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# A plug and play framework for an HVAC air handling unit and temperature sensor auto recognition technique

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# A plug and play framework for an HVAC air handling unit and temperature sensor auto recognition technique

by

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# DEDICATION

*This thesis is dedicated to my wife Xiaochun Yang for her endless love and unconditional support during the study; to my parents Jun Zhou and Lijun Mu for raising me to be who I am today; and to my son Alan and daughter Alysa for the happiest days we are together.*

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# LIST OF ACRONYMS

| | |
|---|---|
| ASHRAE | American Society of Heating, Refrigeration, and Air-Conditioning Engineers |
| BAS | Building Automation System |
| BTU | British Thermal Unit |
| CFM | Cubic Feet per Minute |
| DALI | Digital Addressable Lighting Interface |
| DAQ | Data Acquisition |
| DAS | Domain Address Server |
| DDC | Direct Digital Control |
| DHCP | Dynamic Host Configuration Protocol |
| ECG | Electrocardiogram |
| EEPROM | Electrically Erasable Programmable Read-Only Memory |
| EISA | Extended Industry Standard Architecture |
| ERS | Energy Resource Station |
| FTT | Free Topology Transceiver |
| GPM | Gallon Per Minute |
| IEC | Iowa Energy Center |
| IEC | International Electrotechnical Commission |
| IEEE | Institution of Electronics and Electrical Engineers |
| ISA | Industry Standard Architecture |
| ISI | Interoperable Self Installation |
| MCA | Micro Channel Architecture |
| NCAP | Network Capable Application Processor |
| NIST | National Institute of Standards & Technology |
| NTU | Number of Transfer Units |
| NZEB | Net Zero Energy Building |
| PCI | Peripheral Component Interconnect |
| PnP-X | Plug and Play Extensions |
| RFID | Radio Frequency Identification |
| RMI | Remote Method Invocation |
| RTD | Resistance Temperature Detector |
| SC | Shading Coefficient |
| SNVT | Standard Network Variable Type |
| TCR | Temperature Coefficient of Resistance |
| TEDS | Transducer Electronic Data Sheet |
| TES | Thermal Energy Storage |
| TII | Transducer independent interface |
| TIM | Transducer Interface Module |
| UART | Universal Asynchronous Receiver-Transmitter |
| UPnP | Universal Plug and Play |
| USB | Universal Serial Bus |
| VFD | Variable Frequency Drive |
| XML | Extensible Markup Language |

# LIST OF NOMENCLATURE

| | |
|---|---|
| *a,b,c* | free parameters to determine temperature pattern |
| $c_p$ | specific heat, Btu/lbm•ºF |
| $C_p$ | conversion factor, lbf/ft$^2$•in.wc. |
| *Cv* | control valve flow coefficient. |
| *J* | mechanical equivalent of heat, 778.2 ft•lbf/Btu |
| $\Delta T$ | temperature difference, Deg F |
| $\Delta P$ | pressure difference, Inches of Water |
| *P* | density of air, lbm/ft$^3$ |
| $\eta$ | fan efficiency |
| *sse* | sum of squares due to error |
| *sst* | total sum of squares |
| *ssr* | sum of squares of the regression |
| *x* | time stamp for temperature pattern data, integer |
| $\bar{x}$ | average of time stamp, integer |
| *y* | measure temperature value, Deg F |
| $\bar{y}$ | average of measured temperature value, Deg F |
| $\hat{y}$ | predicted temperature value, Deg F |
| *r* | residual of temperature values between predicted and measured values |
| *R-square* | ratio of the sum of squares of the regression *ssr* and the total sum of squares *sst* |
| *R(0)* | resistance at temperature *0*°C |
| *R(T)* | resistance at temperature *T*°C |
| *T* | temperature measured in °C |

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# ABSTRACT

A plug and play framework for an HVAC air handling unit control system is proposed in this study. This is the foundation and the first step towards the plug and play HVAC control system that will eventually lead to self-configuring of HVAC control systems for automatic building controls system set-up, commissioning, more robust HVAC system operations, and automatic detection and repair of potential controls problems. This framework is built on the commercially available smart transducers that are compatible with the IEEE 1451 family of standards, and a data acquisition system that can read and write the smart transducer information. As a proof of concept for the framework, a structural pattern recognition algorithm is developed to automatically recognize temperature sensors in an Air Handling Unit (AHU) at different locations. The algorithm can be a critical part of the self-configuring HVAC control system in establishing a binding list of control system input/output and automated assignment and verification of the binding list.

A prototype of the plug and play framework for an AHU was built. Experiments were designed, setup, and tested to automatically recognize eleven different temperature sensors at various AHU locations on two different AHUs. More than one hundred test cases were implemented at various initial conditions, environmental temperatures, and chilled water system configurations, to demonstrate the robustness of the pattern recognition algorithm.

# CHAPTER 1. INTRODUCTION

## 1.1 Motivation

One of ASHRAE's visions is to develop and providing tools by 2020 that enables the building community to produce market-viable Net Zero Energy Buildings (NZEB) by 2030 [1]. A challenge for the HVAC industry is the need for enhanced building automation systems and controls: from sensors that are inexpensive, reliable and have multi-function capability, to reducing the cost of installing sensors, controls, and programming – which is a huge barrier to wide-scale adoption of building control systems. Smart systems and self-commissioning systems are also needed to save energy over time by continuously monitoring system performance against design intent and auto-tune as needed.

As many people are familiar to the term "Plug and Play" - a computer feature that allows the addition of a new device, normally a peripheral, without requiring reconfiguration or manual installation of device drivers. This technology makes the computer peripheral installation process automatic, easy and efficient. To reach the goal of high performance buildings, maximizing building operation efficiency and energy savings is a critical factor. It is very desirable to have the plug and play feature implemented on building automation systems – especially for large and complicated systems, where installation, configuration, commissioning, and tuning of control systems with thousands of control points are often manual, time consuming, and error-prone [20]. The configuration errors, system faults, and system operation inefficiencies often go undetected for long periods of time, requiring highly trained building controls professionals to debug the problems. A plug and play HVAC control system will greatly reduce the time and complexity for control system setup with multi-vendor products. Improved building performance, energy savings, and comfort can be achieved by continued self-commissioning as the building undergoes many changes during its life-cycle.

Today's building control systems, though, fall far short of the "plug and play" expectation that exists for the computer industry. Achieving this capability in building control systems requires the following conditions [5] [20]:

- Individual components such as transducers (sensors and actuators) to have a "self-describing" feature that provides critical information for the device;
- Network topology exploration and discovery of all components in the network with standardized communication protocols among building automation systems components; and
- Establishment of a binding list of control system input/output and automated assignment and verification of the binding list.

With the sensing technology advancement in the past fifteen years, there are now already commercially available "smart" sensors that have the "self-describing" feature. For example, sensors and actuators that comply with the IEEE 1451 family of smart transducer interface standards all have such feature. These transducers have transducer data (in the form of a Transducer Electronic Data Sheet, or TEDS) inscribed on an EEPROM located on the transducers [25] [40]. Basic data information includes: manufacturer ID, model number, version letter, version number, and serial number. Optional information includes sensor calibration data, operating range, etc. These sensor specific data are essential in a plug and play HVAC controls system.

Unfortunately, no existing communication protocols in the building controls industry, including ASHRAE standard BACnet [2] and widely used LonTalk, can directly communicate with smart transducers that comply with the IEEE 1451 sets of standards. Therefore, efforts are needed to incorporate IEEE 1451 into these communication protocols to be able to use these smart transducers.

While a compatible communication protocol may be addressed by close cooperation among the IT industry, IEEE, ASHRAE and other related organizations, a more critical problem specific to HVAC controls is how to automatically establishing a binding list for building control system inputs/outputs and assignment and verification of the binding list. Unlike a plug and play device on a computer, the logical location of the HVAC controls components (sensors and transducers, actuators, etc.) needs to be known so different control loops in the HVAC control system can be configured correctly. So far, there is no known algorithm or scheme developed in this area since it is difficult to automatically determine the sensor or transducer logical location in the HVAC control systems.

I strongly feel that with the advancement in technologies, standards, and commercialization of smart sensors, it is closer and closer to reality that the plug and play feature of IT industry can be implemented to HVAC controls. The motivation of this thesis is to start building a framework for plug and play HVAC control systems so self-configuring of a building automation system can be realized in the future for faster, easier, and error free HVAC control system configuration.

## 1.2 Objectives

The objective of this study is to develop a plug and play framework for an Air Handling Unit (AHU) control system – an essential part of the HVAC control systems that would eventually lead to self-configuring of Building Automation Systems (BAS). The goal is to advance the plug and play technology in the HVAC industry by developing a break-through concept and pattern recognition algorithms to automatically identify temperature logical locations on the AHU. The detailed tasks are:

- Review current plug and play technologies and applicability to HVAC control systems and the current state-of-the-art of existing concepts applicable to this study;
- Analyze the technological advancement necessary to bridge the gap between today's HVAC control set-up process and a full plug and play process;
- Develop a plug and play framework for an AHU;
- Develop an automatic pattern recognition algorithm to determine smart temperature sensor logical locations in an AHU;
- Build and test a prototype of the plug and play framework for an AHU.

## 1.3 Thesis Outline

Chapter 2 is the background and literature review of the related technologies such as plug and play, smart sensors, IEEE 1451 family of standards, self-configuring HVAC control, and pattern recognition techniques in time series data. Technology gap analysis of traditional HVAC control system set-up process vs. a plug and play system is done in Chapter 3. In Chapter 4, a plug and play framework for an AHU is proposed. Chapter 5, a new pattern recognition algorithm to resolve system component's ambiguity is developed and discussed – specifically, to solve the problem of automatically identifying AHU temperature sensor locations. Chapter 6 supplies the description of the testing facility and details of a prototype built to test the plug and play framework and algorithms. Test results and data analysis are presented in Chapter 7. Finally, conclusions and contributions of this study and recommendations of future studies are given in Chapter 8.

# CHAPTER 2. REVIEW OF LITERATURE

## 2.1 Self-Configuring HVAC Systems

A few years ago, ASHRAE technical committee smart building system subcommittee members Kintner-Meyer et al. [20] proposed a research project “Conceptual Design of a Self-Configuring HVAC Control System”. It summarized the technology up to that time and stated that the next logical step for the advancement of HVAC controls industry is to develop plug and play and self-configuring technologies. Unfortunately, the research topic did not officially become a work statement submitted for bidding. Possible reasons are that a lot of technology barriers still exist to implement a “self-configuring” HVAC system envisioned by the authors. Nonetheless, it provides a roadmap and useful information for this research. In 2005, the U.S. Department of Energy published a report “Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways”. A self-configuring system is regarded as one of the strategies for future new HVAC control applications. One of the proposed research topics is developing intelligent sensors to support plug-and-play applications. It also recognized that automated verification of correct input and output assignments of control devices is an essential part of technology advancement for a self-configuring HVAC control system.

The plug and play framework for HVAC control systems is one of the “Enabling Technologies” that indirectly facilitate energy savings. This technology will save energy through 1) Improvement or better use of BAS (building automation system - more accurate sensors, automatic building controls system set-up and commissioning, more robust HVAC system operations, and automatic detection and repair of potential control problems), 2) More widespread use of BAS because of easier installation, configuration and maintenance, and 3) Reduced cost of BAS installation.

A study by Katipamula and Gaines [19] has estimated that the U.S. commercial buildings total energy consumption is 5.32 quadrillion BTU per year. The total energy consumption of commercial buildings with BAS installed is 1.71 quadrillion BTU per year. Total energy savings from improvements of BAS ranging from 0.04 quadrillion BTU (assuming 25% of all buildings with BAS have control problems and 10% savings are achievable from the advanced technology in HVAC controls) to 0.51 quadrillion BTU (assuming 100% of all buildings with BAS have control problems and 30% savings). For building floor space greater than 56,000 $ft^2$, the total energy consumption of buildings without BAS is 0.86 quadrillion BTU. Total energy savings attributable to more widespread use of BAS range from 0.02 quadrillion BTU (assuming 25% have control problems and 10% savings) to 0.26 quadrillion BTU (assuming 100% have control problems and 30% savings).

Since the plug and play and self-configuring technology for HVAC controls involves areas across a wide spectrum of industries, the literature review and background information will be divided by several sections: plug and play; smart sensors and the IEEE 1451 standards; HVAC control system and plug and play; and pattern recognition and its application on time series data.

## 2.2 Plug and Play in the IT Industry

The classic “plug and play” concept started in the computer industry for computer devices to have the self-detection and self-configuration capabilities. The specification was initially developed by Microsoft and various computer hardware manufacturers in the form of EISA, ISA and MCA computer bus, and later progressed to PCI computer bus for internal hardware devices [29]. For external computer peripheral devices, two popular standards are Universal Serial Bus (USB) and IEEE 1394 interface standard. However, these specifications or standards only address the “plug and play” issue on a computer directly connected device.

According to Shanley [29], a typical (simplified) configuration process for a plug and play device on an E/ISA bus is as follows:

1. Writing a special key sequence to the device prepares them all to listen.
2. Performs a special series of reads among all connected plug and play devices and decide which device will enter isolation mode.
3. Configuration software assigns an identification number to the isolated device. The card leaves isolation state and enters the configuration state.
4. The software reads the isolated device’s resource requirement list to determine its requirement. Then the card is issued a command to go to sleep.
5. Steps 1 to 4 are repeated for all detected devices until all have been isolated, assigned an identification number, and their resources need.
6. The configuration software then uses each identification number to place the device into configuration mode. Its configuration registers are then written to assign non-conflicting resources to the device.
7. The card is then enabled (activated) for normal operation.
8. Step 6 and 7 are repeated until all devices have been configured and enabled.

To expand the “plug and play” concept beyond a single computer to a networked environment, several networking protocols and specification such as Jini [16], Universal Plug and Play (UPnP) [37], and Plug and Play Extensions (PnP-X) [35] were implemented by different companies or groups in the IT industry. The purpose of these protocols is to address the issue of auto-configuration of dynamically distributed networked devices and for distributed computing.

Jini refers to both a set of specifications and an implementation (Jini starter kit). It was invented by Sun Microsystems in 1994, and is a distributed object system architecture that defines a programming model based on and extends the Java technology in a distributed environment. The key concepts in Jini include: 1) Service - an entity that can be used by a person, a program, or another service. 2) Look up service - the central bootstrapping mechanism for the system and provides the major point of contact between the system and users of the system. 3) Java Remote Method Invocation (RMI) – a Java extension to traditional remote procedure call mechanisms and allows various types of objects (including data and code) to be passed around the distributed network. Jini architecture is illustrated in Figure 1. The working process of Jini is simplified as the following steps:

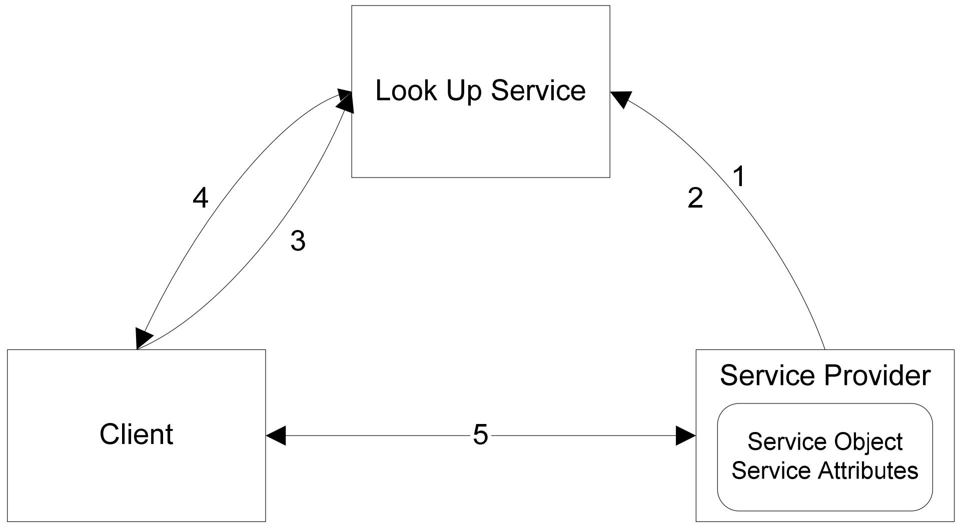



Figure 1. Jini architecture

1. Service provider discovers lookup server through multicast discovery.

2. Service provider registers service object and service attributes with lookup server using "join".

3. Client discovers lookup server through multicast discovery.

4. Client performs lookup to known lookup server and receives server location from .service proxy

5. Client directly accesses server and executes code on the server

Jini technology is a simple infrastructure for providing and gaining access to services in a network. The use of Jini technology decentralizes the control system, eliminates reprogramming or configuration and enables vendor independent systems. A major challenge for it to be used in the HVAC controls is that it is not a widely used protocol in HVAC control networks. Another challenge is that all Jini-enabled devices need to have some memory and processing power, but the memory included in the HVAC sensors and control devices is generally too small to accommodate Jini services. Finally, there is no standard in defining the control device characteristics and interaction mechanisms for control loops. There are also no Jini-based sensors, transducers, and actuators that are commercially available.

UPnP defines architecture for peer-to-peer network connectivity of intelligent appliances, wireless devices, and PCs. It is designed to support zero-configuration, "invisible" networking, and automatic discovery for a breadth of device categories from a wide range of vendors. It provides a distributed, open networking architecture using TCP/IP and the Web technologies for control and data transfer among networked devices. UPnP is supported by Windows Me, Windows XP and Windows Vista. This technology is defined by the Universal Plug and Play Forum – established in 1999 by a group of 200 industry leaders in consumer electronics, computing, home automation and security, home appliances, computer networking, and mobile devices. The basic key concepts in UPnP are controlled devices (or “devices”), control points (or “controllers”), and services. They are illustrated in Figure2.

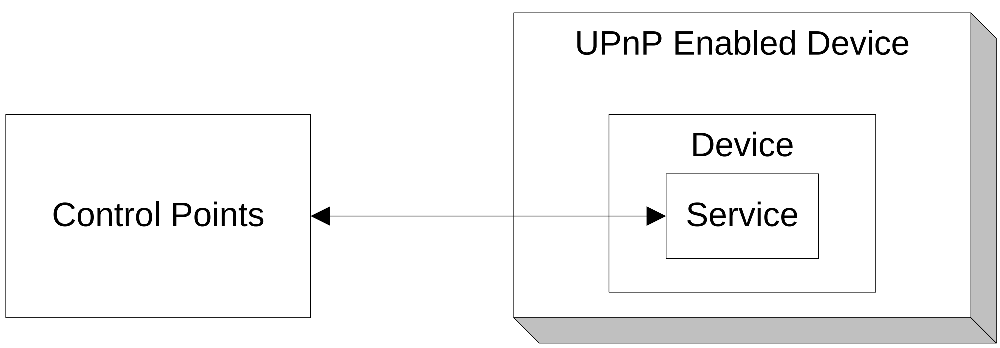



Figure 2. UPnP control points, device, and service

The smallest unit of control in an UPnP network is a service. A service exposes actions and models its state with state variables. An UPnP device is a container of services and nested devices. Devices may contain multiple services. A device responds to requests from control points. Both control points and controlled devices can be implemented on a variety of platforms. A control point in an UPnP network is a controller capable of discovering and controlling other devices. After discovery, a control point could retrieve the device description and get a list of associated services, invoke actions to control the service, and subscribe to the service's event source. The working process of UPnP is simplified as the following steps:

Step 1: Addressing. Each device is assigned an IP address via DHCP or use auto IP when connected to the network.

Step 2: Discovery. Device will advertise its services to control points on the network. When a control point is added to the network, it will search for devices of interest on the network.

Step 3: Description. The control point retrieves the device's description expressed in XML and includes vendor-specific, manufacturer information including the model name and number, serial number, manufacturer name etc.

Step 4: Control. A control point sends an action request to a device's service expressed in XML. In response to the control message, the service returns action specific values or fault codes.

Step 5: Eventing. The service publishes updates when a list of variables that model the state of the service change, and a control point may subscribe to receive this information.

Step 6: Presentation. The control point can retrieve and load a presentation page from device into a browser, and allows a user to control the device and/or view device status.

The applications for UPnP in the past have been mostly in home automation, printing and imaging, audio/video entertainment, and kitchen appliances. Even though the UPnP Device Control Protocol (DCP) has been written for limited HVAC devices like temperature sensor, control valve, zone thermostat, and fan speed, etc., it is very rare that such UPnP enabled devices exist in the market. Same as Jini, UPnP is not widely used as a networking protocol in the HVAC industry.

Plug and Play Extensions (PnP-X) is another newer version of distributed network protocol, but is only available for Windows Vista operating system. Similar to UPnP, it integrates network-connected devices into the Windows. PnP-X allows network-connected devices to appear as devices inside Windows and provides an installation experience that is similar to attaching a physically connected device.

None of these architectures have been widely adopted in the HVAC industry for building automation systems because of limitations to these protocols and the applicability to HVAC controls systems. Yet the overall process to realize the plug and play feature can be borrowed to build the framework of the plug and play and self-configuring of HVAC controls.

## 2.3 Communications and Control Networks in HVAC

Current HVAC control systems in commercial buildings are primarily direct digital control systems (DDC). A typical system mainly consists of sensors, actuators, controllers, networking devices, and operator workstations, all in a multi-layer networked environment. The local area network or LAN is the medium that connects multiple intelligent devices. It allows these devices to control, communicate, share, display, and print information, as well as store data. The most basic task of the system architecture is to connect the DDC controllers so that information can be shared among them. Kastner et al. had a comprehensive review on the communication systems in building controls in 2005 [18].

Generally speaking, there is three-level functional hierarchy in a building automation network [18] (as illustrated in Figure 3): Management level, Automation level, and Field level.

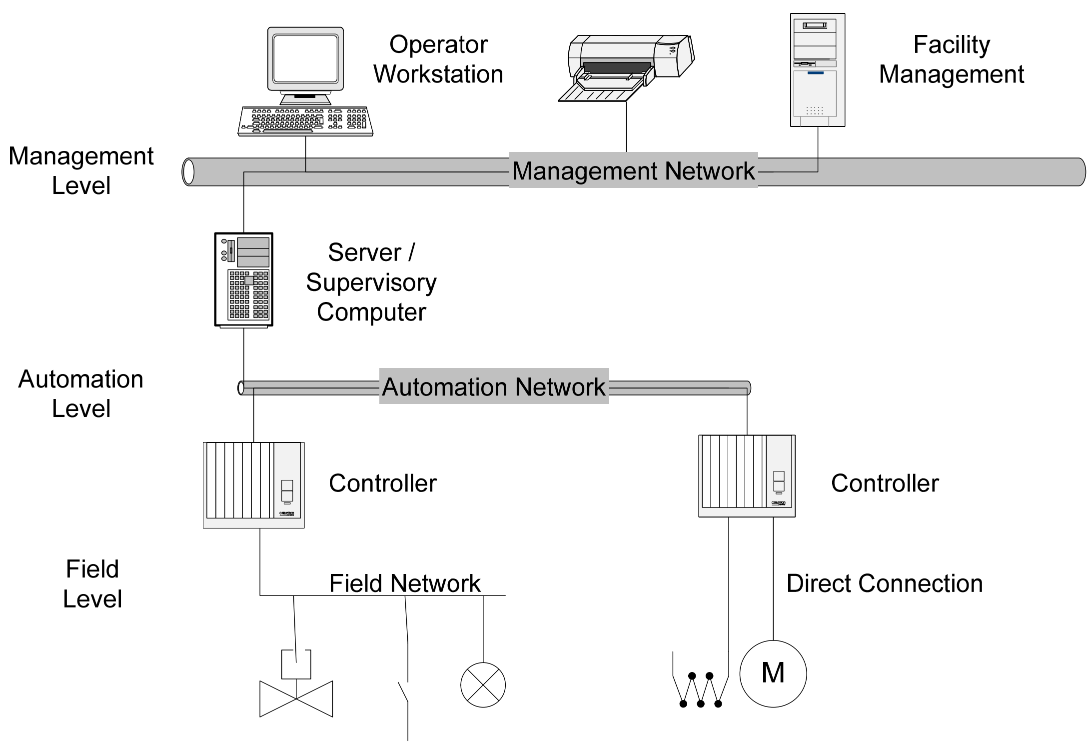



Figure 3. A general building control network architecture

The lowest level is the field level – where the actual local sensing and control execution happens. At this level, sensors/actuators and the controllers are either mostly direct connected using dry contacts / analog signals (voltage, e.g. 0~10VDC, or current, e.g. 4~20mA), or to a local field network. The most common PID control loops execute at this level. This is also where the most sensors/actuators and controllers configuration are needed during system installation and setup. The local field network for HVAC applications has the following characteristics: high-speed is not required as normal HVAC process is slow; low volume traffic, peer to peer communication; or event driven (vs. time driven). Many field network buses are proprietary: for example, Johnson Controls' METASYS system "N2" bus, Siemens APOGEE system's "P1" bus, etc. One of the "open" protocols at this level is Modbus, which supports serial communication using a simple master–slave protocol over EIA-485. Wireless standards like IEEE 801.11, IEEE 802.12.4, and the new ZigBee standards also have gained some relevance recently, because of easy installation and no need for cabling. In lighting system, there is an IEC standard "DALI" (Digital Addressable Lighting Interface) that has been widely used. "DALI" is an open communication standard that specifies how lighting data and command are exchanged among lighting components (such as electrical ballast) though a lighting network. It replaces 0–10 VDC interface for dimmable electronic ballasts. A DALI loop data rate is 2400 b/s [18]. However, because of the promotion by ASHRAE and the market success of the LonWorks, the BACnet standard [2] and the LonWorks [8] protocol are still the widely adopted open standard now in the DDC systems. BACnet is designed to provide system level and field level standards for routine functions such as data exchanges, alarms and event management, scheduling, and trending for the benefit of "interoperability". At field level, BACnet MS/TP (Master–

Slave/Token-Passing) and BACnet PTP (Point-to-Point) are mostly used. The BACnet MS/TP use twisted pairs and EIA-485 signaling that can transfer data at speed ranging from 9.6 kb/s to 78.4kb/s. The BACnet PTP supports dial-up communications and other point-to-point applications using serial communication EIA-232 and modems or other data communication equipment. The LonWorks system consists of the LonTalk communication protocol, a dedicated controller (neuron chip), and a network management tool [8]. The most popular field level LonTalk protocol used in building automation system network is the 78.1 kb/s speed free topology twisted pair profile (FT-10).

