating. These would need to be replaced/supplemented with electronic pressure and temperature indicator transmitters. Another common data weakness is the lack of electronic watt (or at least amp) meters on major motors. The adequacy of input-output (I-O) capabilities must also be assured. Verified P&ID's, design specifications and field investigation are very helpful in identifying such 'blind' spots.

Packaged Software Requirements

Any number of Supervisory Control and Data Acquisition (SCADA) software systems are available to provide the computing power and user friendly interface required for intelligent control. Some are friendlier than others, but all will require some custom programming to provide the System Owner as much assistance as possible.

Custom Software Requirements

The 'intelligence' derives from mathematical algorithms that describe the operation of each component or subsystem. These algorithms use operating data to project 'expected' results. 'Expected' results are then compared to 'actual'. If the difference between 'expected' and 'actual' exceeds limits, the intelligent control system 'alerts' the Owner that the system has strayed from design. Custom software is required to translate the algorithms for each component to use on-line data.

A Case Study

System Overview

The Intelligent Controls concept was recently applied to a process utility. While we can't discuss the specifics of the project due to client confidentiality, this was a fairly complex process utility system consisting of several pumps, heat exchangers and a high horsepower, medium voltage (4160V) compressor controlled with variable inlet vanes.

The operation is automated through the use of Allen-Bradley PLC's and RSView operating software. Technicians are able to operate the system on-site via local HMI. They are also able to monitor the system remotely via Internet. The control system also includes a dialer to automatically notify the "ON CALL" technician of any alarms that need to be investigated.

Algorithms

Pumps

This system has several centrifugal pumps that are process critical. Each pump has a characteristic curve which defines its flow and horsepower in terms of differential head. A sample is shown in Figure 1.

Design engineers specify pumps to operate at a particular point on the curve, as shown in Figure 1's 'Acceptable Operating Range' window. A curve fitting technique was used to write an equation for each pump's curve. Then, by measuring: 1) fluid flow through the pump, 2) amperage, 3) suction pressure, and 4) discharge pressure; the actual brake horsepower, actual total differential head and actual efficiency are calculated. Logic checks use this information to determine if the actual flow, amperage, total differential head, efficiency and brake horsepower are within acceptable design variation. If not, an 'alert' is shown on the operating screen.

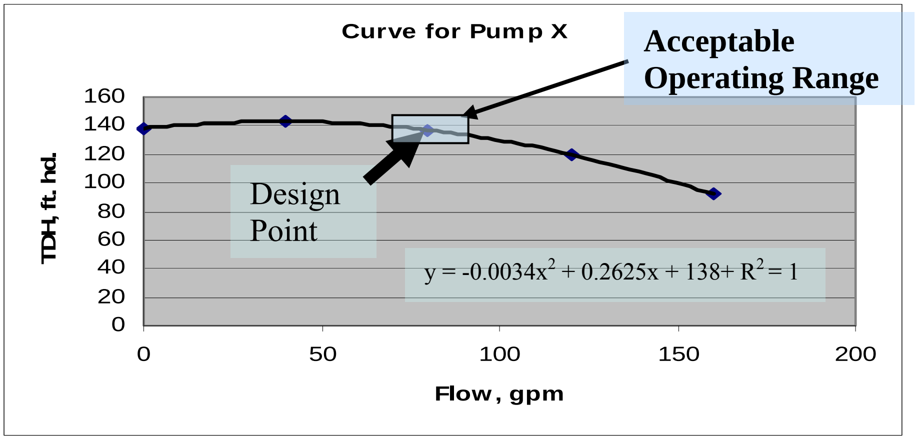


Figure 1: Sample Pump Curve

Heat Exchanger

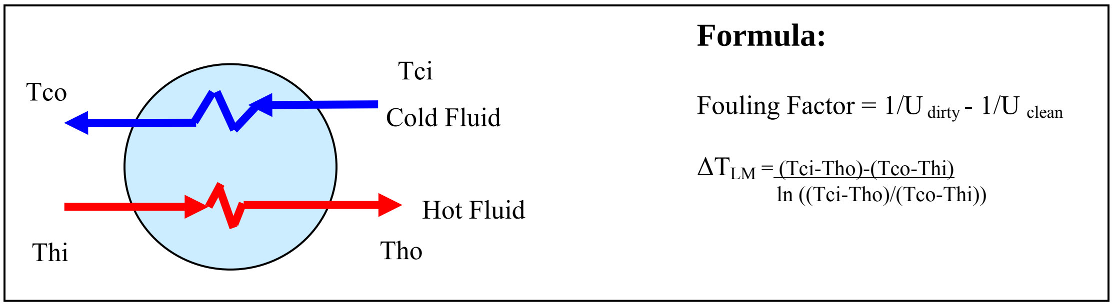
As with all HVAC and utility systems, heat exchangers play a critical role in the proper operation of the case study project. The defining relationship for a heat exchanger/coil is provided by the following equation:

$$Q = U*A* \Delta T_{LM}$$

Where:

