AUTOMATION AND CONTROL OF HVAC SYSTEMS

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Contents

Summary

The building services industry can, in general, be regarded as a more classical industry. The pace of advancement of technology in the field of building and construction, in particular, building services, is relatively slower compared with that of the electronics and control industries or information technology. Fortunately, research and development works on HVAC control have been substantial over the past two decades. Some achievements

have already been implemented in real HVAC systems and some still need further improvements for marketing. In this chapter, we have first considered the basic initiatives and elements of HVAC control, i.e., indoor air quality, sensors and the structure of a typical HVAC system in modern buildings. Then, well proven control strategies, i.e., PID control, PLC control and DDDC control, for modern HVAC systems have been highlighted. The structure and features of a typical building automation system have been described.

A typical example on the conventional control of an air handling unit is included. Control networks and state-of-the-art building automation are discussed. Finally, various advanced control techniques and their applications in HVAC systems have been briefly introduced, including system modelling, digital control, multivariable control, system identification, adaptive control, robust control, expert system based control, artificial neural network based control, fuzzy logic based control, computer vision based control and comfort based control respectively.

A discussion on the difficulties that will be faced by the HVAC control industry is also made to provide designers with some vision on the road ahead of us. As a quick summary, I would predict that the HVAC control systems in decades to come will be focusing on three aspects, namely full open network communications between all controllers and all levels of control, distributed high intelligence of all components and breakthroughs in energy efficiency.

1. Introduction

It is generally accepted that citizens spend almost 80% of their lives in buildings. Besides a holiday in the rural district, the destination of most citizens travelling outside a building is another building. We live, work and entertain ourselves inside buildings. Therefore, a comfortable, healthy, and work-effective environment inside buildings is critical for ensuring efficiency and quality in our daily activities.

In order to maintain a comfortable and healthy indoor environment, the installation of a heating, ventilation and air-conditioning system (HVAC) in modern buildings is a “must”. Based on recent surveys, the HVAC system can normally consume up to 50% of the total energy consumption inside a modern office building. These are the reasons why interior environmental control, or HVAC control, are so important when comfort, health, working efficiency and energy conservation are seriously considered.

The first environmental control systems for large buildings were pneumatic. They were capable of maintaining acceptable environmental conditions in a building and of performing some relatively complex control sequences. However, since they were hardware-intensive, the initial installation costs and maintenance requirements can be substantial.

There were also problems of limited accuracy, mechanical wear, and inflexibility. In recent decades, the integration of building systems such as heating, ventilation, air-conditioning, lighting, fire safety, and security has proven economically advantageous, while simplifying system interaction. First of all, let us have a look at the history of control development in buildings.

There was a general expansion in the construction industry after World War II. A desire to improve comfort inside new, larger buildings resulted in more complex mechanical systems. The impact of this was the development of better heating and cooling control systems. Pneumatic controls and electrical switches were mounted everywhere while excessive numbers of panels were installed near equipment controlled areas. The involvement of human operators to monitor the status of systems and to record readings was necessary.

In the 1950s, the introduction of the pneumatic sensor-transmitter permitting local indication and remote signalling plus the receiver-controller with optional remote adjustment were the major reasons that led to pneumatic centralisation. The number of local control panels was thus highly reduced to a more-or-less single center, which was located in a control room. Another trend, miniaturisation, resulted in the reduction of the physical size of instruments. The use of electronic sensors and analog control loops by the end of that decade resulted in a hardwired centralised control center.

In the 1960's, the growth of control companies for commercial buildings helped the development of new technologies. Electro-mechanical multiplexing systems were introduced, resulting in a reduction in installation costs and maintenance. Wires were reduced from hundreds to a few dozens per multiplexer. The control center panel was transformed into a control center console. Commercial digital indication and logging systems were available on the control center console to permit the automatic recording of selected parameters during unusual conditions and to provide information regarding these selected parameters.

Automatic control of systems, like air-handling units (AHUs), became possible. Temperature, flow, pressure, and other equipment parameters were monitored on the console. Intercom systems and phones were also a part of the console. The first computerised building automation control center was marketed late in this decade and data communication was done by means of coaxial cables or twisted pairs. Up to this stage, building automation technology was based on the concept of a centralised control and monitoring system (CCMS).

The use of mini-computers or central processing units (CPUs) and programmable logic controllers (PLCs) in building automation systems increased dramatically due to the oil crisis of 1973. People began to appreciate the importance of energy conservation. A new term, energy management system (EMS), was derived and became a standard in control manufacturers' sales brochures. New application software packages were incorporated into their basic automation systems.