At the automation level, the main purpose of the network is to transfer global data between network controllers (which manage/control/store data for the sub-network) for global control and data collecting. Speed is more important than at the field level. For building automation system vendors, many have their own propriety or legacy communication protocol. Some examples include Johnson Controls' "N1" bus and Siemens' "P2" protocol. However, most of them already implemented either BACnet/IP, BACnet over Ethernet or LonWorks/IP in their system architecture or at least in some of their product lines, due to the popularity of interoperability and interchangeability that are required by the users.

Standard IT communication protocols are predominant in the management level networks (or "backbone") in HVAC control systems. It is a natural choice to use the existing IT network infrastructure for building automation purposes, as there is little "local control" function involved in the operator workstation except user interface and some management and system diagnostic function. The protocol that is most widely used at this level is Ethernet with IP (Internet Protocol).

Unfortunately, neither BACnet, LonWorks, or any other proprietary communication protocols in the HVAC industry addresses the issues of complicated control system programming, configuration, and setup at the system level – which include mostly field level and some automation level. None had fully incorporated the "plug and play" feature into their specifications. One major reason is that the components in a HVAC control system, especially the small sensing components and actuators, are not real "smart" components. These temperature, humidity, air flow, water flow sensors and valves and damper actuators only send and/or receive analog or digital signals to and from the controller, but they do not have an internal memory device that can identify and describe itself about critical information such as type of transmitter, manufacture, serial ID, calibration information and scaling factor, etc. This is the information that needs to be used during control system setup and configuration process. Normally, after a control system is designed and wires connected, the controls engineer has to manually configure this information into the system. For large systems with many components, the setup and configuring process is very complicated, time consuming, and error prone, let alone that highly trained professions are required.

For the field level controllers, there are many BACnet and LonWorks compatible controllers on and some multi-purpose "high end" BACnet and LonWorks sensing and control devices with "management functionality" inside, like a networked thermostat or "smart" actuator are commercially available. However, due to the reasons mentioned above, they are not "plug and play" features.

## 2.4 Smart Transducers and the IEEE 1451 Standards

Traditional analog sensors and actuators used in the control industry are voltage type (0~10VDC, 1~5VDC, etc.), current type (0~20mA, 4~20mA, etc.), or resistance type (ohms). These sensors/actuators have neither communication capability with controllers nor capability to store critical sensor information (manufacturer ID, device type, serial number, calibration information, etc.) about them. To make a plug and play HVAC control system, all the components (controllers, sensors, actuators, etc.) have to be able to communicate and have the "self-describing" feature. In 1982, Ko and Fung introduced the concept of "intelligent transducer" [21]. Their definition of an intelligent or smart transducer is the integration of an analog or digital sensor or actuator element, a processing unit, and a communication interface. In the case of a sensor, the smart transducer transforms the raw sensor signal to a standardized digital representation, checks and calibrates the signal, and transmits this digital signal to its users via a standardized communication protocol [4]. In case of an actuator, the smart transducer accepts standardized commands and transforms these into control signals for the actuator. A smart transducer comprises a hardware or software device consisting of a small, compact unit containing a sensor or actuator element, a microcontroller, a communication controller and the associated software from signal conditioning, calibration, diagnostics, and communication [47]. The conceptual block diagram is illustrated in Figure 4.

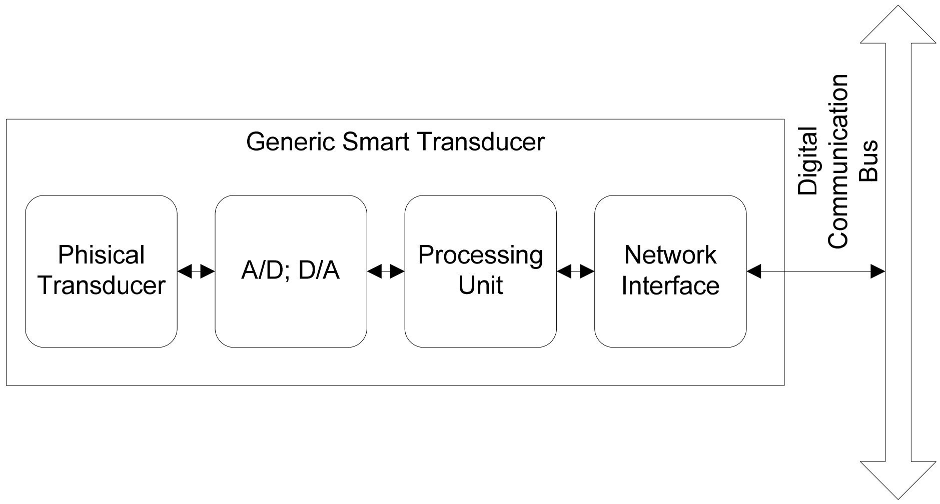



Figure 4. Block diagram of a generic smart transducer

The past twenty years have seen increased market in digital sensors/actuators, many of them though, use proprietary communication protocols – they can only communicate with the controllers from the same manufacturer – or are restricted to only one field data network. Trying to solve the problem of multiple communication standards between transducer and data networks, transducer, measurement-and-control and data-network, industries discussed the concept of smart transducers, during the September 1993 IEEE TC-9 meeting (IEEE Instrumentation and Measurement Society Technical Committee on Sensors). The working groups are trying to develop draft standards to provide: a) Common communication interface between transducers and processors; b) Compatibility with multiple sensor actuator bus standards; c) Interconnect analog transducers with digital networks; and d) Don't develop a new network standard. Base on this work, in later years, National Institute of Standards and Technology (NIST) and IEEE develop them into a set of smart transducer standards – IEEE 1451 family of smart transducer standards.

The IEEE 1451 family of smart transducer interface standards describes a set of open, common, network-independent communication interfaces for connecting transducers to microprocessors, instrumentation systems, and control/field networks in a networked system. A key feature of these sets of standards is the definition of Transducer Electronic Data Sheets (TEDS). All sensors and transducers manufactured according to these standards store transducer identification, calibration, correction data, and manufacture-related information in the TEDS - a memory device embedded in the transducer. Because of this feature, these smart transducers allow self-identification, easy calibration, simplified device maintenance and documentation, and thus facilitate plug and play and automatic system self-configuration. The block diagram for an IEEE 1451 smart transducer is illustrated in Figure 5.

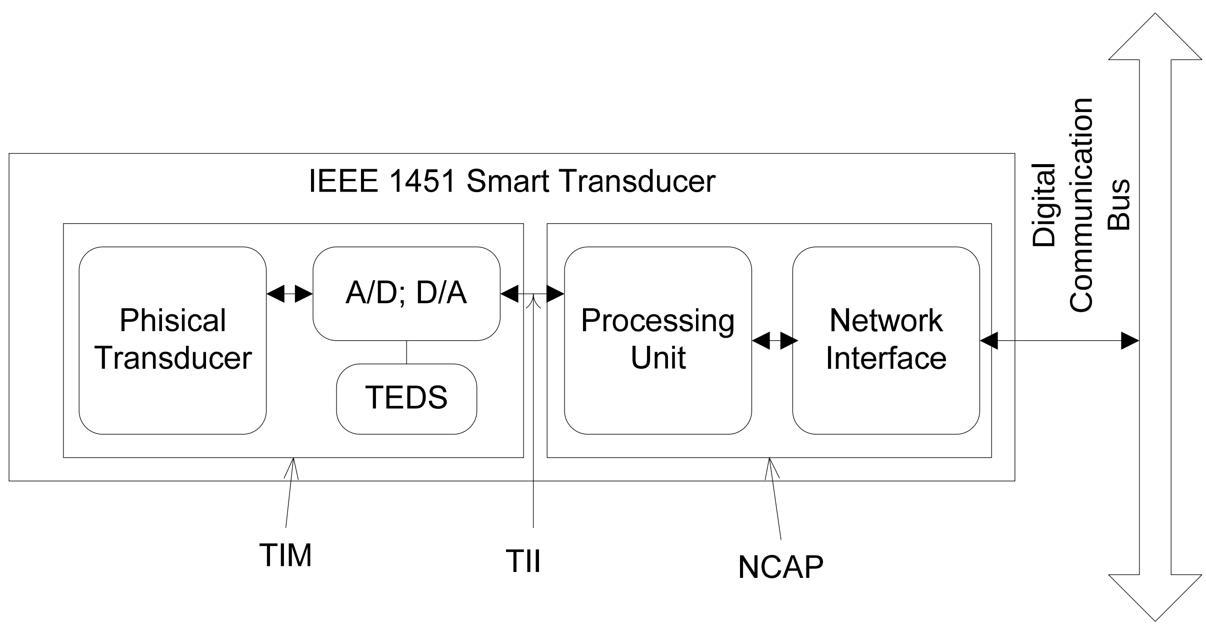



Figure 5. Block diagram of an IEEE 1451 smart transducer

As can be seen, IEEE 1451 smart transducer model separates the unit into two major components— a Transducer Interface Module (TIM) and a Network Capable Application Processor (NCAP) with a transducer independent interface (TII) between them. The transducer independent interface defines a communication medium and a protocol for transferring sensor information.

The IEEE 1451 family of standards currently consist of following sub-standards:

1. IEEE 1451.0-2007 [41]: Define smart transducer interface for sensors and actuators -common functions, communication protocols, and Transducer Electronic Data Sheet (TEDS) formats. This functionality is independent of the physical communications media (1451.X) between the transducer and NCAP.
2. IEEE 1451.1-1999 [42]: Defines a common object model and interface specification for the components of a networked smart transducer. It is applicable to distributed measurement and control applications. It mainly focuses on the communications between NCAPs and between NCAPs and other nodes in the system.
3. IEEE 1451.2 – 1997 [43]: Defines a transducers-to-NCAP interface and TEDS for point-to-point configurations. Transducers are part of a Smart Transducer Interface Module. It describes a communication layer to interface with IEEE 1451.0 and to support two popular serial interfaces: UART and Universal Serial Interface.
4. IEEE 1451.3 – 2003 [44]: Defines a transducer-to-NCAP interface and TEDS using a multi-drop communication protocol. It allows transducers to be arrayed as nodes, on a multi-drop transducer network, sharing a common pair of wires.

5. The IEEE 1451.4 – 2004 [45]: Defines a mixed-mode interface for analog transducers with analog and digital operating modes. IEEE 1451.4 mainly focuses on adding the TEDS feature to legacy analog sensors. A TEDS was added to a traditional two-wire sensor. The TEDS model was also refined to allow a minimum of data to be stored in a physically small memory device, as required by tiny sensors.
6. The IEEE 1451.5 – 2007 [46]: Defines a transducer-to-NCAP interface and TEDS for wireless transducers. IEEE 1451.5 specifies radio-specific protocols for achieving this wireless interface. Wireless standards such as 802.11 (WiFi), 802.15.1 (Bluetooth), 802.15.4 (ZigBee), and 6LowPAN are adopted as the IEEE 1451.5 wireless interfaces.
7. The IEEE P1451.6: Defines a transducer-to-NCAP interface and TEDS using the high-speed CANopen network interface.
8. The IEEE P1451.7: Defines an interface and communication protocol between transducers and Radio Frequency Identification (RFID) systems.

A graphical illustration of IEEE 1451 family of smart transducer standards is illustrated in Figure 6 [24]:

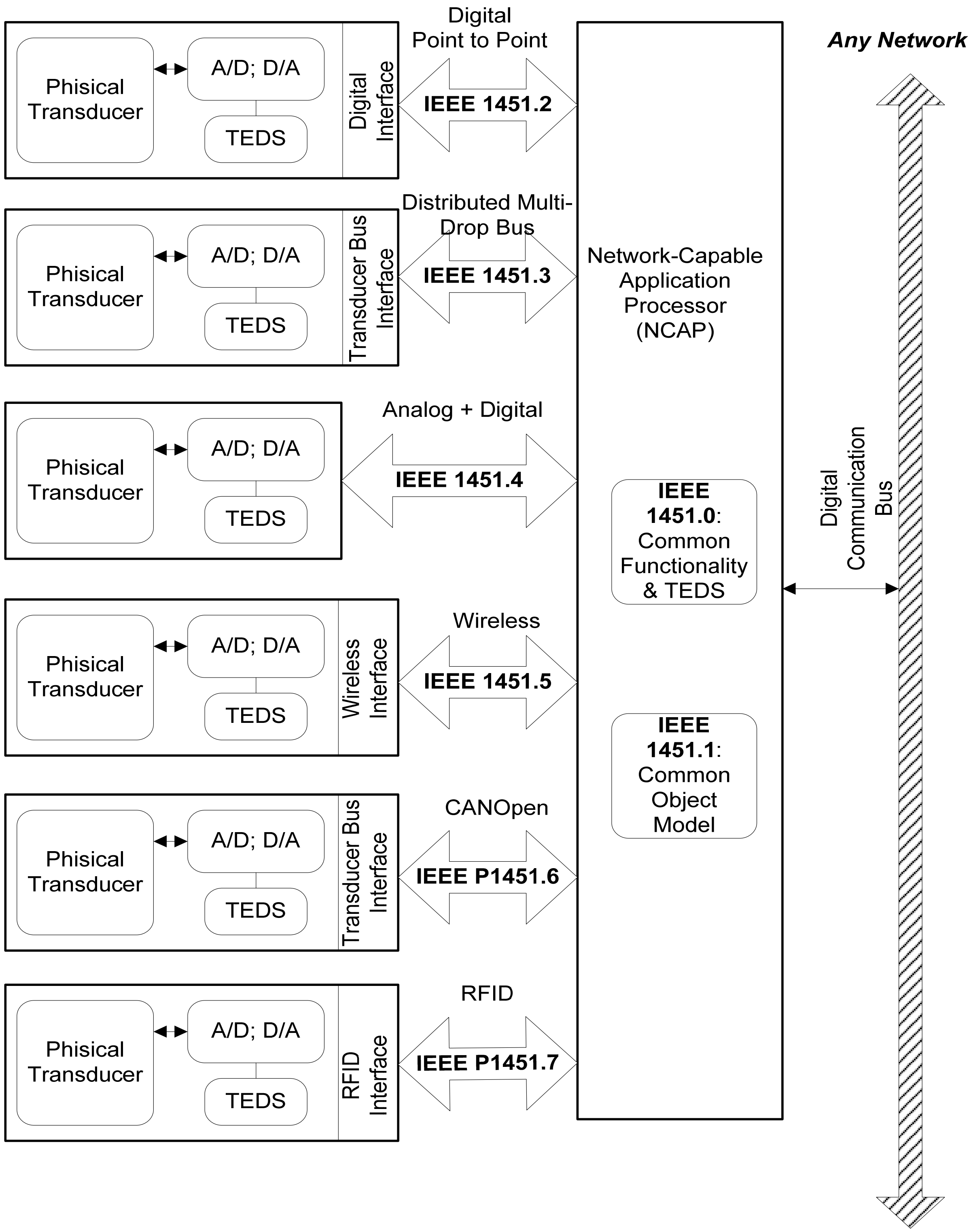



Figure 6. IEEE 1451 family of smart transducer interface standards

Besides the benefit of TEDS – self-identification and descriptions, self-documentation, and easy installation, another advantage of IEEE 1451 standards is the plug and play capability. A TIM and NCAP can be connected with a standardized physical communications media and operate without any change to the system software. Figure 7 illustrates the plug and play features for TIMs and NCAPs that complies with IEEE 1451 standards. Thus sensors/actuators manufacturer can focus on making sensors/actuators unit only (TIM). The sensor network builders can focus on making sensor network interface. For the vendors who combine both TIM and NCAP into a single module and sell it as an integrated, networked sensor, the interface between the TIM and NCAP is hidden, but the integrated sensor is still IEEE 1451 compatible at the network level.

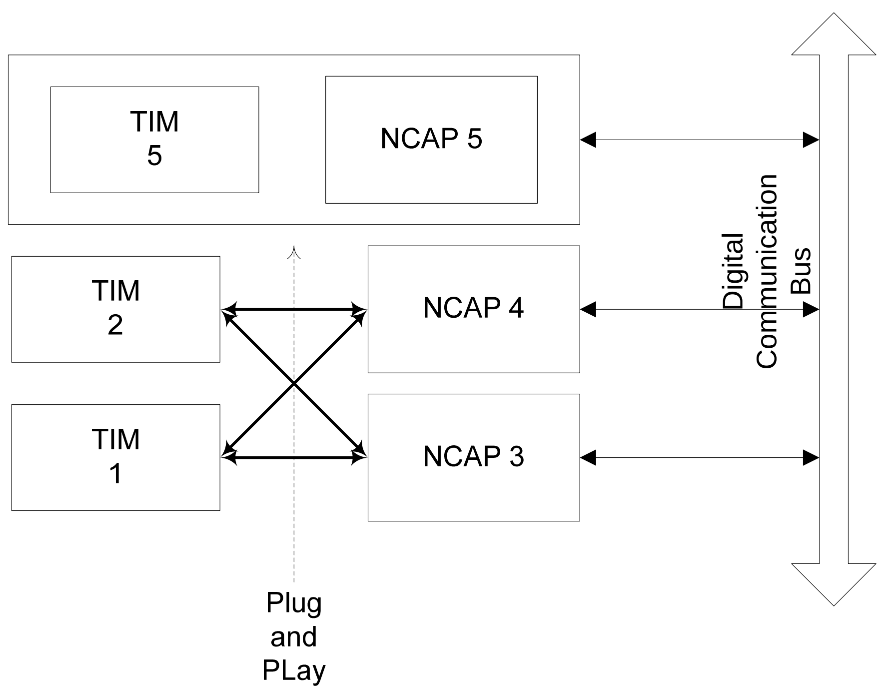



Figure 7. Illustration of IEEE 1451 plug and play

Currently, there are temperature (RTD, thermistor, and thermocouple), pressure (absolute and differential), and other types of IEEE 1451 smart sensors on the market but mostly they are used in the distributed measurement and control, aerospace, and automotive industries. It is also worth mentioning that many TEDS sensors are not cost prohibitive at all, some are even very close to the same price as comparable conventional sensors without the TEDS chips. A major obstacle for the use of these smart sensors in the HVAC industry is the compatibility between prevailing BACnet and LonWorks with the IEEE 1451 standard. Once the usefulness of TEDS sensors is demonstrated, BACnet and LonWorks will most likely adopt the protocols needed include these sensors in their systems.

## 2.5 Pattern Recognition and Applications in Time Series Data

To tackle the problem of automatically identifying air handling unit inputs/outputs, pattern recognition techniques can be used to analyze time series data collected by various sensors. One major assumption is that each sensor in an air handling unit system serves a unique purpose and is placed in a unique location. Thus a specific sequence of operations by the outputs (actuators, fan or pump on/off, etc.) on an air handling unit should cause an identifiable, unique pattern on each of the input sensors (temperature, humidity, air flow, pressure, etc.) To resolve system component ambiguity, the key is to identify these sequences and recognize the sensor data patterns using an automated pattern recognition algorithm.

Pattern recognition is a technique to identify objects. The application of pattern recognition extends to very wide areas: image processing, speech recognition, seismic analysis, electro-cardio graphic signal analysis, computer vision, artificial intelligence, and remote sensing, just to name a few. Automatic pattern recognition technique is an essential part of artificial intelligence and machine intelligence, and uses mathematical algorithms to process data (mostly colleted through different kinds of sensors). The algorithms used for automated pattern recognition are often divided in two major tasks: Description and Classification, as illustrated in Figure 8 [39]:

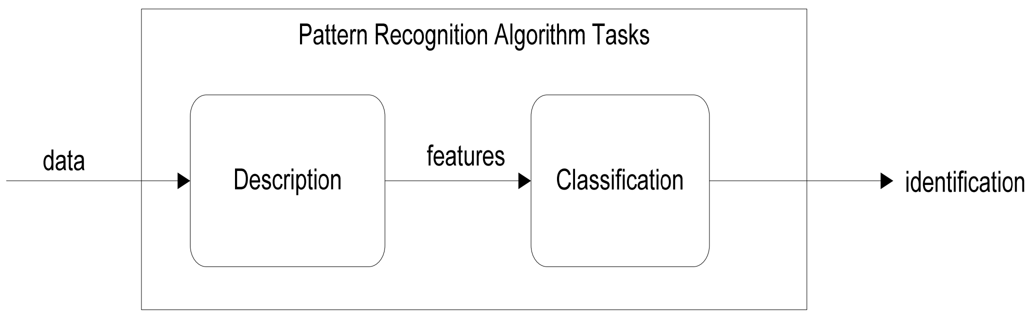



Figure 8 . Pattern recognition algorithm tasks

The "Description" task is to categorize, convert, or transform data collected and extract features from it. This is the more critical task between the two, and is often the more difficult one. The "Classification" task is to classify the object being identified based on the features extracted.

Three major approaches to pattern recognition algorithms are: statistical (based on decision-theory), structural or syntactic (based on structural information), and neural network [39]. Each approach is suitable for different problems and applications. The statistical approach [15] assumes known priori information, and develops classification strategies based on similarity, probability, boundaries, and clustering. The structural approach assumes the data pattern "structure" is quantifiable by using either a formal grammar or relational descriptions based on basic graph patterns, and classifies the pattern using parsing (for formal grammars) or graph pattern matching (for relational graphs). The neural network approach is based on the predicable properties of neural networks that are trained by a set of data representing known patterns. The pattern generation basis is a stable state or weighted array. The limitation for this approach is that very little semantic information can be obtained from the network.

Real world automated pattern recognition techniques involving time series data also have been successfully applied to process control, speech recognition, electrocardiogram diagnosis, and other detection and identification applications [12] [22] [23][27][38][49]. Both statistical and structural approaches can be used for pattern recognition of time series data. Generally speaking, structural techniques have been shown to be effective in applications in time series data [9].

For the purpose of this research, considering a given type of commercial air handling unit: the size, capacity, and the model of each components (duct size for each section, heating and cooling coil capacity, designed water and air flow rate, supply, return fan and damper model, etc.) can all be different [26]. However, the major function for each component should be similar. In time series data applications, while statistical pattern recognition is based on the "*quantitative*" feature of the data, the structural approach is based on the arrangement of "*morphological*" (shape-based) events evident in the waveform—e.g., speech recognition, electrocardiogram diagnosis, seismic activity identification, radar signal detection, and process control. Since each AHU component's functions are similar, given a specified sequence of operation, the "*morphological*" information and the interrelationship embedded within the sensor data *should* be similar for each component and be identifiable. Therefore the structural pattern recognition method was selected for use in this research.

In the structural approach to pattern recognition, each pattern is expressed in terms of a composition of its components – called primitives. The primitives are the smallest units or basic patterns in a structural pattern recognition problem. A simple example [10]: considering the simple terminal graph patterns illustrated in Figure 9, the left side is the possible pattern (shape) of a simple terminal, and right side is the string representation of the terminal graphic pattern. The {a,b,c,d} are primitives defined in this representation, the sequential combination of the primitives represent different terminal shapes.