Q is the total heat transferred, BTUH
U is the Overall Heat Transfer Coefficient, BTU/(hr*ft^2*°F)
A is the heat transfer area, ft^2
ΔT_{LM} is the Log Mean Temperature Difference (see Figure 2), °F

Also, the overall energy balance must hold. The heat lost by the warm fluid must equal the heat gained by the cold fluid.



Formula:

Fouling Factor = $1/U_{\text{dirty}} - 1/U_{\text{clean}}$

$$\Delta T_{LM} = \frac{(Tci-Tho)-(Tco-Thi)}{\ln((Tci-Tho)/(Tco-Thi))}$$

Figure 2: Algorithm for Log Mean Temperature Difference

The data collected for the key heat exchangers include: 1) hot and cold fluid flows, 2) temperatures in and out, and 3) pressures in and out. This actual data is then used to calculate the heat gained by the cold fluid, the heat lost by the hot fluid, the log mean temperature difference, and the fouling factor.

Logic checks then determine if the heat exchanger is functioning properly, instruments are properly calibrated, etc. These logic checks use flows, temperature and pressure differences, heat exchanger effectiveness, energy balances and the fouling factor.

Compressor

Similarly to the pumps, compressor performance is also defined by a characteristic curve. The compressor algorithm is complicated, however, by its variable inlet vane control. This requires the modeling of multiple curves at various inlet curve positions as shown in Figure 3. This family of curves allows expected performance to be established by interpolating between curves.