Some packages such as duty cycle, demand control, optimum start/stop, optimum temperature, day/night control, and enthalpy control were introduced. Additionally, fire and security systems were emerging from the fundamental infrastructure of building automation. The building owner could directly oversee the systems by keeping track of energy usage and cost. These new tools helped management to make better predictions and compare relative costs of products. By the mid 1970's, the cost of hardware began to decrease. Systems became "user-friendly" and it was possible to program and generate new data bases on the same system. Printers with keyboards (KBs) and cathode ray tubes (CRTs) with KBs were the primary man-machine interface with the CPUs. "Dumb" multiplexers were becoming "smart". The small microprocessor embedded inside some multiplexers could "stand-alone", providing analog alarm detection, which reduced communication transactions. Field interface devices (FIDs) appeared and were the remote processing units compatible with the CPUs.

In the 1980's, the introduction of personal computers (PCs) revolutionised the control industry. The comparatively low cost of chips was the principal cause of the development of new technology in building automation and energy management. The resultant rapid change motivated manufacturers to engage in research and development rather than investing in their existing hardware and software.

The production of individual microprocessor based distributed direct digital control (DDDC) was accepted by users because of the popularity of PCs. The DDDC systems were replacing conventional pneumatic control systems. The building operator console (BOC) became the major man-machine interface and all programming was done through high level languages such as Pascal or C. The BOC was directly linked to remote local microprocessor control panels (LMCPs) using proprietary local area network (LAN) protocols.

2. Conventional HVAC Control and Automation

2.1. Indoor Air Quality

As mentioned in the first paragraph in “Introduction” of this chapter, modern buildings must provide us with an environment that is comfortable, healthy, energy conservative and enhances our working efficiency. The way how we feel in an environment very much depends on the quality of air that is surrounding us. Indoor air quality (IAQ) is becoming a hot topic for developers, building owners, building proprietors, facilities managers, architects, interior designers, engineers, contractors, manufacturers and suppliers of building appliances and materials, health and safety consultants, building operators and tenants.

This issue of IAQ has drawn great interest in almost all developed countries. Besides comfort, another issue of growing concern during recent years is the Sick Building Syndrome (SBS). The problem of SBS can very much downgrade the image and thus the value of a building. There does not exist a universally accepted world-wide standard how many parameters that the issue of IAQ should refer to. The author would like to recommend the following parameters that should be paid attention to when considering IAQ.

Three physical parameters are closely related to IAQ. The dry bulb temperature of air, measured in ^{o}C or ^{o}F by using thermometers or thermistors, surrounding the occupants seriously affects the thermal comfort of them. The relative humidity, measured in % by using capacitive humidstats, controls the rate of evaporation of moisture out of the human body, thus seriously affecting human comfort. Air movement, measured in m/s by using hot-wire anemometers, is also important to ensure heat loss from the human body is appropriate.

Besides these three parameters, there are other factors affecting thermal comfort for human beings, namely the metabolic rate (measured in W/m^2), clothing insulation (measured in $m^{2o}K/W$) and moisture permeability (measured with a dimensionless index), mean radiant temperature (measured in ^oK). These additional parameters are not included in the study of IAQ. Readers who are interested in studying human thermal comfort can refer to ASHRAE Standard 55, "Thermal Environmental Conditions for Human Occupancy".

Besides the three physical parameters, there are eight chemical parameters and one biological parameter:

i) carbon dioxide (measured in ppm by non-dispersive infrared monitors or others);
ii) carbon monoxide (measured in ppm by electrochemical monitors);
iii) radon (measured in picoCuries per litre by electronic monitors);
iv) formaldehyde (measured in ppm by a sampling method according to ASTM method 5014-94);
v) nitrogen dioxide (measured in ppm by using absorbent filters containing triethanolamine and analysis with spectrophotometry);
vi) ozone (measured in ppm by using absorbent filters containing nitrite-based solution and analysis with ion chromatography);
vii) respirable suspended particulates (measured in $\mu m/m^3$ by using impactors and collection on preweighed filters and determination gravimetrically by analytical balances);
viii) total volatile organic compounds (measured in ppb by using photo-ionisation sensors);
ix) airborne bacteria (measured according to "Field Guide for the Determination of Biological Contaminants in Environmental Samples" published by the American Industrial Hygiene Association, 1996).