As illustrated in Figure 8, the first task for solving structural pattern recognition problems is to describe the pattern. The key to a successful solution is to select the primitives properly for a specific application. Good primitive selection should not only catch the essence of the internal structural relationship of the pattern for that specific application, but also make it easier to interpret and classify for the later classification phase. Unfortunately, there is no general solution for extracting structural features from data and the selection of primitives is often highly domain and application dependant [30][34]. Olszewski [34] concluded this is because simple primitives are domain and application independent, but they capture very little structural (relational) information and often cause difficulty and complexity in later classification phase. On the other hand, a good or proper primitives selection for domain specific applications needs assistance from a domain expert with deep understanding of the internal relationships among data patterns.

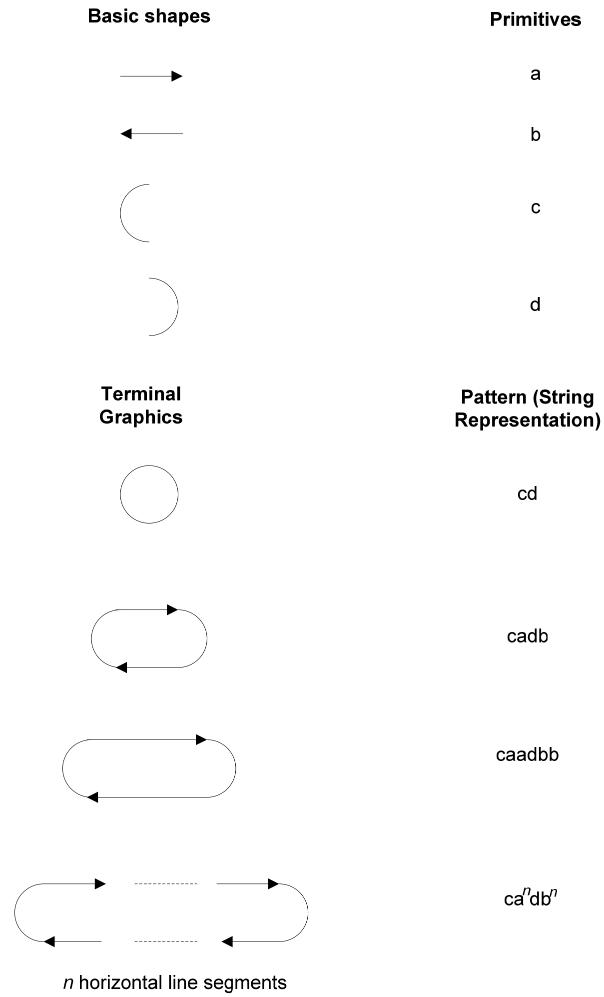



Figure 9. Example of terminal graphics and their pattern representation

The feature extraction techniques in structural pattern recognition for time series data include curve fitting, piecewise-linear regression, and chain codes to generate basic shapes (primitives) that encode sequential, time-ordered relationships. Stockman and Kanal [50] used curve fitting to identify instance of parabolic and straight line primitives in developing a waveform parsing system called WAPSYS. Rengaswamy and Venkatasubramanian [38] also selected parabolic and straight line as primitives in monitoring sensor data for process control and fault diagnosis. The structural approach is also commonly used for electrocardiogram (ECG) diagnosis. Straight line, parabolic, and peak are picked to be primitives in Trahanias and Skordalakis [47] system for ECG data recognition. Olszewski [34] developed a domain-independent structural pattern recognition system that is "capable of acting as a black-box to extract primitives and perform classification without the need for domain knowledge". The generalized approach uses the following six simple shapes as primitives: a) constant; b) straight line; c) exponential; d) sinusoidal; e) triangular; and f) rectangular. These are simple patterns that are commonly used in waveform or time-series data. The main feature extraction techniques used in his approach (structure detector) is the linear regression for linear structures (line, constant) and simplex method (commonly used in optimizing non-linear functions) for non-linear structures (exponential, sinusoidal, triangular, and rectangle). So far no literature has been found to use structural pattern recognition technique to detect patterns for HVAC applications.

## 2.6 Summary

There is very little research and development in the area of Plug and Play and Self-Configuring HVAC systems. The technologies involved cover multiple fields including mechanical engineering, information systems, electrical and controls engineering, and artificial intelligence. The main purpose of this research is to develop a Plug and Play framework for one of HVAC system's main component – an Air Handling Unit, and also develop a temperature pattern recognition algorithm to support the framework. This requires bringing all related available technologies together and integrating them into a single system.

# CHAPTER 3. TECHNOLOGY GAP ANALYSIS

## 3.1 Plug and Play and Self-Configuring HVAC Control Systems

For large commercial and industrial buildings, modern HVAC control systems consist of computerized and networked control and sensing devices, usually called direct digital control system (DDC) systems. The goal of a DDC control system is to operate the HVAC equipment efficiently for maintaining a better building environment with minimum energy consumption. A typical HVAC control system architecture is illustrated in Figure 6 in Chapter 2.

Due to the complexity and proprietary nature of DDC systems, it has become difficult to design, install, setup, operate, and maintain a DDC system. Highly trained professionals are usually required to carryout a DDC project from installation, setup, configuring, tuning, and troubleshooting, before it is operational. The whole process is often difficult, time-consuming, and very expensive. A normal DDC control system setup process is generalized as the following steps (assuming the DDC system design phase is already finished):

1. Network setup

   In this step, the management, automation, and field network layers of network wires/cables are connected to the control system server(s), operator workstation(s), network controller(s) and other networking devices, according to network architecture.

2. Component (sensors, controllers, actuators, etc.) install and function test

   Local controllers are connected to its own automation level or field level network; Sensors and actuators are connected to their assigned controller addresses and are correctly identified by the control system. Individual component functions should be checked at this stage to make sure they are working properly.

3. System configuration and programming

   Based on design intent, system will be configured and programmed to implement control functions. Schedules, trend logs, etc. are setup at this step.

4. System commissioning, tuning and debugging

   Control PID loops are tuned, sensor offsets adjusted, and system tested to verify that control system works as intended.

Because a complicated HVAC control system may involve hundreds to thousands of components, Steps 2 and 3 often involve the most labor intensive and time-consuming work.

The plug and play concept is borrowed from the IT industry. When used in a HVAC control network, *a Plug and Play HVAC control system means that the control system components are recognized automatically once they are installed on (or removed from) the network. Specifically, step 2 of the DDC system setup mentioned above should be done AUTOMATICALLY.*

However, only correctly identifying components do not make a complete control system. Unlike the plug and play components in the IT industry - where the physical or logical location of the components are not important as long as a sequential identification number can be given to components of the same type – *the logical location of components in a control system is critical*. Since each sensor is measuring a property specific to a zone, system or location, and a control system has control loops which involve specific logical inputs and outputs, component identification without knowing its logical location in the system is not acceptable. Therefore, the plug and play feature in HVAC controls not only needs to detect and identify component types, it also REQURIES identification of their logical locations.

After the control system components are detected identified, and logical locations assigned, the next step is the configuration of the system (step 3). *A Self-Configuring HVAC control system is a control system that can configure itself automatically without human intervention, given the design intent of the system. Specifically, steps 2 and 3 of the DDC system setup mentioned above should be done AUTOMATICALLY.*

As can be seen from the above definitions, a "self-configuring HVAC control system" encompasses a "plug and play HVAC control system". A "self-configuring" HVAC control system involves a much more complicated issue of mapping (or translation) of design intent to actual control strategies and logics. Standardizing common control logic or strategy is the first step to make this happen. Then technology needs to be developed to automatically convert the standardized control logic to actual control programs for different building automation system venders. Though ASHRAE has started to work towards the first goal, it is still a long way to go before the "mapping" of selected control strategies to actual control programs is feasible.

## 3.2 Technology Gap Analysis for Components

Plug and Play and Self-Configuring technology both have basic requirements for the components. From the Chapter 2 literature review of plug and play technology in the IT industry, a common requirement for all plug and play enabled devices is the capability to store information about itself on the device. This is referred to as the "self-describing" feature. The self-describing information can vary from device type to device type. The most common information about a device includes: manufacturing ID, device type, serial number, etc.

Current HVAC control systems components include the following categories (excluding network and communication):

1. Computers;

   Operator workstations, supervisory computers, independent web servers for the control system, and computers for facility management use.

2. Network controllers;

   Controllers that coordinate system global operations over the automation level network, some controllers have web server embedded too.

3. Field controllers;

   Controllers executing local control loops for unitary or simple equipment or zone control

4. Independent HVAC equipment;

   HVAC equipment that runs independently and may have its own controller. Some equipment may get setpoint from HVAC control system (chiller, boiler, etc.)

5. Sensing inputs;

   Analog or digital inputs measuring different properties (temperature, humidity, air and water pressure, air and water flow rate, on/off status for controlled equipment, etc.)  Most of these inputs are connected to field controllers for monitoring and control purpose.

6. Executing outputs;

   Analog or digital outputs for executing controller command (e.g. various types of actuators, pump and fan start/stop, VFD speed control outputs, etc.)

In the above component categories, category 1 ~ 4 all have internal memory and storage space and have no difficulty embedding "self-describing" information on itself. However, *most HVAC grade sensing inputs and executing outputs are low cost, not very accurate, and do not have information embed on the device to provide the "self-describing" feature.* For example, a simple RTD temperature sensor can only provide a resistance value to the controller, nothing more. The same can be said for many other types of sensing inputs.

For the sensing inputs category, recent developments in BACnet and LonWorks promote some new developments in sensors conforming to these standards. For example, there are commercially available BACnet compatible thermostats for temperature control in a zone, but these are multi-function units combined with a controller and are much more expensive than a single simple temperature sensor. There are also BACnet compatible air flow stations but this product includes a separate transmitter to provide information.

For analog inputs, the selected BACnet object properties are listed in Table 1. For digital inputs, the selected BACnet object properties are listed in Table 2.

Table 1. Selected properties of the BACnet analog input object type

| Property Identifier | Property Datatype | Conformance Code |
|---|---|---|
| **Object_Identifier** | BACnetObjectIdentifier | R(equired) |
| **Object_Name** | CharacterString | R |
| **Object_Type** | BACnetObjectType | R |
| **Present_Value** | REAL | R |
| **Description** | CharacterString | O(ptional) |
| **Device_Type** | CharacterString | O |
| **Status_Flag** | BACnetStatusFlags | R |
| **Event_State** | BACnetEventState | R |
| **Reliability** | BACnetReliability | O |
| **Out_Of_Service** | BOOLEAN | R |
| **Update_Interval** | Unsigned | O |
| **Units** | BACnetEngineeringUnits | R |

Table 2. Selected properties of the BACnet binary input object type

| Property Identifier | Property Datatype | Conformance Code |
|---|---|---|
| **Object_Identifier** | BACnetObjectIdentifier | R(equired) |
| **Object_Name** | CharacterString | R |
| **Object_Type** | BACnetObjectType | R |
| **Present_Value** | BACnetBinaryPV | R |
| **Description** | CharacterString | O(ptional) |
| **Device_Type** | CharacterString | O |
| **Status_Flag** | BACnetStatusFlags | R |
| **Event_State** | BACnetEventState | R |
| **Reliability** | BACnetReliability | O |
| **Out_Of_Service** | BOOLEAN | R |
| **Polarity** | BACnetPolarity | R |

For LonWorks compatible input sensing devices, besides the LonWorks compatible networked thermostats, there are now some commercial available sensors: temperature, pressure, light, IAQ, and occupancy sensors that use conventional sensors embedded with a Free Topology Transceiver (FTT) plug-in module that converts present raw signal to LonWorks digital signal. The signals exchanged in LonWorks are called “Network Variables” which may be a single value or a structure or union of multiple values. A LonWorks component or device may have multiple network variables. A Standard set of Network Variable Types (SNVTs - pronounced snivets) defining standard units, ranges, and resolution for most common measures used in HVAC includes over 100 types and covers a wide range of applications. SNVTs are "self identifying", and "may also have a self documentation string that can be used to provide more information to a network tool. For example, a device that contains two temperature sensors, one for input temperature and one for output temperature, has two network variable outputs. These outputs are both declared using SNVT_temp, automatically identifying the values as encoded Celsius values with a resolution of 0.1°C. Each of the network variables has a self documentation string defined by the device application. The string for the first device is: 'Input Temperature Sensor' and the string for the second is 'Output Temperature Sensor.'"[8] However, these devices do not provide serial number and calibration information (at least for now). Figure 10 is a sample temperature sensor object details including SNVTs.

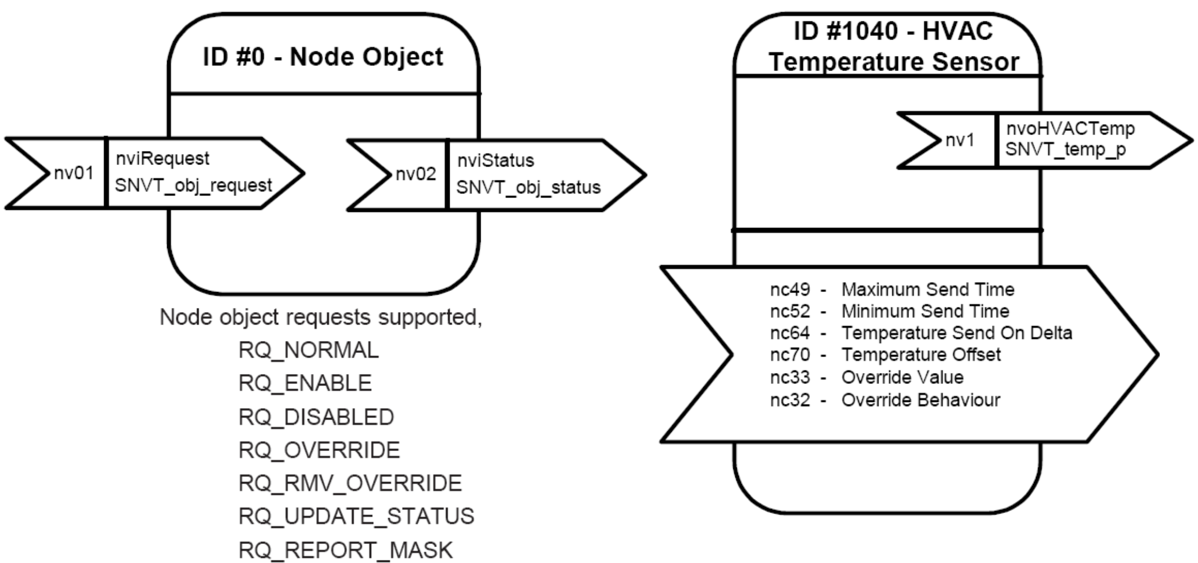



Figure 10. Example of object details for a LonWorks temperature sensor

Regarding the outputs category, there are limited numbers of "smart" actuators that use BACnet or LonWorks protocols. There are also BACnet and LonWorks relay modules commercially available. The selected BACnet object properties for analog outputs are listed in Table 3, and the selected BACnet object properties for digital outputs are listed in Table 4. Figure 11 is a sample smart actuator that uses LonWorks protocol object details including Standard Network Variable Types.

Table 3. Selected properties of the BACnet analog output object type

| Property Identifier | Property Datatype | Conformance Code |
|---|---|---|
| **Object_Identifier** | BACnetObjectIdentifier | R(equired) |
| **Object_Name** | CharacterString | R |
| **Object_Type** | BACnetObjectType | R |
| **Present_Value** | REAL | W(ritable) |
| **Description** | CharacterString | O(ptional) |
| **Device_Type** | CharacterString | O |
| **Status_Flag** | BACnetStatusFlags | R |
| **Event_State** | BACnetEventState | R |
| **Reliability** | BACnetReliability | O |
| **Out_Of_Service** | BOOLEAN | R |
| **Units** | BACnetEngineeringUnits | R |
| **Priority_Array** | BACNetPriorityArray | R |
| **Relinquish_Default** | REAL | R |

Table 4. Selected properties of the BACnet binary output object type

| Property Identifier | Property Datatype | Conformance Code |
|---|---|---|
| **Object_Identifier** | BACnetObjectIdentifier | R(equired) |
| **Object_Name** | CharacterString | R |
| **Object_Type** | BACnetObjectType | R |
| **Present_Value** | BACnetBinaryPV | W |
| **Description** | CharacterString | O(ptional) |
| **Device_Type** | CharacterString | O |
| **Status_Flag** | BACnetStatusFlags | R |
| **Event_State** | BACnetEventState | R |
| **Reliability** | BACnetReliability | O |
| **Out_Of_Service** | BOOLEAN | R |
| **Polarity** | BACnetPolarity | R |
| **Priority_Array** | BACNetPriorityArray | R |
| **Relinquish_Default** | REAL | R |

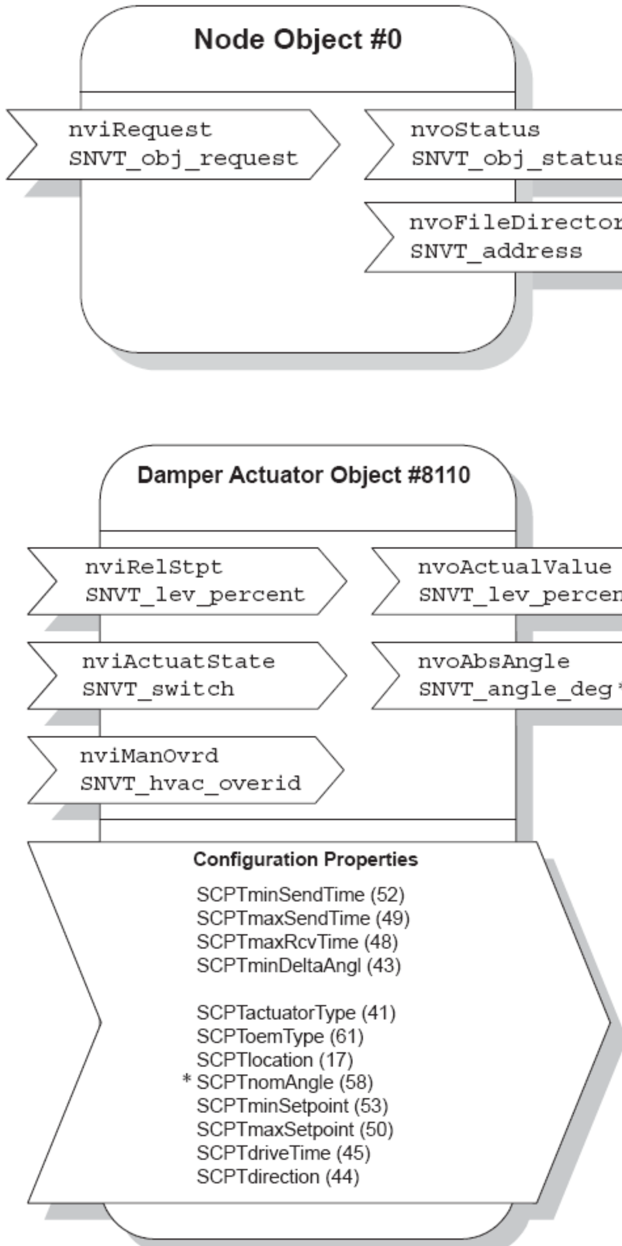



Figure 11. Example of object details for a LonWorks damper actuator

Outside the HVAC industry, "smart sensor" technologies are fast developing in the past decade. The most promising ones are smart transducers (including smart sensors and transducers) that comply with the IEEE 1451 set of smart transducer interface standards for sensors and actuators. As introduced in previous chapter, an IEEE 1451 smart transducer consists of a non-volatile memory called Transducer Electronic Data Sheet (TEDS) that stored critical transducer specific information and a processing unit to convert the raw signal to the IEEE 1451 signal. An example of a TEDS format defined by IEEE 1451.4 (for mixed mode interface) specification is illustrated in Table 5: it consists of multiple sections chained together: The first section is the basic TEDS information, which includes the Manufacturer ID, model number, version letter, version number, and serial number. IEEE standardized sensor/actuator types to 15 different categories (listed in Figure 12). For each category a standard template is specified in the standard. Following standard template data (optional) are calibration template data, which has three different categories by itself. The last section is the user defined data.

Table 5. A TEDS format for mixed mode interface smart transducer

| |
|---|
| Basic TEDS |
| Template ID |
| Standard Template TEDS (ID = 25~39) |
| Calibration Template TEDS (ID = 40~42) |
| User Data |

| Type | Template ID | Name of template |
|---|---|---|
| Transducer Type templates | 25 | Accelerometer/Force transducer w. const. curr. ampl. |
| | 26 | Charge amplifier (incl. attached accelerometer) |
| | 27 | Microphones w. built-in preamp. |
| | 28 | Microphone preamps. w. attached micr. or system |
| | 29 | Microphones (capacitive) |
| | 30 | High-level voltage output sensors |
| | 31 | Current loop output sensors |
| | 32 | Resistance sensors |
| | 33 | Bridge sensors |
| | 34 | AC linear/rotary variable differential transformer (LVDT/RVDT) sensors |
| | 35 | Strain gage |
| | 36 | Thermocouple |
| | 37 | Resistance temperature detectors (RTDs) |
| | 38 | Thermistor |
| | 39 | Potentiometric voltage divider |
| Calibration templates | 40 | Calibration table |
| | 41 | Calibration curve (polynomial) |
| | 42 | Frequency response table |
| Transducer Type templates | 43 | Charge amplifier (incl. attached force transducer) |

Figure 12. IEEE 1451.4 transducer type template ID

It can be seen from the above table and figure that the advantage of these "smart transducers" is that they all have a memory chip that stores important transducer information – so it has the "self-describing" feature that the plug and play technology needs. The communication protocols are also standardized across various fields and applications including the latest wireless standards. The disadvantages are they are mostly used in industries outside the HVAC area, and the transducer types do not cover common sensor/actuators used in HVAC controls. There are already commercially available smart temperature sensors and pressure sensors.

In summary, there are no readily available commercial smart sensor/actuators that both meet the requirement for plug and play technology and fit for HVAC applications. The

IEEE 1451 smart transducers are probably the closest fit in terms of sensor technology. They just need to be custom fit for the HVAC industry and to solve the communication problem from IEEE 1451 to BACnet and/or LonWorks. Another solution would be to develop common smart BACnet/LonWorks sensors/actuators that can store related useful information.

## 3.3 Technology Gap Analysis for Communications and Networks

As stated in Chapter 3.1, the Plug and Play and Self-Configuring technology in a HVAC system means that the system components (smart sensors and transducers , controllers, etc.) can be automatically detected and configured once exposed to the control network (or removed from the network). The first implication is that the components (including the server/operator workstation where the main software resides) use the same protocol, or some kind of gateway or converter is needed to “translate” the information. The second implication is that, like the Plug and Play technology in the IT industry reviewed in Chapter 2, there must be a pre-defined configuration mechanism or procedure in the main software to detect, identify, and configure these components into a control system.

The most common commercial “open” communication protocols for HVAC control systems in U.S. now are BACnet and LonWorks. However, “open” does not mean “plug and play”, even for a simple task. For example, for a HVAC control system using all BACnet protocols, it is not possible (at least for now) to just replace a BACnet thermostat with another one, even if it is the same model, without some human intervention (configuration, etc.). Some BAS (Building Automation System) venders do have the “auto discovery” feature, which it can scan the whole network and discover all the exposed BACnet objects by mapping BACnet object names to a binary ID and network addresses. This feature can reduce a lot of setup time but it still cannot fully automate the system configuration step covered in Chapter 3.1.

LonWorks provides significantly more plug and play capabilities than BACnet by using the recently developed "Interoperable Self Installation" (ISI) protocol [6]. ISI is an "open" company standard licensed by Echelon in 2005. The protocol is a peer-to-peer protocol, and detects the addition and removal of system components by periodically broadcasting the assigned components in the system. The manufactures claim LonWorks devices can self-install automatically or at the push of a button by using ISI. The basic self-installation procedures are as follows [6] [7]:

1. Domain Acquisition

   Each component in a LonWorks/ISI networks is assigned a domain ID - a 6-byte ID that is initially derived from the one of the component Neuron IDs, or assigned by a Domain Address Server (DAS).

2. Network Address Assignment

   Each component is assigned a subnet and node ID when it is installed for the first time.

3. Network Address Verification

   Periodically verify the network address for each component is still valid.

4. Device Discovery

   Enables any device to learn the network address and program types for all devices in a network.

5. Connection Enrollment

Connections may be created using *automatic*, *controlled*, or *manual* enrollment method. When using *automatic enrollment*, no user intervention is required to create connections. When using *controlled* or *manual* enrollment, the user chooses the device that becomes the connection host. The connection host assigns a unique connection ID to a component based on design intent, and then gets acceptance.

6. Connection Verification

   Network variable connections are automatically verified and maintained

7. Connection Discovery

   One or more connection controllers may be in the network to coordinate connection enrollment as well as recover the current connection status of each device in the network. The connection controller can create a table of all components in a network

8. Connection Removal

   Removes network variable connections among devices in a network *automatic*, *controlled*, or *manual* connection removal.