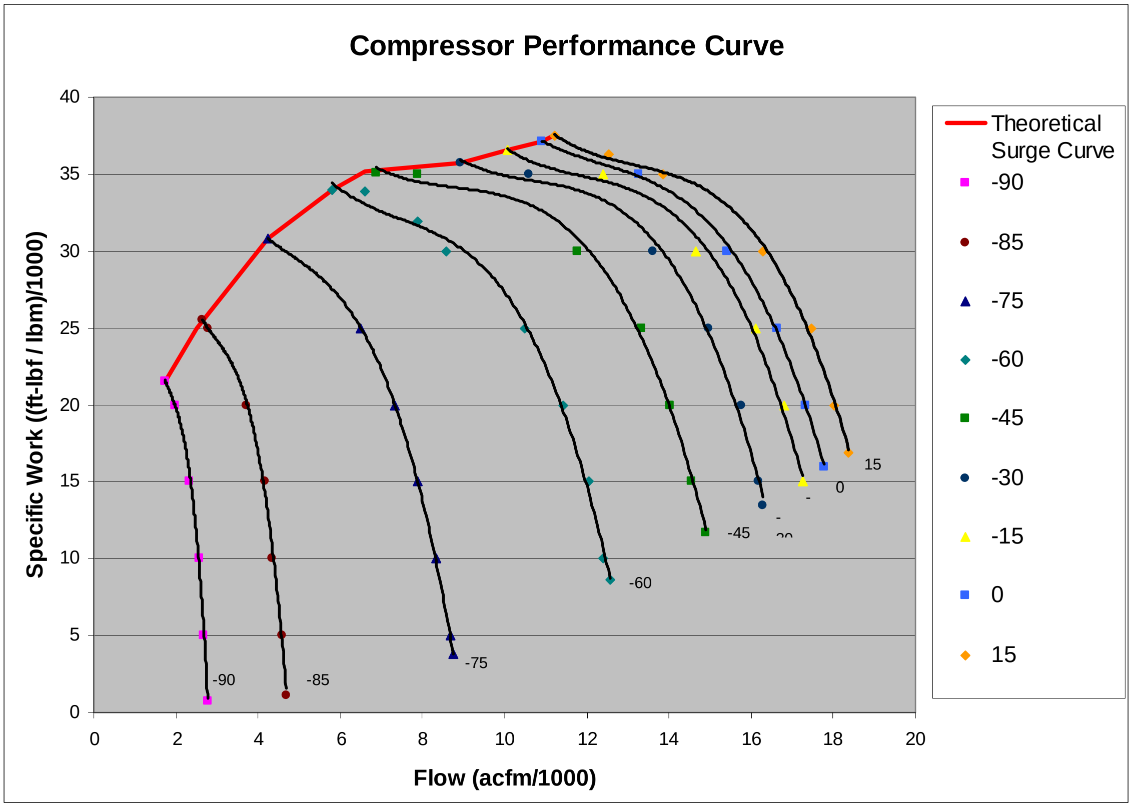


Figure 3: Compressor Performance Curve

Just as with the pump and heat exchanger examples; actual pressures, flows and amperages are compared to the design flows, pressures and amperages projected by the performance curve. Unacceptable variances are 'alerted' to the System Owner.

Intelligent System Requirements

Required System Instrumentation

This project consisted of a new design and installation. The Owner was very supportive of the system concept and the need to include the required instrumentation as part of the initial installation. Heat exchangers had pressure and temperature transmitters on the inlet and outlet sides of both fluid streams. Pumps were fitted with inlet/outlet pressure transmitters and current transmitters on the motor controls. Similarly, the compressor motor included current transmitters and inlet/outlet pressure sensors. Flow rates were also measured through major equipment.

Interestingly, the additional instrumentation cost was not excessive in terms of overall project cost. A key reason for this is that no redundant sensors or transmitters used. Any transmitters used for process inputs were the same as those used for control. Packaged equipment was also required to 'talk' to the central system. This allowed the team to avoid installing several sensors where many projects normally install them.

Integrating the Intelligent System with SCADA Infrastructure

The control system architecture for this process includes multiple programmable logic controllers (PLC's) aligned to serve various sub-processes. The PLC's in turn, utilize remote I-O configurations to reduce field wiring. The PLC's are networked using the manufacturer's communication protocol. The entire system is tied to a PC based SCADA work station that facilitates full system monitoring and control. The SCADA system also allows for un-attended, "lights out" operation -- communicating via phone and internet to off site operators as conditions warrant.

A "bolt-on" software package provided by the SCADA software supplier serves as the basis of the intelligent control system design. Some custom software was configured to interface the PC with the SCADA system. This brings data into the custom software for algorithm computations – and accepts resultant data for display and storage.

Data Management

The process time constants allowed the use of a relatively slow, five second sampling rate. This interval provides adequate, reliable inputs to both the process control and the intelligent system. This would also be the case with typical building HVAC and utility systems. Slow transfer rates minimize network communication data transfer issues.

Some process data is stored as part of the manufacturer's standard package and made available for historical trending. Data required by the intelligent system algorithms is moved into the custom software arena. Resultant data is then moved back to the standard data storage canisters.

The PC architecture includes a second hard drive for all data storage. Data management routines allow operators to periodically write historic data to CD's. Precautionary limiting routines were added to insure that hard drives do not become clogged with accumulated data.

HMI Interface

The Intelligent Control system uses the same graphical interface software as the process control system. Key equipment performance parameters are password protected and displayed (real time) adjacent to the respective equipment icons on the operator interface screen. This essentially makes the information the same as the more traditional, HMI-displayed process information.

Operators can call up and trend heat exchanger fouling or pump performance as easily as they can a process fluid's control temperature. Similarly, 'alert' limits can be placed on intelligent equipment performance parameters as easily as 'alarm' limits are placed on a controlled parameter.

The on-line friendliness of the information allows maintenance to be planned and performed based upon equipment condition instead of calendar time. In the event of an emergency, having all process data available greatly assists the troubleshooting process. This, in fact, turned out to be one of the key uses of the intelligent system in the case study. The system owner can now monitor the drift of key parameters away from a fully commissioned state – and properly schedule corrective action.

Benefits

Intelligent controls pay for themselves in several ways. Systems more consistently meet design flows, temperatures and pressures. This results in happier tenants.

Systems operate more reliably – with fewer unplanned outages and fewer incidents of costly breakdown maintenance. Mechanical systems rarely fail without providing some advance indication of distress. Intelligent controls allow the System Owner to 'listen more carefully' to these previously hidden communications.

Importantly, intelligent systems use less energy. They assure, with proper Owner follow-up, that systems operate day in and day out as 'green' as they were designed to be. The commissioned building – stays commissioned.

Summary

Careful thought and a little investment can add intelligence to most control systems. Intelligent control systems provide knowledge to System Owners – not just data. This knowledge empowers Owners to keep systems performing at a higher level of quality – while reducing maintenance, energy and other operating costs.