Legionella bacteria are amongst the most famous bacteria found in HVAC systems. There are other contaminants such as saprophytic bioaerosol (free floating yeasts and molds), toxins (from molds and fungi), pathogens (viruses of common cold, influenza and tuberculosis bacteria), allergens (biological origin or breakdown products), pesticides (contained in indoor dust), tobacco smoke, asbestos, lead and polychlorinated biphenyls (PCBs used in electrical appliances) etc.

The job of a HVAC system is to ensure the IAQ of the indoor environment is as good as possible. Contaminants from the outdoor air must be filtered as far as possible before they are brought into the indoor environment with the fresh air supply. Similarly, contaminants generated inside the building must be removed as soon as possible with the exhaust air stream.

2.2. Sensors in HVAC Systems

Sensors belong to the first and most primary level of a control system. Sensors must provide reliable inputs to the control system by converting real-world fluctuations into conveniently quantified parameters or data, such as current, voltage or number, for the system to respond to and issue correct instructions to the actuators.

According to ASHRAE Fundamentals Handbook 1997, a sensor is a device that responds to a change in the control variable, such as a physical property – temperature or quantity – flow rate. The response, which is a change in some physical or electrical property of the primary sensing element, is available for translation or amplification by mechanical or electrical signal. All sensors respond to changes in the control variable to create a signal. In selecting a sensor for a specific application, the following elements must be considered:

i) operating range of controlled variable;
ii) compatibility of controller input;
iii) accuracy and repeatability;
iv) system response time or process dynamics such as drifting and linearity;
v) control agent properties and characteristics;
vi) ambient environment characteristics;
vii) sensitivity to detect the smallest change;
viii) cost;
ix) maintenance;
x) susceptibility to ambient noise – interference.

According to Underwood, for HVAC control, sensors can be grouped into the following five categories:

i) temperature and comfort;
ii) pressure;
iii) flow;
iv) humidity and enthalpy;
v) indoor air quality.

Most sensors consist of two parts, i.e., a transducer which converts the raw measured signal into a convenient signal, usually electrical, and a signal conditioner to convert the transducer signal into a scalable signal. For temperature sensors, there are resistance temperature sensors, thermistors, thermocouples and the recently manufactured comfort sensors that can even provide the controllers with parameters such as the “predicted mean vote” (PMV).

PMV is the integration of six parameters that are closely related to human thermal comfort, including metabolic rate, clothing insulation, dry bulb temperature, relative humidity, air speed and mean radiant temperature. For pressure sensors, there are capacitive and inductive types, strain gauges, piezoelectric and potentiometric types. For low sensors, there are pitot tubes, orifice plates, venturi meters, hot-wire anemometers, turbine flow meters, vortex-shedding meters, electromagnetic flow meters and ultrasonic flow meters, etc.

For humidity sensors, there are hygrometers, psychrometers, electronic sensors and dew-point sensors. An enthalpy sensors consist of a dry-bulb temperature sensor and a humidity sensor and combines these two measured values into one parameter called enthalpy that is closely related to the amount of heat content in the indoor air. IAQ sensors can simply be divided into two categories to facilitate two types of control, i.e., ventilation control and contamination protection. Ventilation control measures levels of carbon dioxide or other contaminants in a space and controls the amount of fresh air supply into the occupied space.

Contamination protection sensors monitor levels of hazardous or toxic substances and issue warning signals or initiate alarms through the building automation system. In the past, CO_2 sensors dominated the market. As revealed in section 2.1 of this chapter, very often it needs a rather complicated chemical process to determine the concentration of a particular type of gas or contaminant. It is difficult to install one sensor that is able to monitor all required parameters of IAQ. It was reported that one sensor could measure the concentration of all oxidisable gases collectively.

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Bibliography

Anstett M. and Kreider J.F. (1993) Application of neural networking models to predict energy use. *ASHRAE Transactions: Research***1**, 505-517.

ASHRAE, *1997 ASHRAE Handbook, Fundamentals*, Atlanta.

ASHRAE, *1998 ASHRAE Handbook, Refrigeration*, Atlanta.

ASHRAE, *1999 ASHRAE Handbook, HVAC Applications*, Atlanta.

ASHRAE, *2000 ASHRAE Handbook, HVAC Systems and Equipment*.

Boed V.(1999) *Controls and Automation for Facilities Managers: Applications Engineering*. CRC Press, Boston.

Brandt S.G. and Shavit G. (1984) Simulations of the pid algorithm for direct digital control application. *Proc. Workshop on HVAC Controls, Modelling and Simulation,* G.I.T., Atlanta.

Carlson, R.A. and Di Giandomenico R.A. eds. (1991) *Understanding Building Automation Systems*. R.S. Means Company, Kingston. [This book is a summary on modern building automation systems].