9. Instance Identification

   User can perform an action on a component upon request by a connection controller.

10. Deinstallation

    User can perform an action on a component to remove all configuration data, which includes the domain, network address, and network variable connections.

However, the ISI protocol has limitations. According to ISI protocol specification [6], it "is suitable for small networks with simple network topologies. Example applications in a small building or home network include monitoring and control for appliances, HVAC systems, lights, remote A/V equipment, and security devices." The ISI network limits the maximum number of components to 32 for simple ISI-S networks, and up to 200 devices if using a Domain Address Server (DAS) and all the devices are ISI-DA (for self-installed network) compatible. Furthermore, *controlled* or *manual* methods are still the most used methods in connection enrollment and connection removal procedures, due to the complexity in mapping I/O points and resolving system ambiguity for larger or complicated network topologies.

IEEE 1451 defines a comprehensive set of standards for smart transducers, normally used outside the HVAC industry. It provides plug and play capability between a Transducer Interface Module (TIM) and a Network Capable Application Processor (NCAP), as illustrated in Figure 5 in Chapter 2. The NCAP is used to communicate and convert IEEE 1451 compatible smart transducers (sensors and actuators) information to any network [41], independent of the network protocol, as the NCAP and Networked Smart Transducer Model shown in Figure 13.

Lee [25] gave a simple application example of IEEE 1451 similar to Figure 14. The NCAP not only can convert smart transducer signals (NCAP 2 and NCAP 3) to and from the operator workstation, but also can run local application software to form a distributed control loop (NCAP 1). Now Ethernet NCAPs are commercially available and can be acquired easily to build web-based applications.

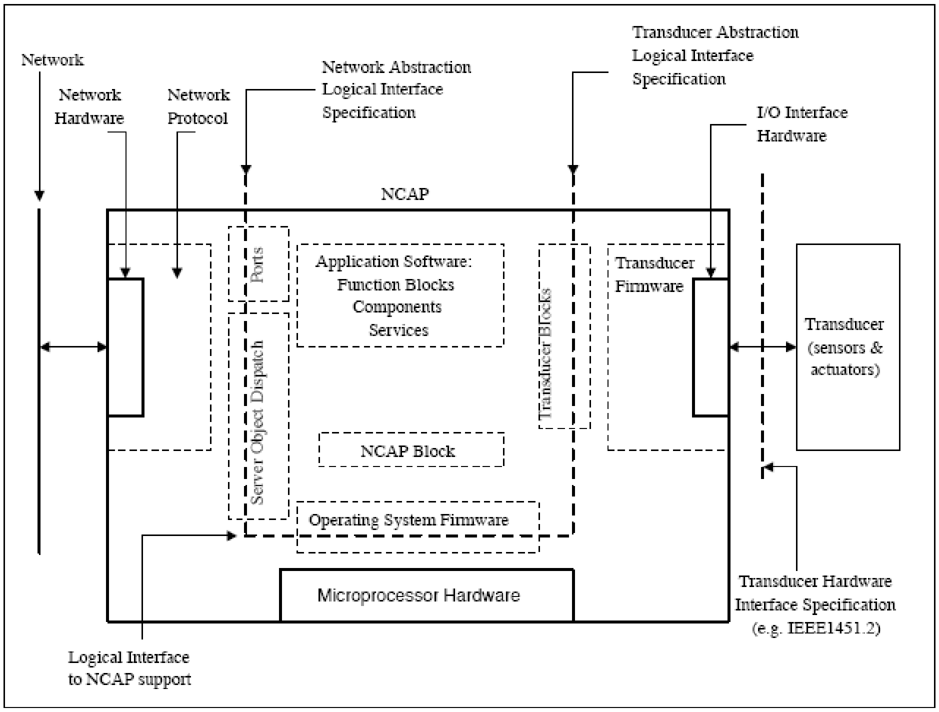



Figure 13. NCAP and networked smart transducer model [24]

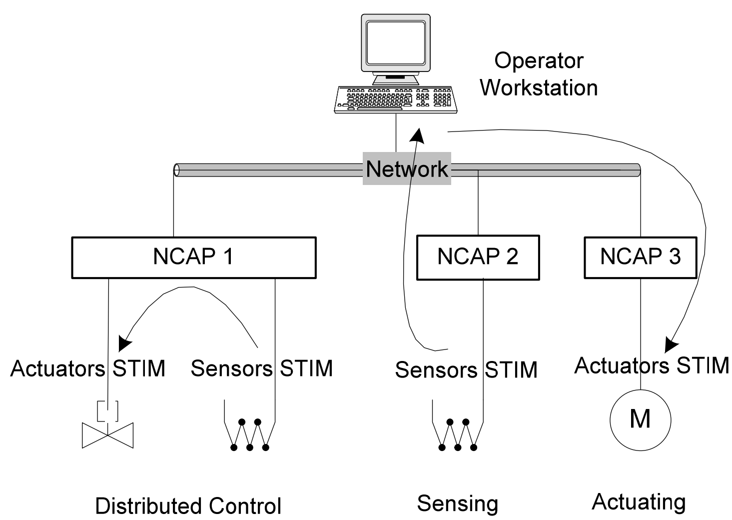



Figure 14. A simple example of IEEE 1451 smart transducer application

The major limitation for IEEE 1451 compatible sensors and actuators being used for HVAC applications is that there are no sub-standards to define an IEEE 1451 smart transducer with BACnet object model and LonWorks protocol yet. Therefore there is no NCAP available to convert smart transducer information directly to BACnet or LonWorks protocols. To accomplish this, IEEE 1451 standards committee and ASHRAE BACnet / Echelon LonWorks standards committee need to work together to resolve this issue. Currently there is not enough market demand in the HVAC industry for the IEEE 1451 smart transducers. Another limitation is that the IEEE 1451 family of standards defines the low level plug and play capability, but depends on the individual measurement and data acquisition manufacturers to implement the plug and play and self configuring feature at higher levels. The reason is that it does not have a standardized configuration procedure similar to the LonWorks ISI protocol.

## 3.4 Technology Gap Analysis for Resolving System Component Ambiguity

A big technology gap exists in applying the Plug and Play and Self-Configuring technology from the IT industry to the HVAC industry (and other industries like process control). This is because a HVAC control system involves many control loops, and the logical locations of the inputs and outputs involved need to be correctly identified, which means the system component ambiguity needs to be resolved. For example, an important piece of equipment in a commercial building HVAC system is the Air Handling Unit (AHU). Many components are involved in operating and controlling the AHU – multiple temperature, relative humidity, pressure, air flow, water flow sensors as well as pumps, dampers, valves, etc. For different sensing and actuating components, even though some smart sensors and actuators described in Chapter 3.2 have the "self-describing" feature, the logical location information for the same type of sensor/actuator may be different when used on a specific project. A temperature sensor manufacturer does not know a specific temperature sensor sold will be used to measure supply air temperature or return air temperature on an AHU. Another point is that the logical location of a component may not be recognized based on the physical location of the component (e.g. a room temperature sensor in Zone A is different logically than a temperature sensor in Zone B, even though the two sensors may only be on the opposite side of a thin wall that separate the two zones). Therefore, after the smart sensors/actuators are automatically discovered by the control system, the next step is to distinguish the logic locations of these components so the binding list of inputs and outputs of all control loops and monitoring points can be generated.

So far there is no generic methodology or algorithm that has been developed for automatically resolving system ambiguity for HVAC control systems. Neugschwandtner [32][33] recognized that for mapping or binding the correct inputs/outputs in the system, each component needs to be told its purpose in the control system based on the project design. Ideally each component should be able to find this information automatically. He suggested a way of resolving system ambiguity in a semi-automatic way: for control system with central configuration manager software, first, the user needs to enter a serial number or assigned unique device tag of each component at manager and broadcasting the tag, then put device into "listening mode" and retrieve back its identification. In the final step, the configuration manager will list possibilities for each device and user has to confirm or disprove.

To map component inputs/outputs in the LonWorks ISI protocol, a connection model was developed and used in the self-installation procedure for *automatic*, *controlled*, or *manual* enrollment modes [6] [7]. ISI connections (or mapping) are created among *connection assemblies*. A single network variable is called a simple assembly, and a connection assembly consisting of more than one network variable (e.g. a control loop) is called a *compound assembly*. The procedure of mapping input and output are similar to the steps discussed above. No algorithm for resolving HVAC system ambiguity is developed in the protocol, and the "self-installation" procedure is only good for small building or home automation applications with simple network topology and simple inputs/outputs mapping, where not much component system ambiguity is involved and some human intervention is still need during the setup and commissioning process.

## 3.5 Technology Gap Analysis for Self-Configuring HVAC Control System

In Chapter 3.1, a desired fully "self-configuring" building automation system setup process is discussed. In the Step 3 "System Configuration and Programming" phase (which after all the components of the control system are fully identified), a major step is to *automatically* create the binding list of inputs/outputs based on the design intent, and then make the correct connections. There is a huge technology gap in doing this because of the following reasons:

1. There are many possible different designs for HVAC projects
2. For a specific HVAC design, different building automation system manufacturers often implement the control strategies differently. There are no standardized

control strategies (like a “template”) available, though ASHRAE is working now towards this goal.

3. Even with a standardized control system design, how to *automatically* convert the design to a computer object model and then into different control languages is a big question. For small and simple projects, it may be easy to do as LonWorks ISI protocol demonstrated in its specification and programmers’ guide [7], but it is very hard, if not impossible, to do for a complicated large project with many control loops at field levels and global controls at higher levels.

To fill these gaps, the following technology advancements need to be in place:

1. The most common HVAC designs need to be categorized and standardized;
2. Theoretic development for mapping design intent to a computer object model. The algorithm needs to be flexible and scalable to cover most common HVAC functions and control strategies;
3. Standardizing normal HVAC control strategies;
4. Technology advancement in converting a common computer object model for a specified control strategy to different building automation system control languages.

# CHAPTER 4. A PLUG AND PLAY FRAMEWORK FOR AN AHU

## 4.1 Introduction

There are two major types of HVAC systems for commercial buildings: a) Radiant system, and b) Forced air system. The radiant system runs hot or chilled water though radiant pipes around the building or under the floor surface to radiate heat/cold into the space. This type is not discussed in this research. The forced air system uses fans to move hot or cold air to different conditioned spaces (or called zones). Commercial HVAC control systems usually include the following sub-systems: Air Handling Unit (AHU), distribution system, terminal systems, heating equipment, and cooling equipment. As discussed in Chapter 2 and Chapter 3, many technology gaps exist to prevent the development of a full blown plug and play or self-configuring HVAC control system. In this chapter, a plug and play framework for an AHU is developed to provide a possible model for future expansion of similar research to the whole HVAC control system.

The AHU (illustrated in Figure 15) is a very important piece of equipment in a HVAC system. It is used to receive heating or chilled water generated by heating equipment (e.g. boiler) and cooling equipment (e.g. chiller), and condition the mixed air through heat transfer mechanisms to provide conditioned air to the terminal units in different zones. The major components in an AHU include supply fan and return fan for delivering air, cooling coil and heating coil for heat transfer, outside air, return air and exhaust air dampers for regulating air directions, and chilled water pumps and heating water pumps for pumping heat transfer fluid. The typical instrumentation and control outputs in an AHU are categorized as follows in Table 6:

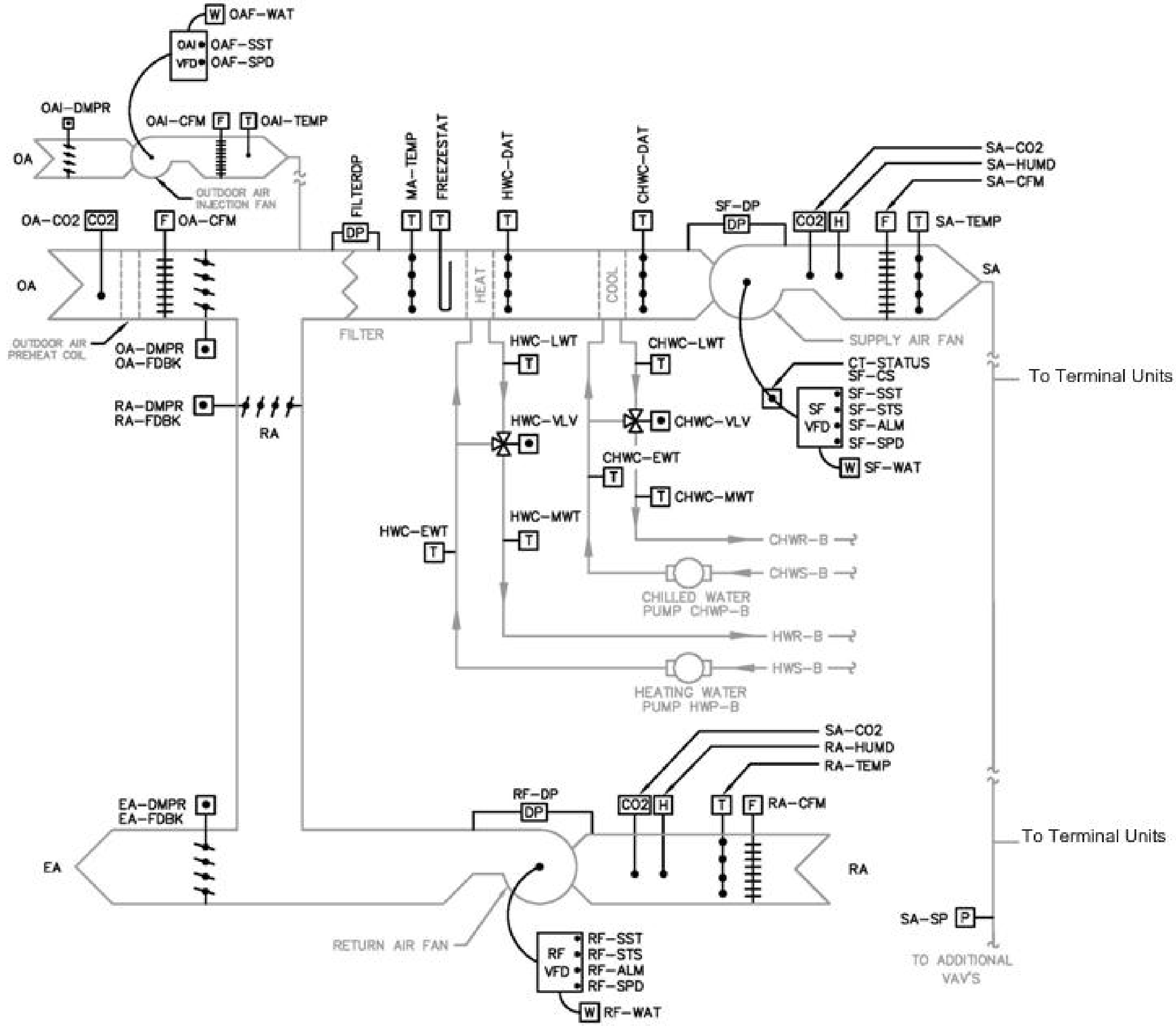



Figure 15. A single duct, variable air volume air handling unit schematic diagram

Table 6. Typical AHU control inputs and outputs

| Category | Point Names | Description |
|---|---|---|
| AI: Temperature | OA-TEMP | Outside air temp. |
| | MA-TEMP | Mixed air temp. |
| | SA-TEMP | Supply air temp. |
| | RA-TEMP | Return air temp. |
| | CHWC-DAT | Chilled water coil discharge air temp. |
| | HWC-DAT | Heating water coil discharge air temp. |
| | CHWC-EWT | Chilled water coil entering water temp. |
| | CHWC-LWT | Chilled water coil leaving water temp. |
| | CHWC-MWT | Chilled water coil mixing water temp. |
| | HWC-EWT | Heating water coil entering water temp. |
| | HWC-LWT | Heating water coil leaving water temp. |
| | HWC-MWT | Heating water coil mixing water temp. |
| AI: Pressure | SA-SP | Supply air duct static pressure |
| | SF-DP | Supply fan differential pressure |
| | RF-DP | Return fan differential pressure |
| AI: Relative Humidity | SA-HUMD | Supply air relative humidity |
| | RA-HUMD | Return air relative humidity |
| AI: Air Flow | SA-CFM | Supply air flow rate |
| | RA-CFM | Return air flow rate |
| | OA-CFM | Outside air flow rate |
| AI: Water Flow | CHWC-GPM | Chilled water coil flow rate |
| | HWC-GPM | Heating water coil flow rate |
| AI: Damper Feedback | OA-FDBK | Outside air damper feedback |
| | RA-FDBK | Return air damper feedback |
| | EA-FDBK | Exhaust air damper feedback |
| AO: Fan Speed | SF-SPD | Supply fan % speed output |
| | RF-SPD | Return fan % speed output |
| AO: Valve Position | CHWC-VLV | Chilled water coil control valve output |
| | HWC-VLV | Heating water coil control valve output |
| AO: Damper Position | OA-DMPR | Outside air damper % output |
| | RA-DMPR | Return air damper % output |
| | EA-DMPR | Exhaust air damper % output |
| DI: Fan Status | SF-STS | Supply fan status |
| | RF-STS | Return fan status |
| DO: Fan Start/Stop | SF-SST | Supply fan start/stop |
| | RF-SST | Return fan start/stop |
| DO: Pump Start/Stop | CHWP-SST | Chilled water pump start/stop |
| | HWP-SST | Heating water pump start/stop |

As defined in Chapter 3, a plug and play HVAC control system means that the control system components are recognized automatically once they are installed on (or removed from) the network. *For a plug and play AHU control system, the control system components as listed in Table 6 should be recognized automatically once they are installed on (or removed from) the network without human intervention*. This involves automatic discovery of those control points, as well as resolving system ambiguity about logical locations of these sensors/actuators, etc. A plug and play AHU control system also means that the sensors/actuators of the same type listed above can be freely plugged into any input/output channel (without prior assignment by the control system designer), the configuration software can discover, recognized the logic location of these inputs/outputs, and enable the binding of inputs/outputs *automatically*.

## 4.2 Assumptions

To fill the enormous technology gaps for components, network and communications, as well as algorithms to resolve system ambiguity and develop a framework for plug and play AHU control system is not easy. Many required products or technologies are still not commercially available. Some reasonable assumptions should be made before the framework can be developed.

1. All sensors/actuators should be identifiable by type;

   The components should be able to be distinguished automatically by their types – e.g. temperature, pressure, air flow, damper, or valve, etc., even though the logical location may not be pre-programmed by the sensor/actuator manufacturer.

   BACnet defined 25 object types including “analog input”, “analog output”, "binary input", and "binary output", but it may not be categorized by more details for each sub-type (e.g. temperature and pressure all belong to analog input type), even though some manufacturers put sensor type information on the optional "Device_Type" property in the BACnet object. A workaround is to generate a database of all sensor/actuator model numbers and determine the sensor/actuator type by its "Model_Name" property. For LonWorks devices, the SNVTs can be used to distinguish different sensor/actuator types. The self documenting string in the SNVTs may also help. IEEE 1451 compatible smart sensor/actuators have manufacturer ID, model number, and transducer types on the TEDS embedded in the transducers. Some sensor types (e.g. temperatures) are categorized with substantial detail. However, most sensors types commonly used in HVAC industry may not be available in the current specification yet.

2. All components of the plug and play AHU control system should be able to communicate throughout the network;

   No matter which smart sensors/actuators are used in the plug and play system, as components in the direct digital control system, they have to be able to communicate with the controls network and possibly with each other.

   One choice is to use one communication protocol throughout. For example, an all BACnet control system or an all LonWorks control system. The con of this approach is there may be less or no choice for some of the smart sensors/actuators available on the market. A second choice is to mix up different communication protocols at various levels, but need to have some protocol conversion device as a bridge or gateway to let two different protocols to talk each other. For example, to use IEEE 1451 compatible smart sensors/actuators in a BACnet or LonWorks control system. The con is that there is currently no IEEE 1451 sub-standard developed yet to process the IEEE 1451 compatible smart sensor/actuator information (e.g. TEDS) and convert to BACnet object or LonWorks SNVTs parameters. This is a critical step necessary for this approach to be feasible.

3. All components have to pass functional test in the field;

   All inputs and outputs in Table 6 have to be working properly in the field before the algorithm to solve system ambiguity process starts. This eliminates the possibility of false identification because of a bad or damaged component.

4. Chilled water and heating water should be provided at reasonable temperatures and flow rate.

   The chilled water and heating water provided to the AHU system should at least meet the designed temperature and flow rate for the system. This is critical in the proposed algorithm used to resolve system ambiguity.

## 4.3 A plug and play framework for an AHU

The plug and play framework for an AHU proposed in this research is based on centralized building control system architecture, because all the components really serve a single purpose – provide controllable, stable conditioned air to the building. This could be a sub-system in a decentralized HVAC control system, or part of a centralized HVAC control system. The framework architecture is illustrated in Figure 16.

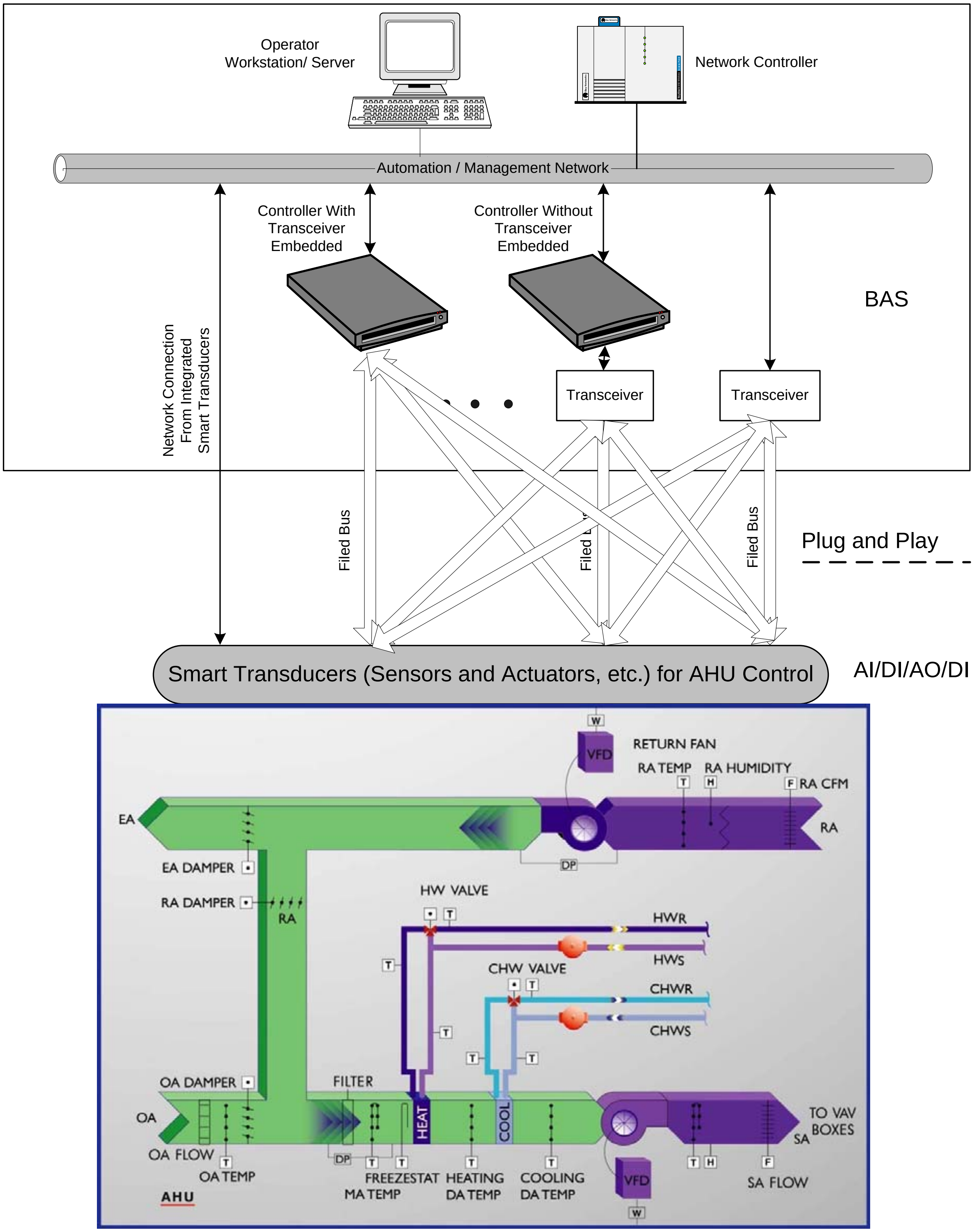



Figure 16. A plug and play framework for an AHU architecture

In this framework architecture, there are two major parts: 1) AHU and its smart sensors/actuators that cover all the points listed in Table 6; and 2) AHU building automation control system. The “smart sensors/actuators” are sensors and actuators that have at least device type information (e.g. temperature, pressure, damper, etc.) embedded in the device. The AHU building control system consists of operator workstation/server (to provide user interface for the building automation system, which also includes a self-configuration manager software), network controller for global networked control, transceivers for converting smart sensor/transducer information from field bus communication protocol to protocol used by the control system, integrated smart sensor with embedded transceiver, local controller and I/O modules with embedded transceiver, and local controller and I/O modules without embedded transceiver . The transceiver here is a general term referring to the independent component that serves the similar function as the NCAP in IEEE 1451 standards. For example, if the sensor/actuators used are IEEE 1451 smart transducers, and the control system’s protocol is BACnet, then the transceivers are the IEEE 1451 NCAPs to convert IEEE 1451.x to BACnet (though it has yet to be developed). If the control system’s protocol is LonWorks, then the transceivers are the IEEE 1451 NCAPs to convert IEEE 1451.x to LonWorks protocol (yet to be developed).

The framework specifies different possible ways for smart transducers to be connected to building automation system:

1. Direct connect. If the smart transducer uses the same protocol with the control system, or it is a integrated smart transducer with the transceiver embedded, it can directly connect to the control network;

2. Through controller with the transceiver embedded so it can also communicate with smart transducers at field level and also with the control network at automation/management level;
3. Through controller without the transceiver embedded plus a separate transceiver;
4. Through an independent transceiver. Smart transducer information will be converted from field bus via this transceiver to network protocol used by the control network.

The plug and play in this framework refers to the interoperability of smart transducers at the physical level (eg. at field bus, all the smart transducers are freely to connect to any channel/port of any transceiver, or local controller with the transceiver embedded), and at the system level (eg. the capability for the BAS to automatically identify the logical location of each smart transducer – a requirement for control points binding and mapping). Therefore, this plug and play framework for an AHU requires the control system to have a "self-configuration manager" software that automatically detects and identifies inputs and outputs that are connected to the AHU. The functions of the software shall have two major processes:

1. Auto-discovery of all sensor/actuator points;
2. Auto-identification of logical locations of those points.

The first process requires that smart transducers have the self-describing feature and a plug and play or self configuring specification defined for the control network (e.g., IEEE 1451 sets of standards, LonWorks ISI protocol). Some BAS already have the auto-discovery feature in their software.

The auto-identification of logical locations of AHU inputs/outputs is the key to the plug and play framework for an AHU as well as the self-configuring control system of the future. The algorithm for the auto-identification is based on the following observation/assumption:

*Any distinct input/output point in an AHU serves a unique purpose (except redundant points used for reliability). Therefore, given a specified sequence of operation on the outputs, the inputs from different logical locations should display identifiable, unique, time-series patterns. The logical locations of these inputs/outputs can be recognized by studying the sequence of operations and the output patterns generated.*

The sequence of operation and the pattern recognition algorithm for each input/output point may be different. It is recommended that the inputs/outputs be identified in a single duct VAV AHU according to the sequence shown in Table 7.

The critical step in the point identification of all AHU inputs/outputs is the identification of logical locations for temperatures. If these temperature sensors are correctly identified, other inputs and outputs are relatively easy to be identified. In Chapter 5, an algorithm to recognize all AHU temperature points is studied in detail.

The control system I/O modules need to be able to read smart sensor/actuator information and communicate over the network in a peer to peer fashion. The overall hardware should have multiple PID control loops that can control the minimum of following AHU processes that are listed in Table 8.

Table 7. Recommended sequence for identifying inputs/outputs for an AHU

| Recommended Identifying Order | Category | Point Names |
|---|---|---|
| **1** | AO: Valve Position | CHWC-VLV |
| | | HWC-VLV |
| | DO: Pump Start/Stop | CHWP-SST |
| | | HWP-SST |
| **2** | AI: Temperature | OA-TEMP |
| | | MA-TEMP |
| | | SA-TEMP |
| | | RA-TEMP |
| | | CHWC-DAT |
| | | HWC-DAT |
| | | CHWC-EWT |
| | | CHWC-LWT |
| | | CHWC-MWT |
| | | HWC-EWT |
| | | HWC-LWT |
| | | HWC-MWT |
| **3** | DI: Fan Status | SF-STS |
| | | RF-STS |
| | DO: Fan Start/Stop | SF-SST |
| | | RF-SST |
| | AI: Pressure | SA-SP |
| | | SF-DP |
| | | RF-DP |
| | AI: Relative Humidity | SA-HUMD |
| | | RA-HUMD |
| | AI: Air Flow | SA-CFM |
| | | RA-CFM |
| | | OA-CFM |
| | AI: Water Flow | CHWC-GPM |
| | | HWC-GPM |
| | AO: Fan Speed | SF-SPD |
| | | RF-SPD |
| **4** | AO: Damper Position | OA-DMPR |
| | | RA-DMPR |
| | | EA-DMPR |
| | AI: Damper Feedback | OA-FDBK |
| | | RA-FDBK |
| | | EA-FDBK |

Table 8. Typical AHU control loops

| Control Loop Name | Related I/O Points | Description |
|---|---|---|
| Supply Air Temperature | SA-TEMP | Supply air temp. |
| | CHWC-VLV | Chilled water valve |
| | HWC-VLV | Heating water valve |
| | CHWP-SST | Chilled water pump |
| | HWP-SST | Heating water pump |
| Supply Fan Differential Pressure | SF-DP | Supply fan differential pressure |
| | SF-SPD | Supply fan VFD speed |
| | SF-SST | Supply fan start/stop |
| Return Fan Speed | RF-SPD | Chilled water coil mixing air temp. |
| | RF-SST | Supply fan start/stop |
| | SF-SPD | Supply fan speed |
| | RF-CFM | Return fan air flow. |
| | SF-CFM | Supply fan airflow |
| AHU Dampers | OA-DMPR | Outside air damper |
| | RA-DMPR | Return air damper |
| | EA-DMPR | Exhaust air damper |
| | SA-TEMP | Supply air temperature |
| | RA-TEMP | Return air temperature |

The real-time information exchange and PID control loop configuration are very flexible in this plug and play framework as illustrated in Figure 17, due to the plug and play feature at field bus level. If the input/output points related to any of the control loops listed in Table 8 are physically connected to the same control module, the PID control can be done in one controller, as commonly implemented in current BAS. The network controller can also be used to apply networked control (vs. physical control in a hardware PID loop in a local controller), where input and output are not necessarily connected to the same controller hardware. Another possibility is to use software PID or advanced control algorithms (e.g. fuzzy logic control) to be executed in a workstation/server. If the transceiver can embed PID control function (similar to the IEEE 1451 NCAP application processing units), simple PID control loop can be executed at the transceiver too.

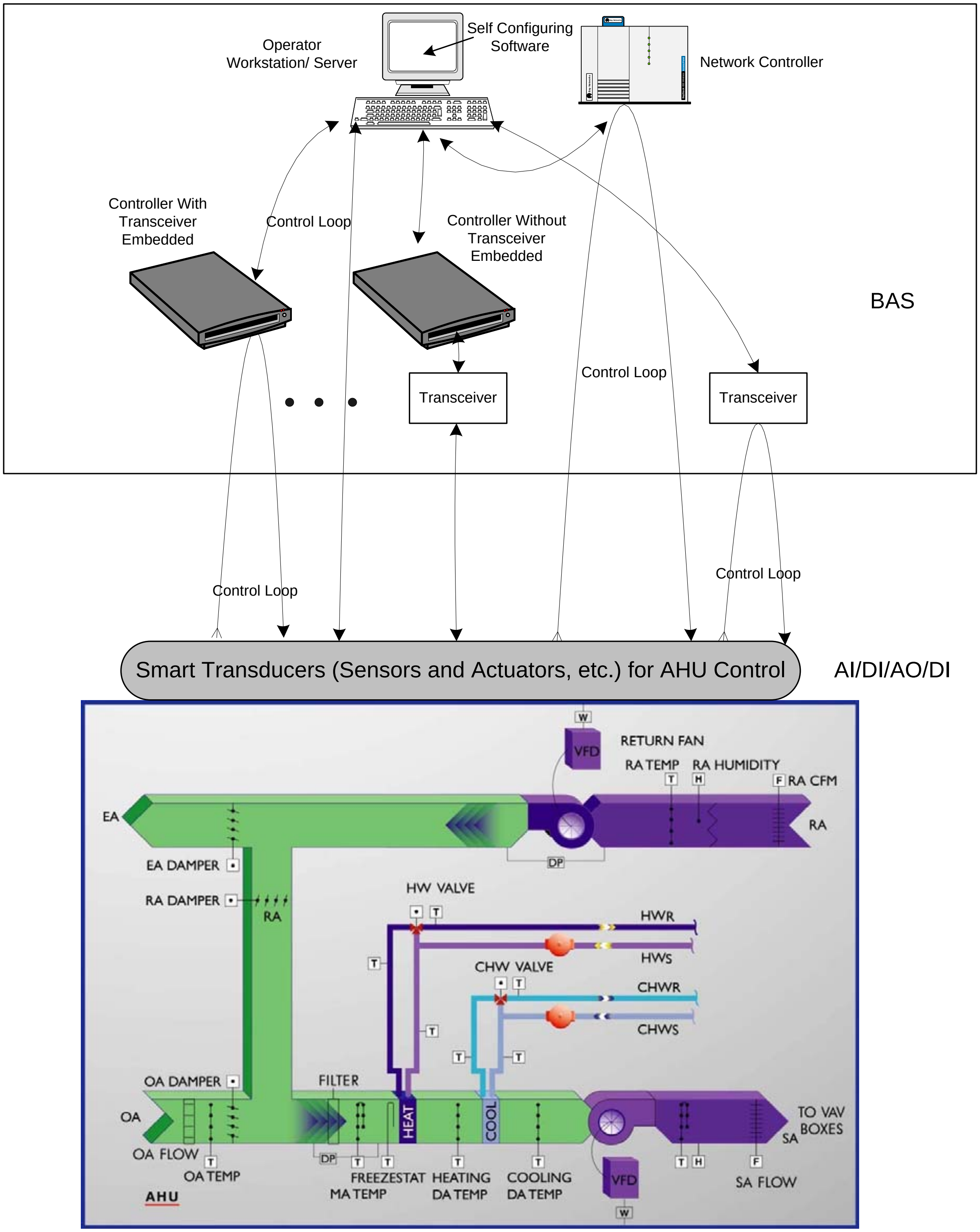



Figure 17. A plug and play framework for an AHU information flow diagram

This plug and play framework for AHU will provide the basis for a future self-configuring HVAC system. Once all the inputs/outputs can be recognized automatically (i.e. system ambiguity can be resolved), the binding and mapping of inputs and outputs can be done based on the control strategy and design intent, thus enabling the “self-configuring” feature. The standardization of common control strategies and converting design intent to a DDC programming language automatically will still need future research.

# CHAPTER 5. AHU TEMPERATUE AUTO RECOGNITION

## 5.1 Introduction, Key Assumptions, and Steps

To resolve system ambiguity problem for an AHU Plug and Play framework, a very important (and maybe difficult) step is to automatically identify logical locations for the temperature sensors. Pattern recognition techniques applied to time series data to identify logical locations of system components is the key to solve this problem. This is based on the previous assumption that, *given a specified sequence of operation (a combination of supply fan, return fan, outside air damper, return air damper, exhaust air damper, cooling coil valve, heating coil valve, chilled water pump and heating water pump, etc.), temperature patterns at different logical locations should show different recognizable patterns.* This should be expected because each AHU component serves different function and thus they will have different impact to the temperatures downstream.

The temperature sensor auto recognition technique should have the following characteristics to ensure it not only works in theory, but also in practice as well:

1. The algorithm should be able to apply in most common conditions: any time of day, any season in a year, most common outside air conditions, and most common environmental conditions for the location of an AHU (usually in the mechanical room)
2. The algorithm should not depend on other (known or unknown) temperature sensor outputs or any other sensor outputs.

3. The algorithm should be applicable to different sizing of the AHU mechanical system components (fans, pumps, cooling coil, heating coil, etc.), as long as the their main functions are similar to the AHU in study

The AHU temperature sensor auto recognition technique development and test steps are illustrated in Figure 18:

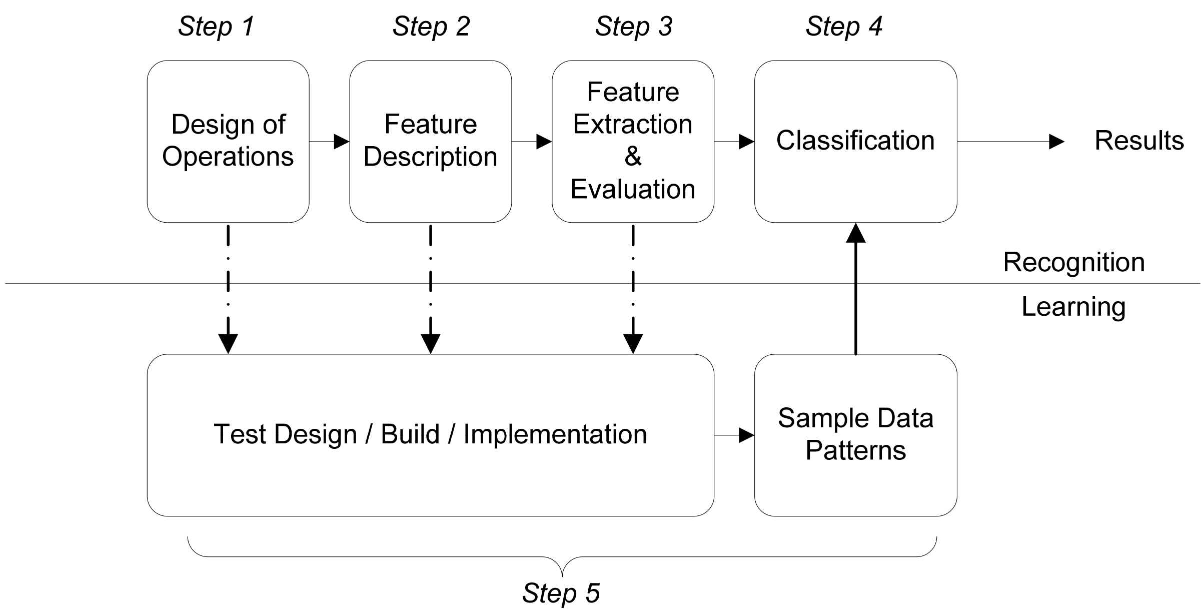



Figure 18. Key steps for AHU temperature auto recognition technique development

*The first step is to design proper sequence of operations for AHU to generate temperature patterns.* This step needs expert domain knowledge of the application. In this study, the function of each component in the AHU and its effect on the other components and temperatures in the system need to be fully understood before the sequence of operations can be properly selected. Sometimes, trial and error may be needed to fine tune the sequence of operation so that the temperature patterns measured at different locations can be unique in common operation and environmental conditions and be easily identified.

Given a well designed sequence of operation for AHU, *the second step is to design a feature description algorithm* – to categorize, organize, and model data patterns into *string* or *graph* representations. During this step, the expected temperature patterns will be analyzed for each logical location based on the designed sequence of operation, and the most common basic shapes will be picked up as the foundation of the AHU temperature sensor structural recognition technique model.

*The third step is to develop feature extraction algorithms and evaluation criteria.* Algorithms will be developed or selected for easy extraction of the features from the time-series temperature pattern data according to the basic shapes.

*The fourth step is the classification of the temperature patterns.* Either parsing or graph pattern matching methods will be developed for classification of the expected temperature patterns for each logical location.

*The final step is the testing and validation of the technique.* Tests will be designed and implemented, and data will be collected as sample patters for supervised learning and recognition. This step will be discussed in detail in Chapter 6 and Chapter 7.

## 5.2 Design of Sequence of Operations

In this section, the impacts of AHU components on different temperature locations are analyzed and then the sequence of operations for temperature recognition is introduced.

### 5.2.1 Input and Output Points Involved

There are two major categories for air handling units: single duct systems and dual duct systems. The system under study is a single duct variable air volume AHU that is illustrated in Figure 15 in Chapter 4. Before the design of a sequence of operations for the AHU, the inputs/outputs available and required for the pattern recognition algorithm need to be identified. Based on the plug and play framework defined in Chapter 4, the related points include all temperature points and all possible output points listed in Table 9, and these inputs/outputs are emphasized in Figure 19 using colored boxes:

Table 9. Input and output points involved in temperature sensor auto recognition

| Category | Point Names | Description |
|---|---|---|
| AI: Temperature | OA-TEMP | Outside air temp. |
| | MA-TEMP | Mixed air temp. |
| | SA-TEMP | Supply air temp. |
| | RA-TEMP | Return air temp. |
| | CHWC-DAT | Chilled water coil discharge air temp. |
| | HWC-DAT | Heating water coil discharge air temp. |
| | CHWC-EWT | Chilled water coil entering water temp. |
| | CHWC-LWT | Chilled water coil leaving water temp. |
| | CHWC-MWT | Chilled water coil mixing water temp. |
| | HWC-EWT | Heating water coil entering water temp. |
| | HWC-LWT | Heating water coil leaving water temp. |
| | HWC-MWT | Heating water coil mixing water temp. |
| AO: Fan Speed | SF-SPD | Supply fan % speed output |
| | RF-SPD | Return fan % speed output |
| AO: Valve Position | CHWC-VLV | Chilled water coil control valve output |
| | HWC-VLV | Heating water coil control valve output |
| AO: Damper Position | OA-DMPR | Outside air damper % output |
| | RA-DMPR | Return air damper % output |
| | EA-DMPR | Exhaust air damper % output |
| DO: Fan Start/Stop | SF-SST | Supply fan start/stop |
| | RF-SST | Return fan start/stop |
| DO: Pump Start/Stop | CHWP-SST | Chilled water pump start/stop |
| | HWP-SST | Heating water pump start/stop |

One important assumption in the plug and play framework discussed in Chapter 4 is that all smart transducers (sensors and actuators, etc.) should be identifiable by their sensing or actuating type. For example, all temperature sensors should be known by their type and the output should be in a standard unit like “Deg C” or “Deg F”, even though the logical location information is unknown. Analog outputs such as “Fan Speed” – usually via variable frequency drive (VFD) - must be differentiated from other analog outputs such as “Valve Position”, which uses a smart valve actuator. Whether a “FAN Speed” output is for supply fan or return fan may not be known at this stage yet. The same thing can be said for “Damper Position” analog outputs and “Pump Start/Stop” digital outputs. However, the analog outputs of “Valve Position” and digital outputs of “Pump Start/Stop” do need to be identified by their logical locations before this temperature sensor auto recognition algorithm is applied. This is because these points will greatly affect the heat transfer functionality and therefore the temperature pattern at (almost) all locations in the AHU. This is the reason why in Chapter 4 it is recommended that these four points’ logical locations need to be identified BEFORE the temperature sensors identification.

The identification of chilled water valve (CHWC-VLV), heating valve (HWC-VLV), chilled water pump (CHWP-SST), and heating water pump (HWP-SST) is very easy. Since the type of smart transducers are known, assign one of the valves to AO1 and the other valve AO2, then assign one of the pumps to DO1 and the other pump DO2. The sequence of operation could be as follows:

1. Open AO1 100% open, and open AO2 100% open;
2. Start DO1

Record all temperature data. If any of the temperatures drop significantly, then DO1 is the chilled water pump. If any of the temperatures rise significantly, then DO1 is the heating water pump. After DO1 is recognized, DO2 is the other pump.

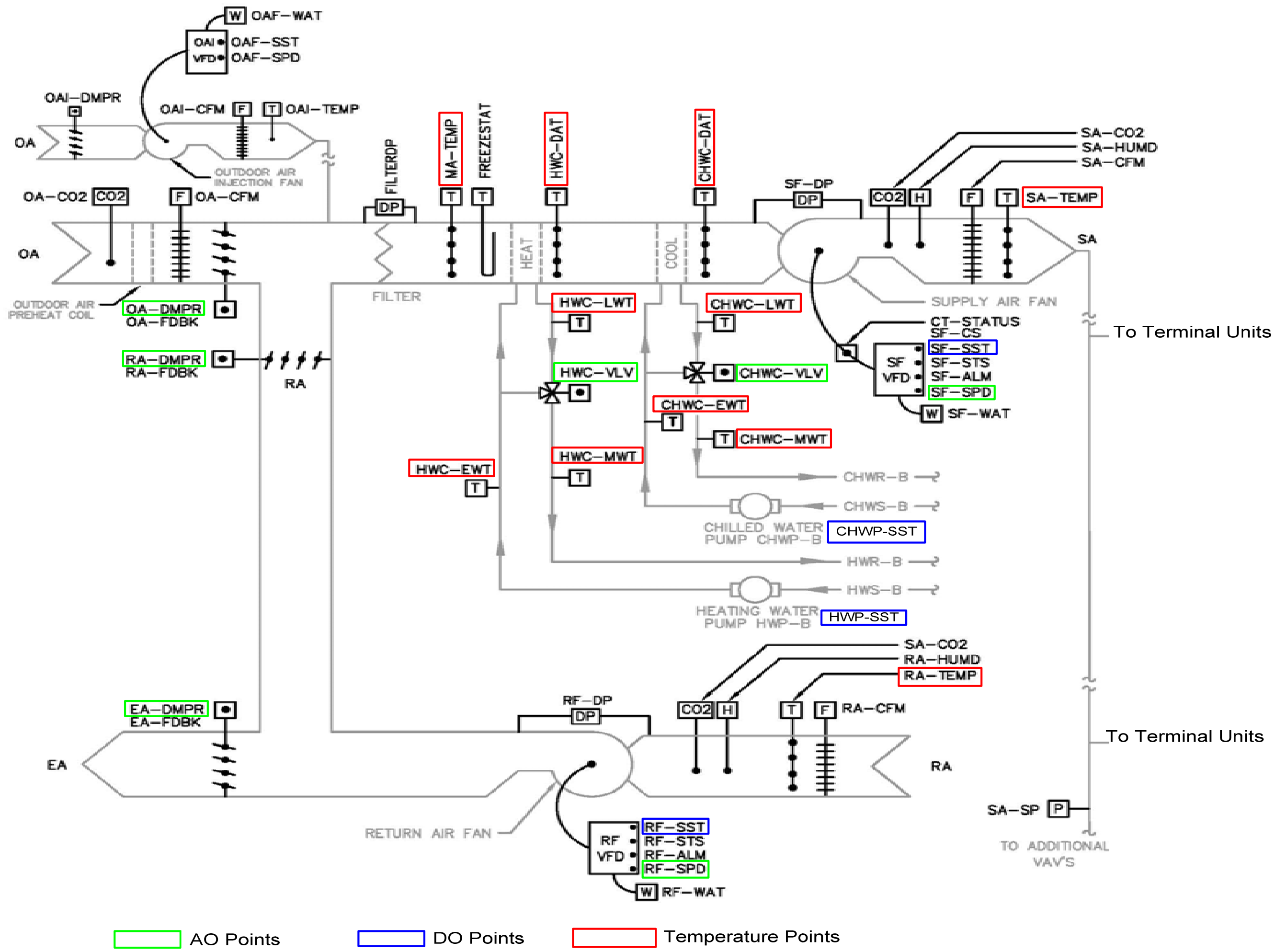



Figure 19. Inputs/outputs related to temperature auto recognition algorithm

To recognize chilled water and heating water valves, implement the following Sequence of operations:

1. Start chilled water pump;
2. Open AO1;

Record all temperature data. If any of the temperatures drop significantly, then AO1 is the chilled water valve. If no temperatures drop significantly, then AO1 is the heating water valve, and AO2 is the chilled water valve.

The sequence of operation to recognize temperature sensors in an AHU needs deep understanding of the function of each AHU component as well as how an AHU operates in normal conditions. The function of each major AHU component and its impact on temperature sensor output patterns is analyzed in the next several sections.

### 5.2.2 Supply Fan and Return Fan Impact

As the major air flow moving components in the AHU, modern supply fans and return fans usually use Variable Frequency Drives (VFD) to vary the frequency of the AC power for the fan motors, therefore changing the fan speed, duct pressure and air flow rate. During the design phase, the sizing of the supply or return fan is based on the designed air flow rate and 100% speed for the fan.

When supply fan and return fan are stopped, there is no air movement in the AHU so all air temperatures in the AHU (except outside air temperature) will drift towards the environment temperature where AHU is located, assuming both cooling coil valve and heating coil valve are closed.