Curtiss P.S., Kredier J.F. and Brandemuehl M.J. (1993) Adaptive Control of HVAC Processes using Predictive Neural Networks. *ASHRAE Transactions: Research*. **1**, 496-504. [A pioneering research work in the application of adaptive control in HVAC systems].

Elgar P. (1998) *Sensors for Measurement and Control*. Addison Wesley Longman, London. [A good reference on sensors].

Gassmann O. and Meixner H. (2001) *Sensors in Intelligent Buildings*, Wiley-VCH, Weinheim. [This book is highly recommended to readers who would like to have a quick look at various topics related to sensors and senor applications].

Lockareff M. (1996) A control networking solution for the utility industry. *LonWorks Technology and the LonMark Standard*.

Newman H.M. (1994) *Direct Digital Control of Building Systems*, Wiley, N.Y. [A good tutorial sort of book for the understanding of DDC technologies in buildings].

Samid T., eds. (2001) *Perspectives in Control Engineering, Technologies, Applications, and New Directions*, IEEE Press, N.Y. [An updated summary on various directions and active applications of control theories].

Seippel R.G. (1985) *Transducers, Sensors and Detectors*, Reston Publishers, Bristol. [A good reference on classical sensors and detectors].

So A.T.P., Chow T.T., Chan W.L. and Tse W.L. (1994) Fuzzy air handling system controller, *Building Services Engineering Research and Technology. CIBSE* **15 (2)**, 95-105. [A pioneering application of fuzzy control on a simulated air handling unit model].

So A.T.P., Chow T.T., Tse W.L. and Chan W.L. (1995) New hvac control by system identification. *Building and Environment* **30 (3)**, 349-357. [A pioneering application of system identification based control on a simulated air handling unit model].

So A.T.P., Chan W.L. and Chow T.T. (1996)A computer vision based hvac control system.*ASHRAE Transactions* **102 (1)**, 661-678. [World's first application of computer vision on HVAC control].

So A.T.P., Chow T.T., Chan W.L. and Tse W.L. (1996) A neural network based identifier/controller for modern hvac control.*ASHRAE Transactions* **102 (1)**, 14-31. [A pioneering application of ANN on a simulated air handling unit model for system identification and real-time control].

So A.T.P., Chan W.L. and Tse W.L. (1997) Self-learning fuzzy air handling system controller.*Building Services Engineering Research and Technology, CIBSE* **18 (2)**, 99-108. [An improvement on the fuzzy air handling system controller published in 1994].

So A.T.P., Wong A.C.W. and Chan W.L (1998) The role of high speed communication in building automatio. *Proceedings of Mainland-Hong Kong HVAC Seminar '98*, ASC, HKIE, CIBSE, ASHRAE, Beijing, March 1998, pp. 6-11.

So A.T.P., Chan W.L. and Tse W.L. (1998) Building automation on the information superhighway.*ASHRAE Transactions* **104 (II)**, 176-191. [A report on a demonstration of an Internet based BAS during the Winter Meeting of ASHRAE in 1997].

Tse W.L. and So A.T.P. (2000) Implementation of comfort-based air-handling unit control algorithms. *ASHRAE Transactions* **106 (1)**,29-44.

Underwood C.P. (1999) *HVAC Control Systems, Modelling, Analysis and Design*, E & FN Spon, London. [This book is highly recommended to readers who would like to study more details of the technologies of modern HVAC control].

Wyon D.P. (1993) Healthy buildings and their impact on productivity. *Proc. Indoor Air'93, 6th Int. Conf. on Indoor Air and Climate*, Helsinki, Finland, July 1993.

Biographical Sketch

Albert T.P. So received BSc(Eng), MPhil and PhD from Department of Electrical & Electronic Engineering, University of Hong Kong. He had been with the Hong Kong Government as an Electrical & Mechanical Engineering for seven years after his graduation, before he joined the City University of Hong Kong. Now, he is Associate Professor with the Department of Building & Construction. Dr. So is a Chartered Engineer in U.K. and a Registered Professional Engineer in Hong Kong, being a corporate member of IEE, CIBSE, HKIE, a Senior Member of IEEE and a Member of ASHRAE. He is also the Chairman of Council and Executive Committee of Asian Institute of Intelligent Buildings and the Scientific Advisor of the International Association of Elevator Engineers. Dr. So has published over 150 technical papers in international journals and conference proceedings and has authored one book. He has also provided invited chapters in three books, including this one.