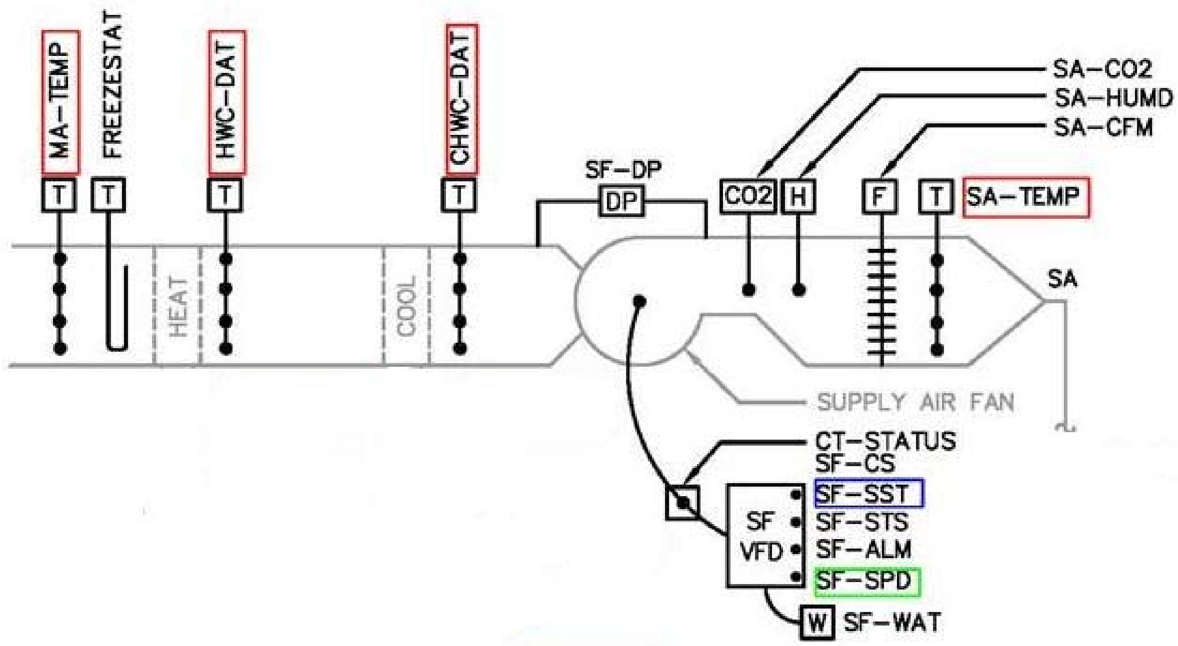



Figure 20. A close-up of AHU supply duct schematic diagram

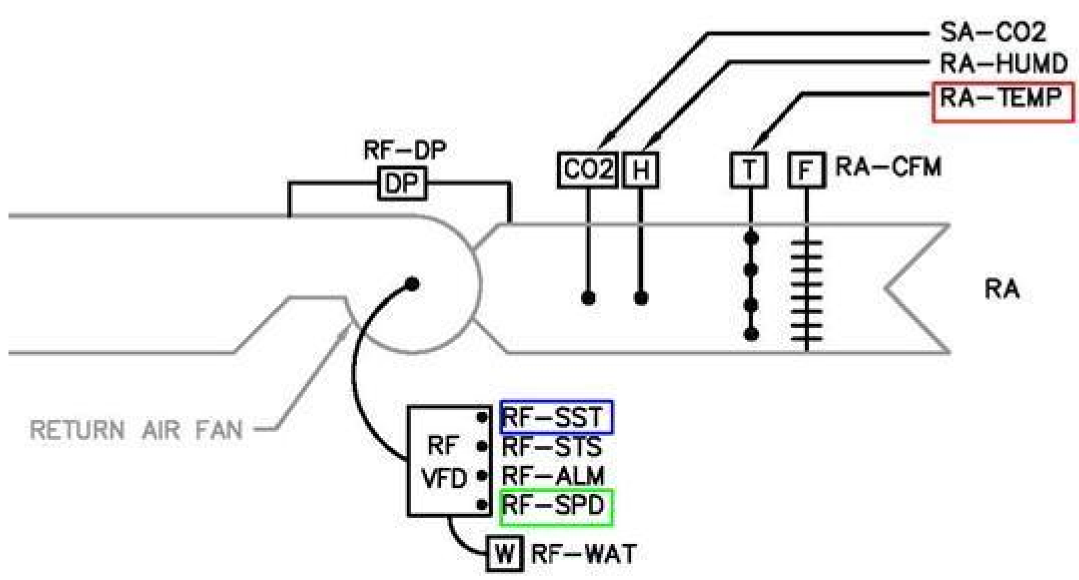



Figure 21. A close-up of AHU return duct schematic diagram

When supply and return fans start, the fan motors usually will generate heat (especially when the fans run at full speed) which is transferred via moving air to the down stream air. For the supply fan (Figure 20), the only temperature sensor that is affected significantly by this is the “SA-TEMP”. All supply fans’ upstream air temperatures and all water temperatures should not be affected. For the return fan (Figure 21), since the “RA-TEMP” is upstream of return fan, it will not be affected. The downstream temperatures (“MA-TEMP”, “CHWC-DAT”, “HWC-DAT”, and “SA-TEMP”) may not be affected much either because 1) it will be depend on the three damper positions; and 2) the return fan usually has less power and the distance to those downstream temperature sensors are relatively far so the heat generated by the motor may already dissipate though the AHU duct.

When supply and return fans stop, the effects are the opposite. The only temperature that is significantly affected is the “SA-TEMP”, which will decrease in temperature because of the motor heat is now removed.

From the above, starting and stopping the supply fan has the potential to be a factor in recognizing the “SA-TEMP”.

### 5.2.3 Chilled Water Pump and Chilled Water Control Valve Impact

The chilled water pump and chilled water valve work together to regulate the chilled water flow into the cooling coil in the AHU, as illustrated in Figure 22.

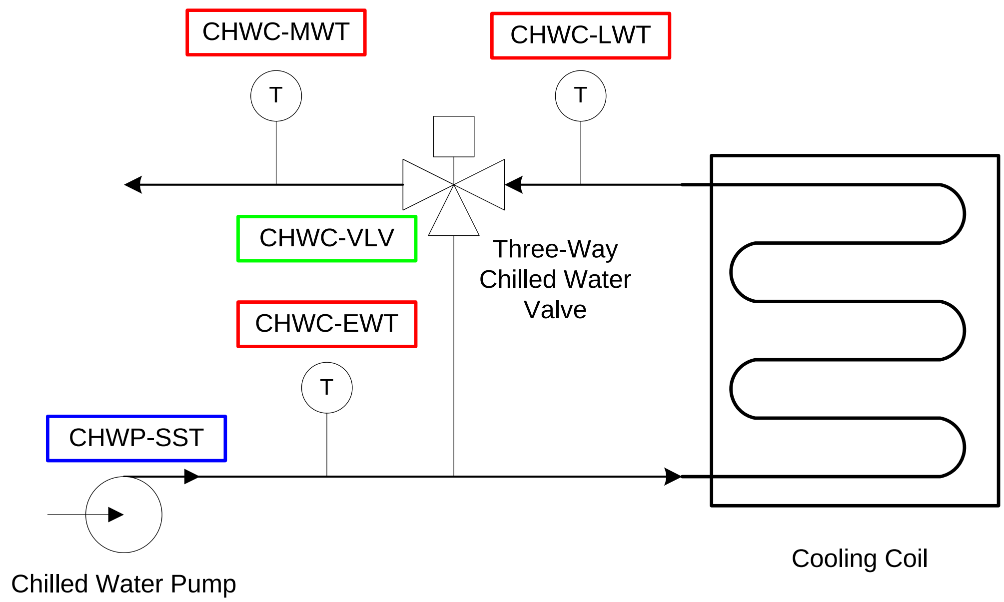



Figure 22. A close-up of AHU cooling system schematic diagram

No matter the type, size, and model of the chilled water pump, cooling coil (heat exchanger), and the chilled water valve, the basic function of the cooling coil and the chilled water system in an AHU is the same, which is to transfer heat from air to the chilled water. When the chilled water pump is running and the chilled water valve (CHWC-VLV) is fully closed, there is no water flow going through the cooling coil because it is all by-passed directly through the three-way control valve back to the chilled water return. The chilled water entering and the mixing temperatures are similar to the supplied chilled water temperature (usually in the range of 40~50 Deg F). The leaving water temperature is somewhere between the entering water temperature and the environment temperature due to heat transfer with the environment through the coil and pipe. When the chilled water valve starts to open to fully open, there is partial to full designed flow going through the cooling coil. The entering water temperature should not change, but the leaving temperature will drop significantly from its original temperature, while the mixing temperature will increase compared to before the valve was opened because of the chilled water temperature increase across the cooling coil. In normal AHU operating condition, the AHU fans need to run in order for heat transfer to occur in the cooling and heating coils. So a combination of chilled water pump start/stop and chilled water valve open/close would change the temperature patterns for all three chilled water temperatures.

The effect of chilled water pump and control valve combination will significantly affect the air temperatures downstream of the cooling coil, especially the chilled water coil discharge air temperature CHWC-DAT. When the pump is running and the valve starts to open from fully closed position, the CHWC-DAT will immediately drop in temperature due to heat transfer from chilled water to air. The supply air temperature SA-TEMP will also decrease significantly, even though the rate may be a little slower. The RA-TEMP and all upstream air temperatures - MA-TEMP, HWC-DAT, will be affected much slower because the colder supply air will be mostly absorbed by the thermal mass in the conditioned spaces. Because of this, the above operation can possibly distinguish air temperatures before and after the cooling coil.

### 5.2.4 Heating Water Pump and Heating Water Control Valve Impact

The heating water pump and heating water valve work the same way as the chilled water pump and chilled water valve discuss the above. An AHU heating system schematic is illustrated in Figure 23. The supply heating water temperature is much higher than normal environmental temperature (usually in the range of 120 Deg F to 180 Deg F). Therefore when the heating pump is running and the control valve starts to open, the leaving temperature will rise quickly and the mixing temperature will drop from the supply heating temperature when the three-way valve is fully closed. The stability of the supplied heating water is based on the boiler characteristics and the system heating load. A combination of heating water pump start/stop and heating water valve open/close would change the temperature pattern for all three heating water temperatures.

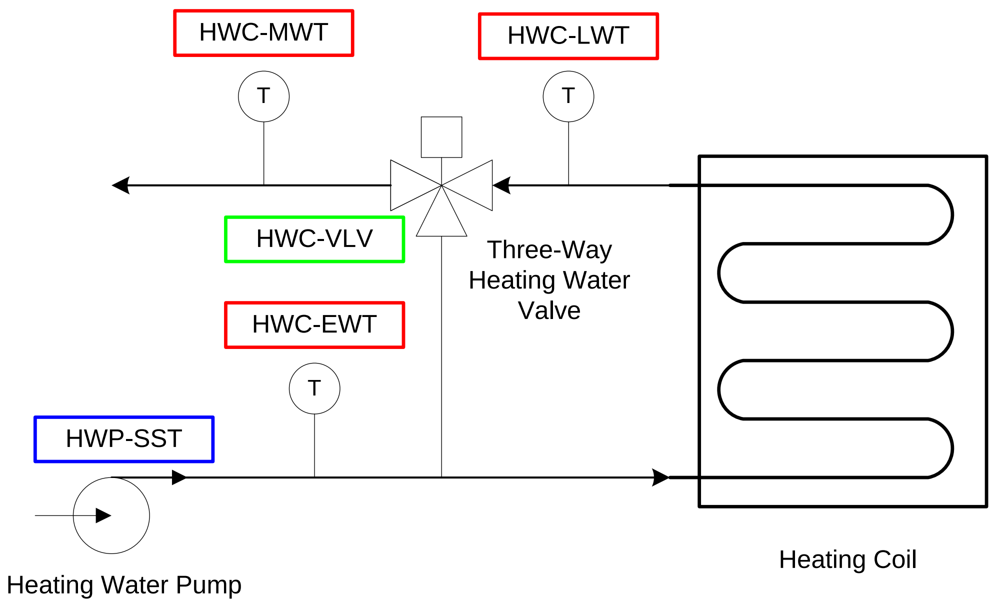



Figure 23. A close-up of AHU heating system schematic diagram

Similarly, by running the heating water pump and opening the heating control valve from the fully closed position, the air temperatures before and after the heating coil can be distinguished.

### 5.2.5 AHU Dampers Impact

There are three dampers in a single duct variable air volume AHU: outside air damper, return air damper, and exhaust air damper, as illustrated in Figure 24. The outside air and return air dampers control the mixing ratio of outside air and return air going to the

AHU mixing air. The exhaust air damper controls how much air is exhausted to the outside. Usually the percentage open for the outside air damper and exhaust air damper are the same as the percentage closed for the return air damper, to maintain the air flow balance for supply and return as well as outside air flow balance in and out of the building.

During AHU operations, these three damper positions greatly affect various temperatures at different AHU locations. If the AHU is operating at 100% recirculation mode, in which OA-DMPR is 0% open, RA-DMPR is 100% open, and EA-DMPR is 0% open, all AHU temperatures approach the same temperature value (assuming chilled water valve and heating valve closed and all zones do not have significant cooling and heating loads). With the opening of outside air damper and corresponding change to the return and exhaust air dampers, outside air will be mixed with return air and quickly affect the temperatures for MA-TEMP, HWC-DAT, CHWC-DAT, and SA-TEMP, then gradually affect RA-TEMP, depending on the AHU zones' thermal capacity. These temperatures will increase if the outside air temperature is higher than the return air temperature, or decrease if the outside air temperature is lower. The rate of increase or decrease in temperatures at different AHU locations will depend on the temperature difference between outside air and return air, the locations of the temperature sensors, air flow rate, and the percentage of open/close of the three dampers. When the AHU is in 100% outside air mode (100% open for OA-DMPR, 0% open for RA-DMPR, and 100% open for EA-DMPR), all AHU temperatures except RA-TEMP will approach the outside air temperature, as all return air is exhausted to the outside.

The impact of AHU damper positions on the heating and cooling water temperatures is not as significant as on the air temperatures. If there is no water flow going through the coils (i.e. water pumps are not running or coil control valve are fully closed), the leaving water temperatures are minimally affected due to small heat transfer from air flow to water flow. If there is water flow going through the coils (i.e. water pumps are running and coil control valve are partially or fully open), the leaving water temperature and the mixing water temperature will be affected due to the entering air temperature before the coils changing (higher or lower) and the heat transfer effects from air to water.

For the sequence of operation to be applicable both in summer and in winter, the percentage open for outside air damper needs to be carefully selected. This is because in the winter, the outside air may be below the freezing point (especially in the North America regions). A hundred percent outside air damper open position will cause freezing of heating and cooling coils if there is no water flow through these coils, thus damaging these components. Therefore only a partial open position is recommended during winter.

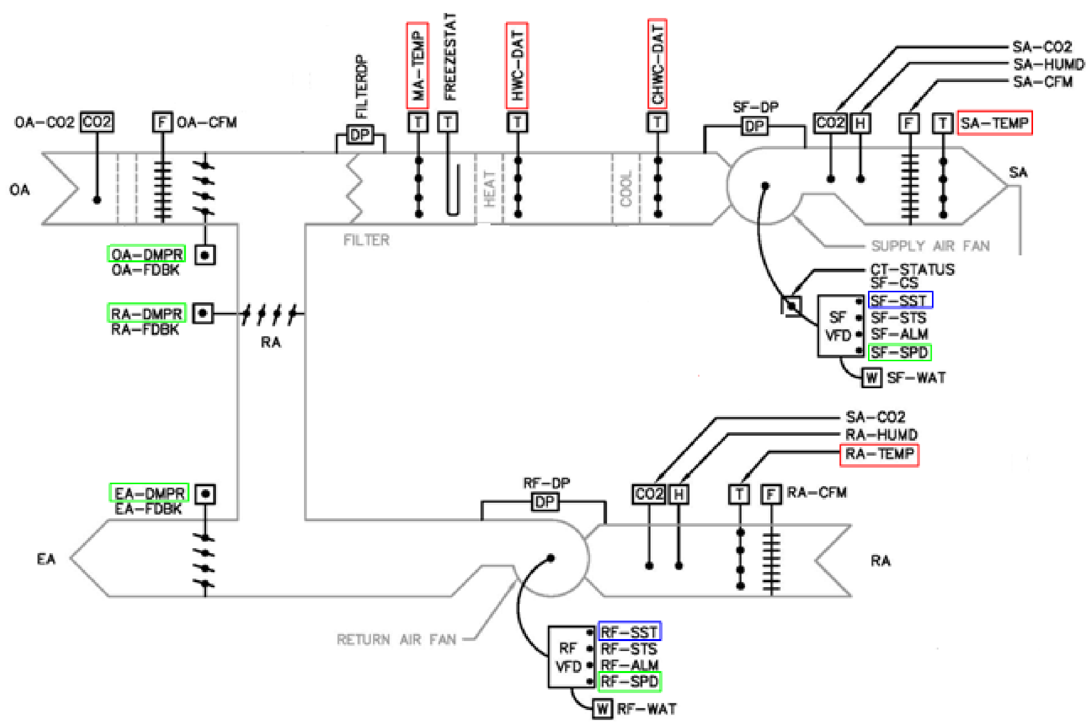



Figure 24. An AHU dampers schematic diagram

### 5.2.6 Put It Together

Based on the above analysis on the effect of component operations on different AHU air and water temperature sensors, the following sequence of operations is designed to achieve the goal of generating distinguishable temperature patterns for temperature sensors at different logical locations. This sequence should also be suitable for various outside and environmental conditions, and different type, size, and models of AHU components:

1. *Put AHU in 100% recirculation mode (OA-DMPR 0% open, RA-DMPR 100% open, EA-DMPR 0% open); Start supply fan and return fan and run at 100% speed. All water control valves fully closed; Start chilled water pump; Stop heating water pump.*

   This first step will make all air temperatures approach a stable temperature. Chilled water entering and mixing temperature should be at normal supply chilled water temperature range. All heating water temperatures should remain nearly constant.

2. *Open chilled water valve 100% open.*

   This operation should make CHWC-DAT and SA-TEMP decrease quickly, while also making CHWC-LWT drop and CHWC-MWT rise. The CHWC-EWT should not be affected. Other air temperatures will decrease also, but at a slower rate. All heating water temperatures should remain nearly constant.

3. *Open heating water valve 100%, and start the heating water pump.*

   The effect of this operation will be the quick temperature rise for all heating water temperatures. All air temperatures will rise also. Even the chilled water leaving temperature CHWC-LWT and mixing water temperature CHWC-MWT will rise because of heat transfer from air to the chilled water. The RA-TEMP and MA-TEMP may rise at much slower rate though, because they are upstream of the heating coil.

4. *Stop chilled water pump; Fully close chilled water valve; Fully close heating water valve (but keep heating water pump running).*

   This step removes the heat transfer effect from the heating and cooling coils. For chilled water temperatures, the mixing water temperature CHWC-MWT will drop quickly to be the same as the chilled water entering temperature. The leaving water CHWC-LWT will be floating because there is still some residual water in the cooling coil that is being affected by the air blowing through the coil. Similarly, the heating coil mixing water temperature HWC-MWT should rise to the entering heating water temperature range, and HWC-LWT will be floating. The HWC-DAT will drop quickly since the heating is removed from the heating coil. All other temperature pattern changes will depend on the relative capacity of heating coil and cooling coil in the AHU unit.

5. *Stop heating water pump; Open OA-DMPR (100% open in the Summer, and 50% open in the Winter); Close RA-DMPR (100% closed in the Summer, and 50% closed in the Winter); Open EA-DMPR (100% open in the Summer, and 50% open in the Winter).*

   These operations switch AHU from 100% recirculation mode to partial or 100% outside air mode and stop all heat transfers from heating and cooling coils. The effect of outside air may be different depending on the actual outside air temperatures and the steady state temperatures after step 4. The 50% can be adjusted to some other values based on the outside air temperature, as long as the freezestat on the AHU is not triggered.

6. *Stop supply fan and return fan.*

   The effect of stopping both fans will be different depending on the difference between outside air temperature and the AHU environmental temperature. However, the initial temperature change on SA-TEMP should always be down because the heat generated by the 100% speed supply fan is removed.

The time for each step is currently set to 1 hour to accommodate some of the slow processing time of heat transfer and temperature sensor response to temperature changes. The sampling time interval is 1 min. The sequence of operation is shown in a tabular format in Table 10.

Table 10. Sequence of operations for AHU temperature sensor recognition

| Point Names | Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 |
|---|---|---|---|---|---|---|
| SF-SST | ON | ON | ON | ON | ON | OFF |
| RF-SST | ON | ON | ON | ON | ON | OFF |
| OA-DMPR | 0%Open | 0%Open | 0%Open | 0%Open | 100%(50%) Open | 100% (50%) Open |
| RA-DMPR | 0%Closed | 0%Closed | 0%Closed | 0%Closed | 100%(50%) Closed | 100%(50%) Closed |
| EA-DMPR | 0%Open | 0%Open | 0%Open | 0%Open | 100%(50%) Open | 100%(50%) Open |
| HWP-SST | OFF | OFF | ON | ON | OFF | OFF |
| HWC-VLV | 0%Open | 0%Open | 100%Open | 0%Open | 0%Open | 0%Open |
| CHWP-SST | ON | ON | ON | ON | ON | ON |
| CHWC-VLV | 0%Open | 100%Open | 100%Open | 0%Open | 0%Open | 0%Open |
| SF-SPD | 100% | 100% | 100% | 100% | 100% | 100% |
| RF-SPD | 100% | 100% | 100% | 100% | 100% | 100% |

## 5.3 Structural Pattern Recognition in AHU Sensor Auto Recognition

As discussed in Chapter 2.5, a good approach for resolving system ambiguity in HVAC control systems is through structural pattern recognition. This section discusses the structural pattern recognition technique specific to AHU temperature sensor auto recognition applications.

The purpose of the designed sequence of operations in the previous section is to generate distinguishable temperature patterns for AHU temperature sensors at different logical locations. For each step in the sequence and at the same logical location, the temperature patterns may still be different in their magnitude and shapes for different AHUs and outside air conditions. This is because the AHU component type, size, model, and capacity may be different, and the time of day when these operations are implemented may be different. This makes the statistical pattern recognition approach (which is based on quantitative features and exact mathematical models) very difficult to be applied effectively. However, the rough shape (transient response pattern) for each step at a given logical location *should* be close, or limited to a number of possible "shapes", because the major function of the same component in different AHUs is the same. Hopefully, the structural pattern recognition technique (which is based on the pattern structural information or shapes) can be used successfully in this application.

One example is the air temperature pattern change when the heating coil or cooling coil control valve opens from a fully closed condition (Steps 2, 3 and 4). For air temperature sensors immediately after the heating and cooling coil (HWC-DAT and CHWC-DAT), their temperature patterns are greatly affected by the coil performance – the most important factor being the overall heat transfer coefficient area product which is determined by the physical properties of the coil. Because these coils are essentially heat exchangers and they have different flow arrangements (parallel flow, counter flow, cross flow), different types of constructions (finned-tube, shell-and-tube, plate etc.), and may use different materials, there is no universal formula for calculating heat transfer coefficients for steady state conditions under various water flow, air flow rates, and air properties. The temperature performance at the outlet of coils (HWC-DAT and CHWC-DAT) in the transition period may be even more difficult to describe mathematically. However, the major function of a heat exchanger is to increase or decrease air temperature after the coil. The rate of temperature increase and decrease after the coil will depend on the physical configuration of the coil, air and water flow rates, and the distance of the temperature sensor from the coil. The transient response of the temperature pattern with time will be likely a step up / step down, or exponential curve, due to transient conduction from air/water flow to the temperature sensors. Yu and Smith [51] studied the dynamic behavior of a cross counter-flow cooling coil by developing simulation models under dry and wet conditions and verifying the model accuracy with steady-state conditions using the effectiveness – NTU method. The dynamic response results were obtained by using explicit numerical methods. The study showed that the dynamic response of the coil discharge air temperature to a step change in inlet air and water temperature under various coil configurations and flow conditions are a combination of step up/down and exponential like curves.

Another example is the air temperature pattern change caused by the three AHU dampers changing from fully closed to fully open (Step 5). When the AHU changes from 100% recirculation mode to 100% outside air mode, the air temperature in the mixing chamber and supply air duct will change from the original stable temperature (whatever it is) to the outside air temperature. The transient temperature pattern will be determined by the damper type, damper actuator running time, air flow rates, temperature sensor response times, etc. The basic pattern should be still the same – exponential curves, whenever the outside air temperature is relatively stable during the period, except the magnitude and rate of change may be different at different AHU logical locations. The return air temperature change should be at a much slower rate because of the thermal mass in the conditioned space. So its pattern could be slow change exponential curve or close to a straight line.

The third example of the applicability of structural pattern recognition on AHU temperature sensor logical location is the temperature transient pattern for supply air temperature (SA-TEMP) when the supply fan stops from full speed running mode (Step 6). Because the only difference between chilled water coil discharge air temperature CHWC-DAT and supply air temperature SA-TEMP is that SA-TEMP is after the supply fan (Figure 19). Any other operations would generate very close temperature patterns for both locations. According to ASHRAE handbook [3], the steady state temperature rise across fans can be expressed as the following equation:

$$\Delta T = \frac{\Delta P C_p}{\rho c_p J \eta} \qquad \text{eq. 5.3.1}$$

where

$\Delta T$ = temperature rise across fan, Deg F

$\Delta P$ = pressure rise across fan, Inches of Water

$C_p$ = conversion factor, 5.193 $lb_f/ft^2 \cdot in.wc.$

$\rho$ = density of air, 0.075 $lb_m/ft^3$

$c_p$ = specific heat, 0.24 $Btu/lb_m \cdot {}^oF$

$J$ = conversion factor, 778.2 ft·$lb_f$/Btu

$\eta$ = fan efficiency, 0.0~1.0

So the steady state temperature rise (or drop if from fan ON to fan OFF) depends on a lot of factors and the exact value will change with the fan size, type, efficiency, etc. However, a common characteristics is that the magnitude of the temperature rise (or drop) on SA-TEMP should be a one to several degrees Fahrenheit and can be easily detectable by air temperature sensors, considering that the designed pressure rise across fans is generally greater than 3 inches of water and the total efficiency of fans are between 0.5~0.9. The rate of temperature drop will depends on AHU duct insulation and other factors, though.

In the six steps of the designed sequence of operations listed in Table 10, each step will generate a temperature pattern at each logical location – called a sub-pattern. Combinations of six sequential sub-patterns form a complete temperature pattern, as illustrated in Figure25 and Figure 26.

Figure 25 shows an example of five AHU air temperature patterns at different *known* logical locations (RA-TEMP, MA-TEMP, CHWC-DAT, HWC-DAT, and SA-TEMP) when an AHU implements the designed sequence of operation in the Winter in 1 hour intervals for each step. Figure 26 shows an example of six AHU water temperature patterns at different *known* logical locations (CHWC-EWT, CHWC-LWT, CHWC-MWT, HWC-EWT, HWC-LWT, and HWC-MWT) during the same period. Each red dot on the figure represents the start/stop point of a step. There are total of seven steps shown on the figures and only the first six steps' patterns are used in the analysis.

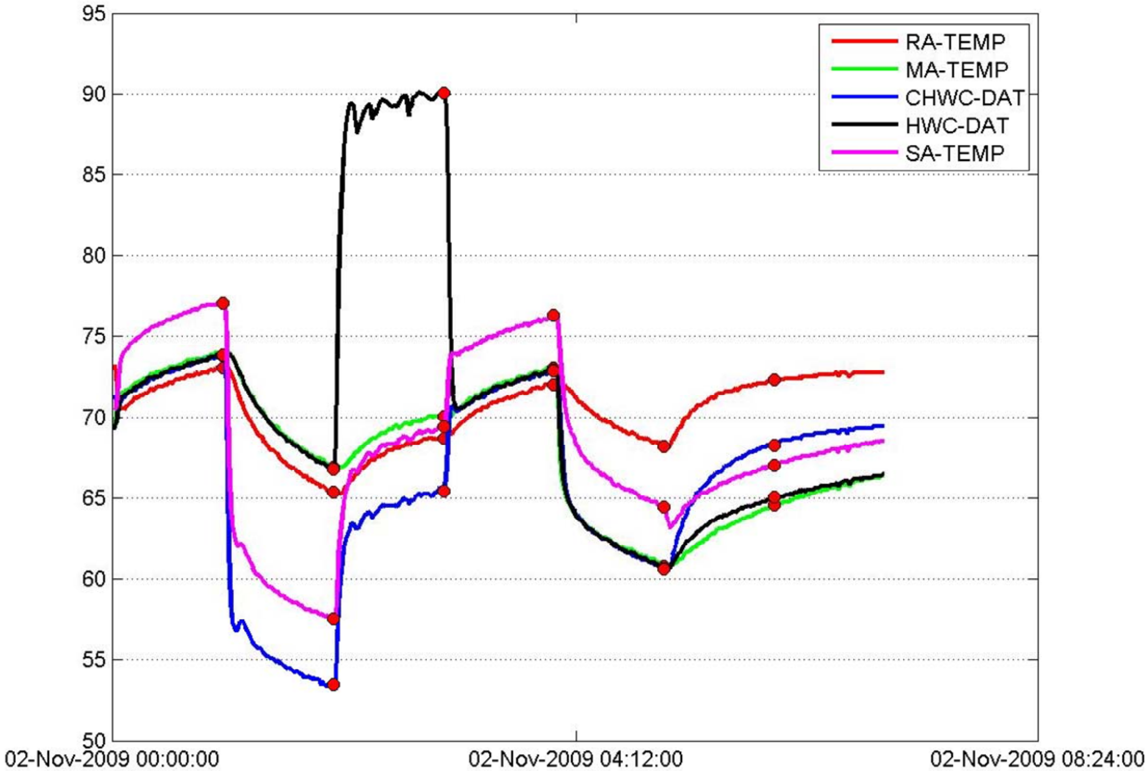



Figure 25. An example of five AHU air temperature patterns

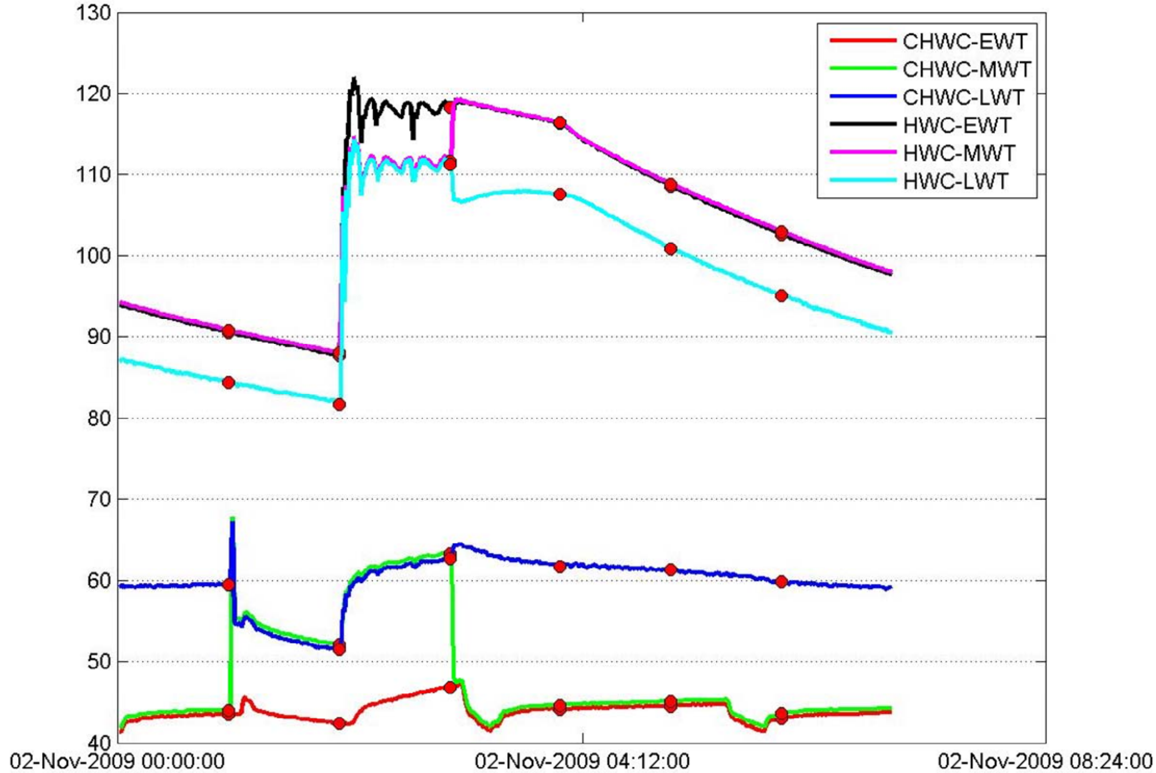



Figure 26. An example of six AHU water temperature patterns

From the above two figures it can be seen that the eleven AHU sensors show different identifiable patterns for that specific test. The challenge is to automatically recognize these temperature patterns for different AHUs, under different outside air conditions, at any time of day (which may affect heating and cooling load in the zones), and may be even with different chilled water and heating water supply temperatures. The idea of using structural pattern recognition to solve this problem assumes that each AHU component's functionality be the same so the basic pattern for each operation step at a AHU logic location can be represented using one or several basic "shapes". Through the recognition or classification of the combination of six sequential basic shapes, the logical location of the temperature sensor that generates the temperature pattern can be identified.

The task of “feature description” in structural pattern recognition is discussed in the next section, followed by “feature extraction” discussion in Chapter 5.5 and “classification” technique in Chapter 5.6.

## 5.4 Pattern Feature Description

Generally, the feature description process includes pattern segmentation and the selection of “primitives”.  Since there are six sequential operations, the time-series pattern segmentation in this problem is relatively straightforward.  It is natural to decompose a full temperature pattern into a combination of six simpler patterns based on the start/stop time of those steps.  This is also because *normally* the pattern in each step is a simple shape.  The basic shapes or “primitives” selected in this study includes five categories: 1) Linear; 2) Exponential; 3) Step; 4) Peaks; and 4) Triangle.

### 5.4.1 Linear Pattern

Linear pattern is illustrated in Figure 27.

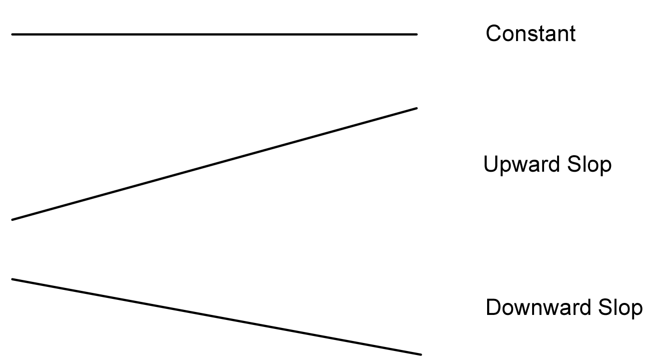



Figure 27. Linear patterns

The linear patterns will occur when a designed AHU operation does not affect temperature at certain logical locations, or temperature at those locations just steadily increases or decreases due to small heat transfer with the environment. For example, in operation step 1, when supply fan and return fan start and AHU runs in 100% recirculation mode, the heating coil entering, leaving and mixing water temperatures will generate linear patterns because the heating water pump is stopped and there is no heating water flow through the coil, therefore the only temperature change for sensors at those locations would be due to no or very little heat transfer with the environment through the heating water pipe insulation. Another example is the chilled water entering temperature: it is always corresponding to the chilled water supply temperature, which is normally relatively stable depending on the chilled water supply source and is not affected by any designed AHU operation steps.

### 5.4.2 Exponential Pattern

The exponential patterns are also very common patterns generated by AHU operations, as illustrated in Figure 28, especially for the type “b” and type “d”.

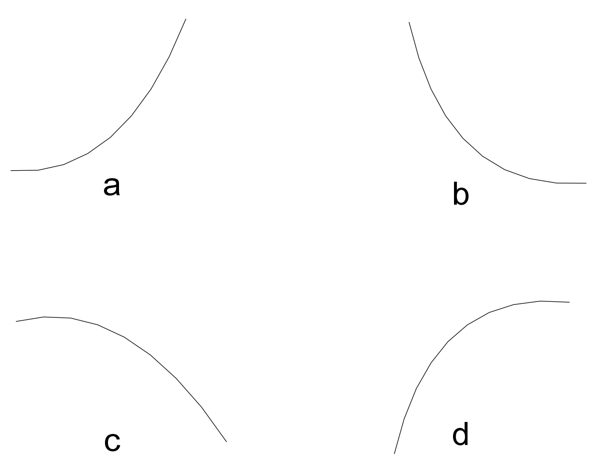



Figure 28. Exponential patterns

There are several possible operations that could generate the exponential patterns:

1. Return air and mixed air temperature's response to sudden supply air temperature change (up or down). This could happen in steps 2, 3 and 4 when cooling coil or heating coil opens and closes to transfer heat (cold) from chilled water and heating water. When the AHU is running, the supply air temperature adds (or removes) heat to (or from) the zone(s). Because of the thermal capacitance in the zone(s), the average temperature in the zone, which is reflected in the return air temperature, should follow a close exponential pattern up (or down) until a new equilibrium state is achieved. Though in each AHU system design the thermal capacitance of the zone(s) and the supply air flow rate may be different, the return air temperature pattern should be always be an exponential like pattern. The possible disturbances to this pattern are the load changes in the zone due to solar radiation (in the daytime) and outside air temperature difference from the zone, and how well the zone is insulated.

2. The response of all the air temperatures (MA-TEMP, HWC-DAT, CHWC-DAT, SA-TEMP and RA-TEMP) when the AHU changes from 100% recirculation mode to 100% outside air mode (50% outside air mode in the winter) in step 5. All air temperatures will change from their original temperatures (before dampers changing positions) to approaching the outside air temperature; with faster response for MA-TEMP, HWC-DAT, CHWC-DAT, and slower response for temperatures further downstream (SA-TEMP, RA-TEMP).

3. In step 6, because the AHU supply fan and return fans are shut off, all air temperatures should increase or decrease exponentially toward environmental temperatures. The only disturbance is that for the supply air temperature the heat generated by the supply fan motor is removed from the system, so SA-TEMP will drop first then change exponentially towards the environmental temperature.

### 5.4.3 Step Pattern

The step up (or down) temperature pattern (Figure 29) is caused by the sudden increase or decrease in temperature due to cooling coil or heating coil valve open/close from its opposite position. The "step" is relative to the 60 minutes periods with 1 minute data sampling rate. Figure 29 shows the "ideal" step patterns (solid line) and "actual" step patterns for AHU operations. There are three AHU operations in the design that could generate these patterns:

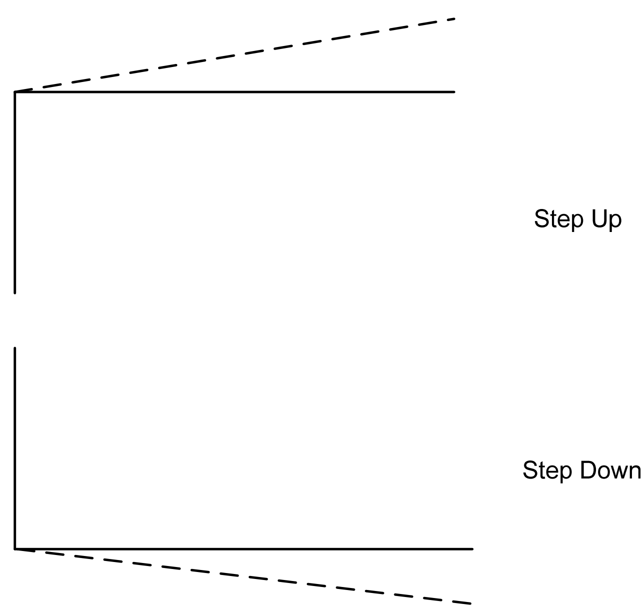



Figure 29. Step patterns

1. In design operation step 2, when the cooling coil opens from fully closed position, the chilled water leaving temperature CHWC-LWT should drop immediately then gradually stabilize during the period (assuming stable chilled water supply temperature). The chilled water CHWC-MWT will rise from its original supply water temperature because heat from the air will be transferred to chilled water. In the mean time, air temperatures after the cooling coil, CHWC-DAT and SA-TEMP, will also be in step down pattern. The magnitude of the water and air temperature drop will depend on the coil heat transfer coefficient, air and water flow rate, etc. However, the main pattern of a step down shape should hold.

2. In step 3, when the heating coil opens from fully closed position, the heating water leaving and mixing water temperatures, HWC-LWT and HWC-MWT, should rise immediately and then maintain at a small temperature range during boiler immediately and then maintain at a small temperature range during boiler start/stop to maintain heating water supply temperature. In the mean time, air temperatures after the cooling coil, CHWC-DAT and SA-TEMP, will also have a similar pattern due to heat transfer. Similarly, the magnitude of the water and air temperature rise will depend on the coil heat transfer coefficient, air and water flow rate, etc.

3. In step 4, the chilled water and heating water valves close from fully open position. All air temperatures will quickly decrease (or increase) to their balanced AHU 100% recirculation average temperatures. If there is no significant zone internal load change, the temperature pattern should resemble a step up (or down) pattern.

### 5.4.4 Peak Pattern

The peak temperature pattern is shown in Figure 30 and Figure 31. It consists of a sharp increase and then a sharp decrease in temperature in a very short period of time (within 5 minutes), and vice versa. This pattern normally happens when water temperature changes at the beginning of an operation when water pumps start/stop and corresponding valves open/close. An example is when a chilled water valve opens from fully closed position, the chilled water mixing temperature CHWC-MWT will rise sharply first from the supply chilled water temperature, then comedown quickly. This is because the residual water in the cooling coil (which is closer to environmental temperature because airflow passing the coil in previous steps) is being flushed to the mixing temperature sensor location first when the coil valve is opening, and then the real cold chilled water supply water flows into the coil so the temperature at the same location drops again. Another possibility is that the heating water supply temperature change due to boiler on/off operation in step 3.

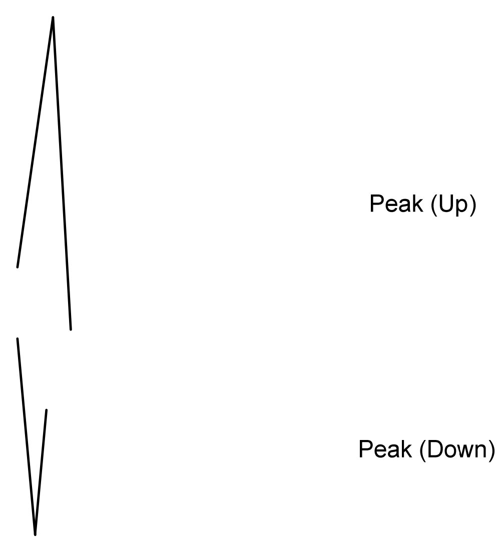



Figure 30. Peak patterns

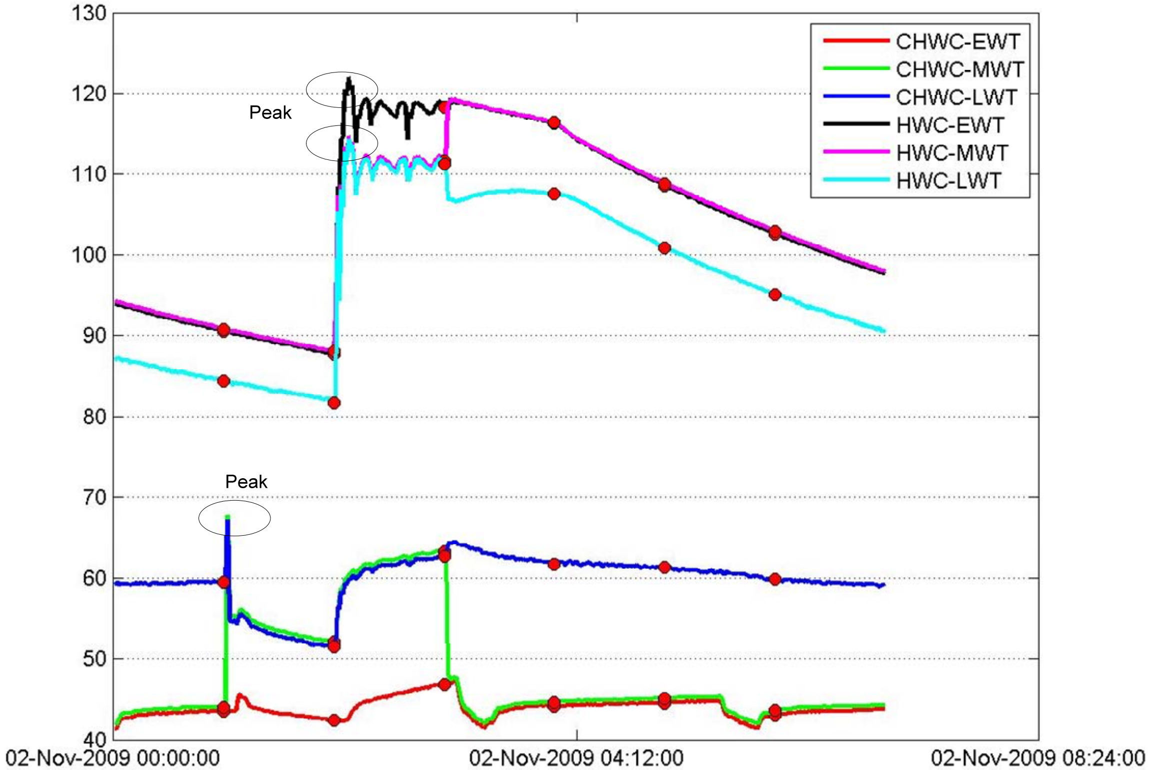



Figure 31. An example of peak pattern in water temperatures

### 5.4.5 Triangle Pattern

In a complete HVAC control system, the chilled water is normally supplied by chiller(s). Different chiller types and chilled water system design can cause different chilled water supply water temperature patterns, and therefore affect other chilled water temperatures (CHWC-EWT, CHWC-LWT, and CHWC-MWT) and possible air temperature patterns (especially CHWC-DAT and SA-TEMP).

There are two main chilled water system designs: single pumping system and primary-secondary pumping system, as shown in Figure 32. Normally the single pumping scheme is used in small systems and the primary-secondary pumping configuration is used in larger systems to provide smoother chilled water supply temperature, as individual load occupies a small percentage of chiller capacity.

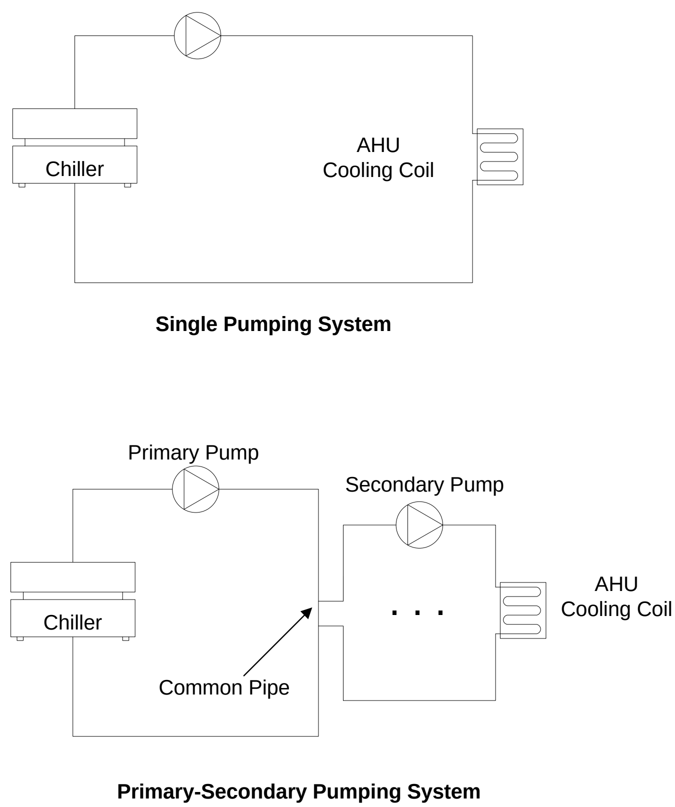



Figure 32. Common chilled water pumping design scheme

The triangle temperature pattern, as shown in Figure 33, often occurs in single pumping system and when the chiller used in the design operates in stages.

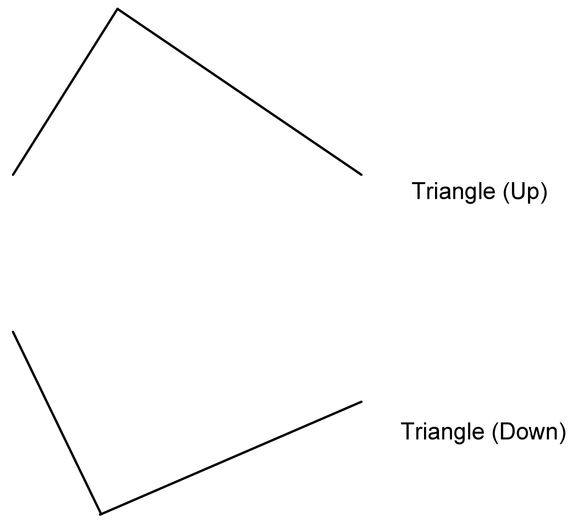



Figure 33. Triangle Patterns

Normally the designed chilled water supply temperature may range from 40 Deg F to 55 Deg F (most common setpoint are 44 or 45 Deg F) [3]. However, the actual supply temperature will fluctuate with the pumping system design and actual real-time load condition. In the single pumping configuration, if the cooling load is really light (like in the designed sequence of operations steps 1, 4,5, and 6, where the 3-way chilled water valve is fully closed to the coil), and the chiller is operating in stages, then the triangle chilled water temperature pattern is very likely to occur (Figure 34). This is because this type of chiller usually starts/stops based on the return water temperature. If there is not much load, the return water temperature will drop linearly when the chiller is running because the heat in the chilled water loop is rejected to the outside of the system by the chiller. When the return water temperature is below certain level, the chiller will stop and the system chilled water temperature will gradually rise because of the heat generated by the chilled water pump, until it reaches a certain temperature (usually setpoint plus a couple of degrees) when it may restart again.

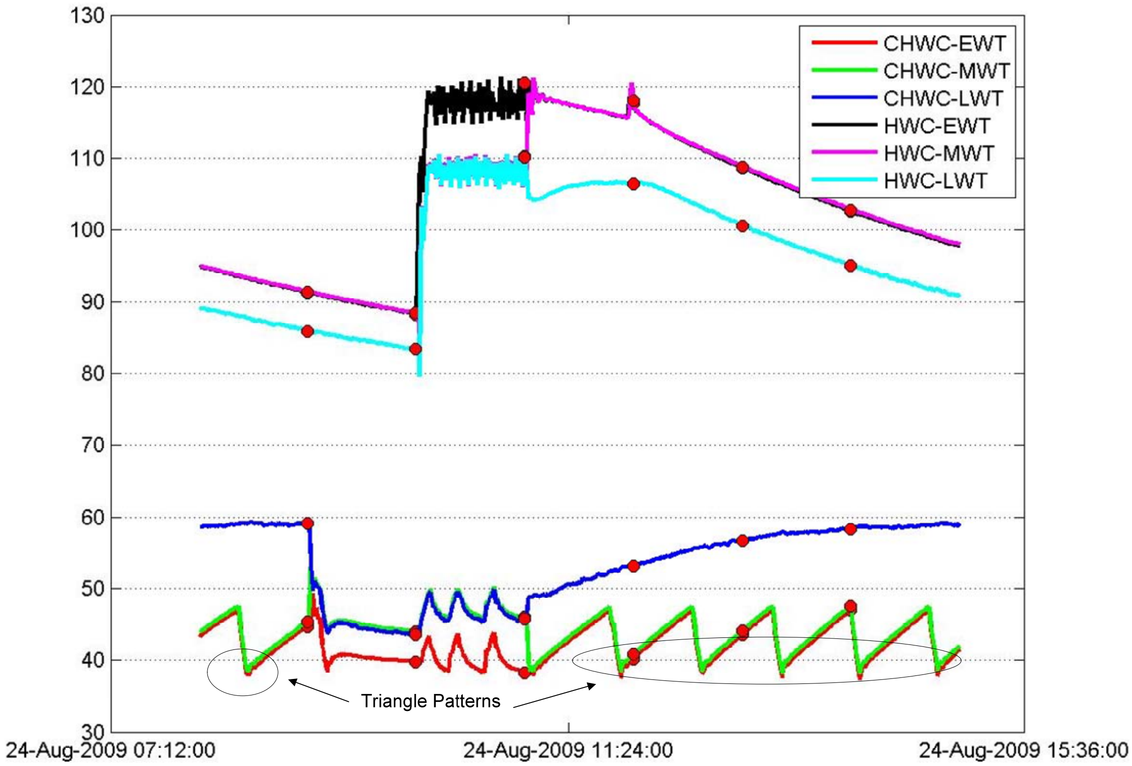



Figure 34. An example of triangle patterns for chilled water temperatures

The selection of these primitives is based on experience, intuition, analysis of many cases of testing patterns, and through a "trial and error process". It should cover most of the basic recognizable temperature patterns. However, some of the temperature patterns generated under certain conditions may not be able to be represented by any of these primitives. It will be discussed in the next section how these special patterns will be modeled and evaluated.

## 5.5 Pattern Feature Extraction and Evaluation

Given the primitives of a structural pattern recognition application in time-series data, a good feature extraction method should be able to recognize the major shape for each period and inter-relationships between periods, as well as model the extracted structure in a compact manner. In this section, the structure detector for each selected primitive will be discussed first, and then the coding mechanism will be developed for representation of a complete AHU temperature pattern.

### 5.5.1 Time-Series Data and Structure Detector

As discussed in section 5.2.6., there are a total of 6 steps of operations, with each step is set to run for 1 hour and the sampling time interval is 1 min. Therefore, at the end of the operation, for each AHU temperature sensor logical location, a time-based data series of 60x6 = 360 samples can be obtained (Figure 35). For each step, define the number of minutes as the $x$ axis (with the starting minutes for the period as 1) and $y$ as the measured temperature values at each sampling minute, the temperature pattern *at each period* can be represented as:

$$y(x) = f(x) \qquad \text{eq. 5.5.1.1}$$

where

$x$ is integer and $1 \le x \le 60$ and $y$ is real number

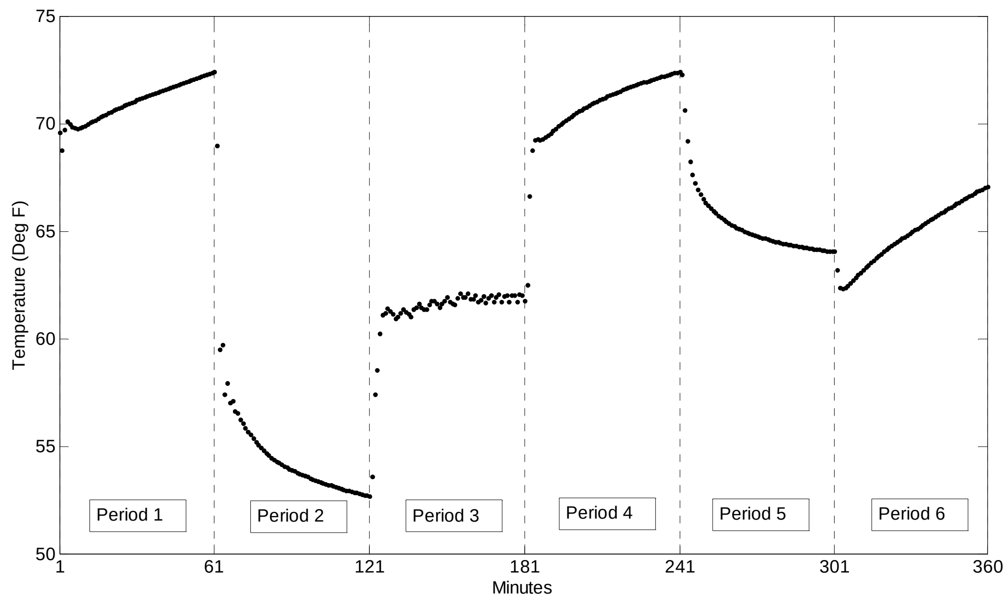



Figure 35. An example of an AHU temperature pattern

A structure detector recognizes a pattern in the sample data series and may be able to generate a new data series representing the sample data structure.

$$\hat{y}(x) = \hat{f}(x) \qquad \text{eq. 5.5.1.2}$$

where

$x$ is integer and $1 \leq x \leq 60$

The quality of a structure detector recognizing a specific data pattern can be evaluated by using several goodness-of-fit statistics for parametric models [28]: residual, the sum of squares due to error, and R-square.

The residual $r$ is the difference between the sample data value and the value generated by the structure detector:

$$r(x) = f(x) - \hat{f}(x) \qquad \text{eq. 5.5.1.3}$$

The sum of squares due to error *sse* measures the total deviation of two data series and is defined as:

$$sse = \sum_{x=1}^{60} (f(x) - \hat{f}(x))^2 \qquad \text{eq. 5.5.1.4}$$

*R-square* is defined as the ratio of the sum of squares of the regression *ssr* and the total sum of squares *sst*:

$$ssr = \sum_{x=1}^{60} (\hat{f}(x) - \bar{y})^2 \qquad \text{eq. 5.5.1.5}$$

$$sst = \sum_{x=1}^{60} (f(x) - \bar{y})^2 \qquad \text{eq. 5.5.1.6}$$

$$R - square = \frac{ssr}{sst} = 1 - \frac{sse}{sst} \qquad \text{eq. 5.5.1.7}$$

where

$$\bar{y} = \sum_{x=1}^{60} f(x)/60 \qquad \text{eq. 5.5.1.8}$$

and 0<R-square<1 (assuming *sst* is not 0. Otherwise the curve is a perfect fit for the pattern generated by the structure detector).

In this research, the *R-square* value will be used as the main determining factor in assessing the quality of pattern identified by a specific structure detector; other criteria may also be used in special situations.

### 5.5.2 Structure Detector for Linear Pattern

Linear pattern can be expressed mathematically using equation 5.5.2.1:

$$\hat{f}(x) = ax + b \qquad \text{eq. 5.5.2.1}$$

where *a* and *b* are free parameters that need to be determined.

The linear pattern detector uses standard least square approach linear regression equations to calculate the two free parameters:

$$a = \frac{\sum_{x=1}^{60}(x-\bar{x})(y-\bar{y})}{\sum_{x=1}^{60}(x-\bar{x})^2} \qquad \text{eq. 5.5.2.2}$$

and

$$b = \bar{y} - a\bar{x} \qquad \text{eq. 5.5.2.3}$$

where $\bar{y}$ is defined in equation 5.5.1.8

$$\bar{x} = \sum_{x=1}^{60} x/60 \qquad \text{eq. 5.5.2.4}$$

Based on the value of *a* and *b*, the linear pattern detector can categorize a data series into more detailed sub-linear patterns:

- Upward slope line: a ≥ ε;
- Downward slope line: a ≤-ε;
- Constant line: |a| ≤ ε;

where ε is a small positive numbers.

### 5.5.3 Structure Detector for Exponential Pattern

Exponential pattern can be expressed mathematically using equation 5.5.3.1:

$$\hat{f}(x) = ae^{bx} + c \qquad \text{eq. 5.5.3.1}$$

where *a, b* and *c* are free parameters that need to be determined. In the equation, parameter *a* represents the magnitude of the curve, *b* the curvature, and *c* the elevation.

Based on different parameters, the exponential pattern will also be categorized into four sub categories (Figure 28):

- Exponential growth up (type a): $a>0$, $b > 0$;
- Exponential decay down (type b): $a>0$, $b<0$;
- Exponential growth down (type c): $a<0$, $b>0$;
- Exponential decay up (type d): $a<0$, $b<0$;

For non-linear functions, usually an iterative approach using a non-linear regression algorithm to select the best set of parameters for the function given. The non-linear regression algorithm tries to fit a non-linear function to the given dataset. It is basically a non-linear optimization problem with the objective to minimize the sum of squares due to error *sse* for the fitted dataset vs. known sample data set. Many methods and strategies exist for solving such problems, for example, method of gradient descent, Gauss-Newton algorithm, Levenberg–Marquardt algorithm, and Nelder–Mead simplex search are some of the common algorithms. In the application of AHU temperature sensor location recognition, any of these algorithms should work because there are only 60 samples in each operation periods and the exponential function is a relative simple non-linear function. In practice, probably any software for curve-fitting can be used, or above mentioned algorithms can be used for computer programming.

### 5.5.4 Structure Detector for Step Pattern

For AHU temperature sensor pattern recognition applications, a step pattern can be expressed using equation 5.5.4.1:

$$\hat{f}(x) = \begin{Bmatrix} a_1 x + b_1; x \le c \\ a_2 x + b_2; x \ge c \end{Bmatrix} \qquad \text{eq. 5.5.4.1}$$

where $a_1$ is a very big number (positive or negative), and $a_2$ is a very small number. Both represent the slope of two straight line segments. $c$ is the location on $x$ axis where the two lines intersect.

Some special cases of the exponential function (equation 5.5.3.1) – where the exponential decay curve with a very big curvature - will also be categorized as the step pattern.

It should be noted that for practical purposes for this application, these mathematical representations are not a strict definition of a step function but just an estimation of the step "shape".

For detecting step patterns, one way is to use the non-linear regression algorithms mentioned in section 5.5.3 on the exponential patterns. Another way is to use piecewise application of structure detectors on two continuous regions to catch two local patterns, and then decide if the combined pattern is a step pattern based on the pattern parameters (such as $a_1$, $b_1$, $a_2$, $b_2$ ) if both sub-patterns are line patterns as illustrated in Figure 36.

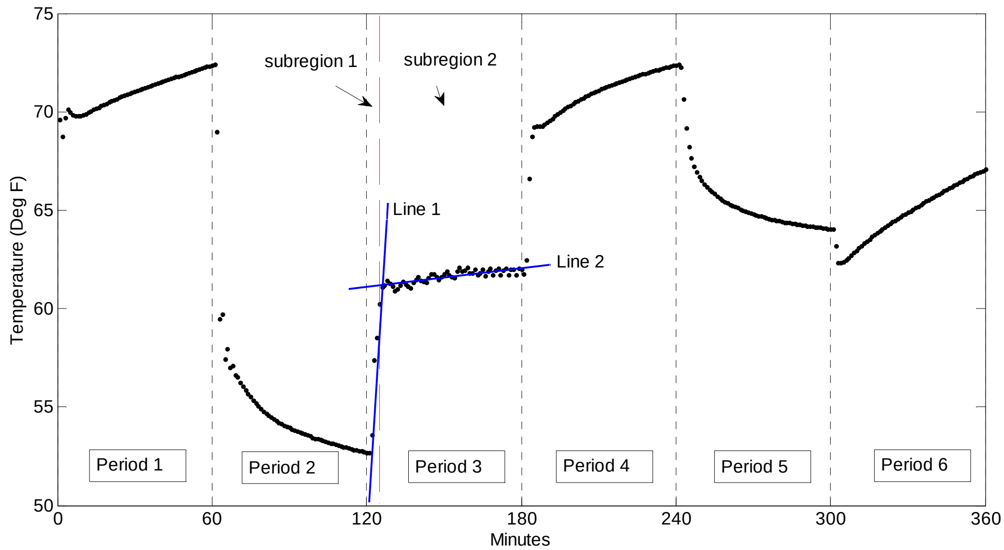



Figure 36. An example of a piecewise application of structure detectors

Olszewski [34] discussed the piecewise application of structure detector in detail. The basic idea is to divide a complete period into *n* continuous subregions, and try to find the best fit pattern in each region. It is shown that with more subregions, the goodness-of-fit will be better with the increase of number of regions, but the overall structural characteristics of the periods may be compromised. For structural pattern recognition in this research, it is appropriate to divide each period into a maximum of two continuous subregions: transition region and main region.

A transition region is the time period that starts with a new AHU operation sequence and ends when the temperature finishes the transition from the last temperature pattern and is ready to start a new pattern. It is caused by the time needed to switch over from the previous status to new operations (fan starts/stops, damper open/close, valve open/close, etc.) and the temperature sensor response time to reflect the switchover. In the transition period, the temperature pattern may appear to be an abrupt change from previous and later main region patterns, show strange shapes patterns, and may not fit to any primitive described above. Therefore in some cases, the transition region needs to be separated from the main region so the main pattern can be recognized easier (e.g. Figure 37). In some other cases (e.g. Figure 38), the whole period pattern can be seen as a combination of two sub-patterns. Based on the experience, the maximum ending time of a transition region is set at the 20th minute. The work flow chart of detecting step pattern is illustrated in Figure 39.

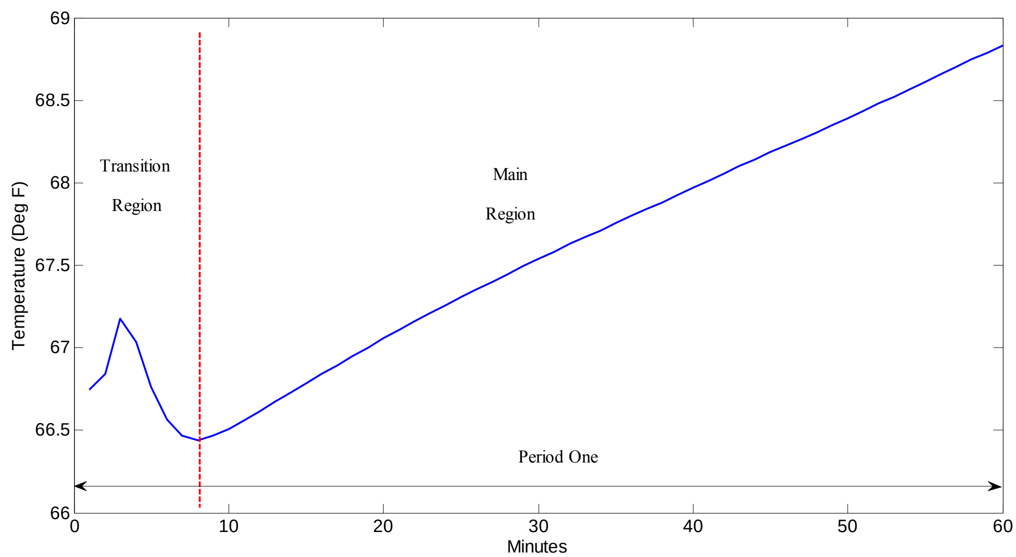



Figure 37. Temperature pattern with transition, example #1

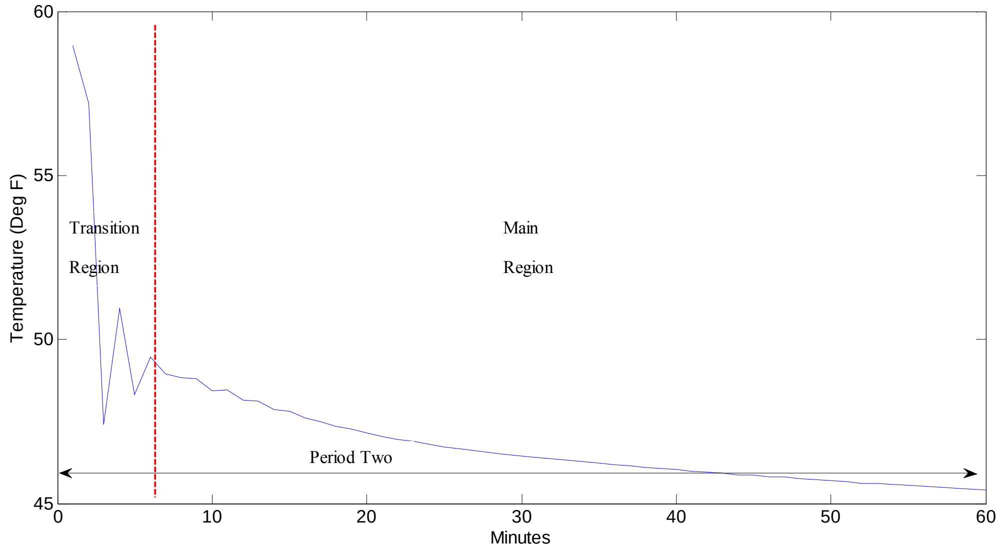



Figure 38. Temperature pattern with transition, example #2

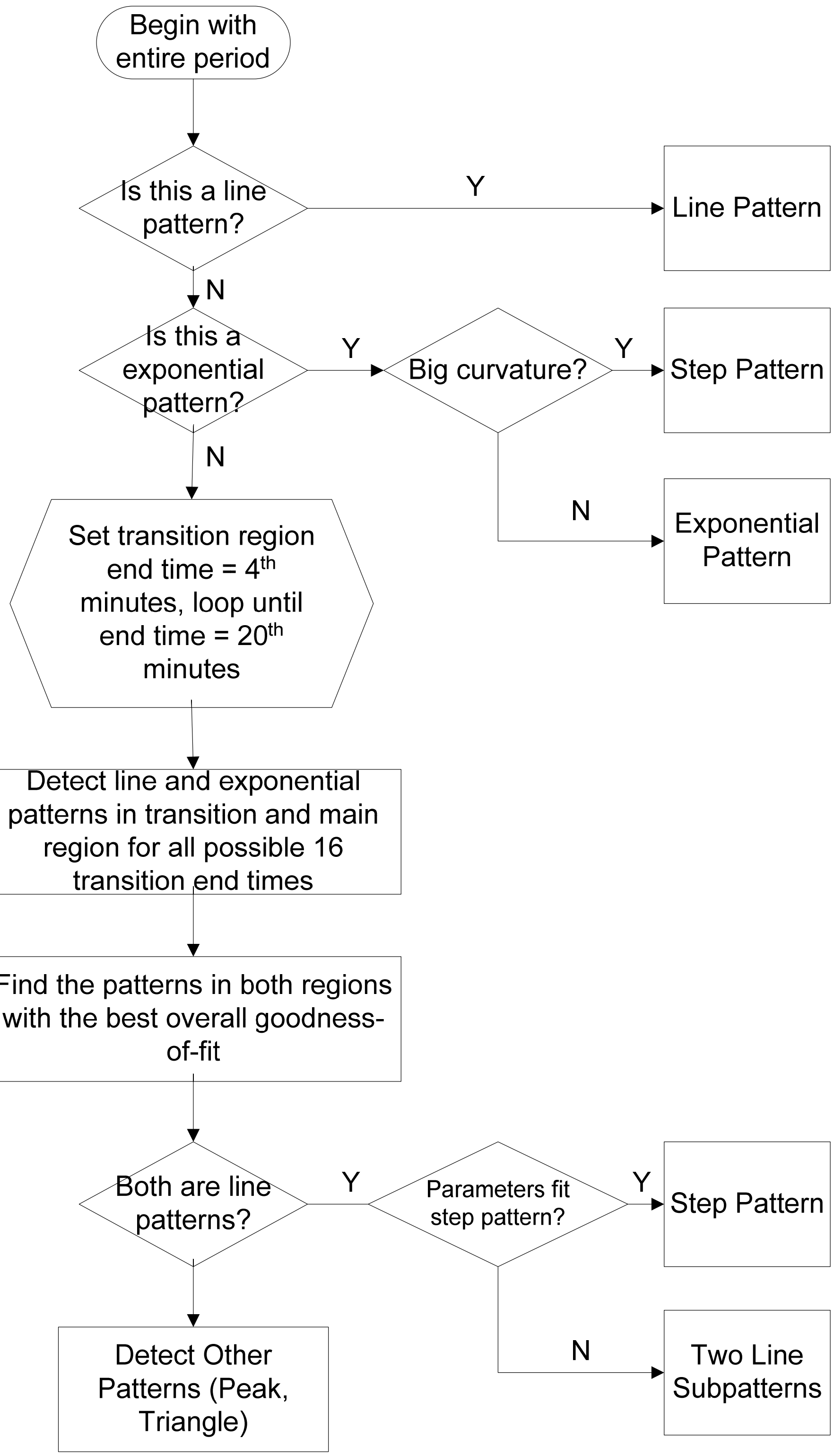



Figure 39. Workflow in detecting step pattern

### 5.5.5 Structure Detector for Peak Pattern

A general peak pattern detection algorithm has been developed by Horowitz [13] using piecewise linear approximation and formal language theory. The algorithm basically approximates a waveform into line segments, then decides based on the line slope if there are two continuous lines with a "/" (representing positive) followed by a "\" (representing negative), or a "\" followed by a "/". The line slopes will be categorized based on their values to see if they are greater (or less) than a threshold to decide if the lines are of a "degree of significance" to be considered lines that can form a peak.

For AHU temperature sensor pattern recognition in this study, a simplified algorithm is used. Since the sampling period is 1 minute, the temperature pattern data is already equivalent to a linear approximation of real time higher frequency data. Another characteristic of temperature data pattern is that the peak pattern usually occurs only once in the transition period. The algorithm first searches for the maximum and minimum temperature data points in the period, and records their time slots (mark as 1 and 2). Then for each data point, calculates the slope to the maximum and minimum temperature data points and finds the biggest positive and negative slopes (s1+ and s1-) with respect to the maximum temperature point, and (s2+ and s2-) to the minimum temperature point. The s1+, s1-, s2+, and s2- values are compared to three different threshold values to decide if the pattern is a peak with "excellent", "good" or "ok" goodness-of-fit. For example, if the value of s1+ is greater than a very big number (indicating a very sharp rise in temperature) and s1- is less than a very big negative number (indicating a very sharp drop in temperature), then the pattern is "Peak UP" with "excellent" fit. The workflow for detecting a peak pattern is illustrated in Figure 40. An example of a peak pattern illustration is in Figure 41.

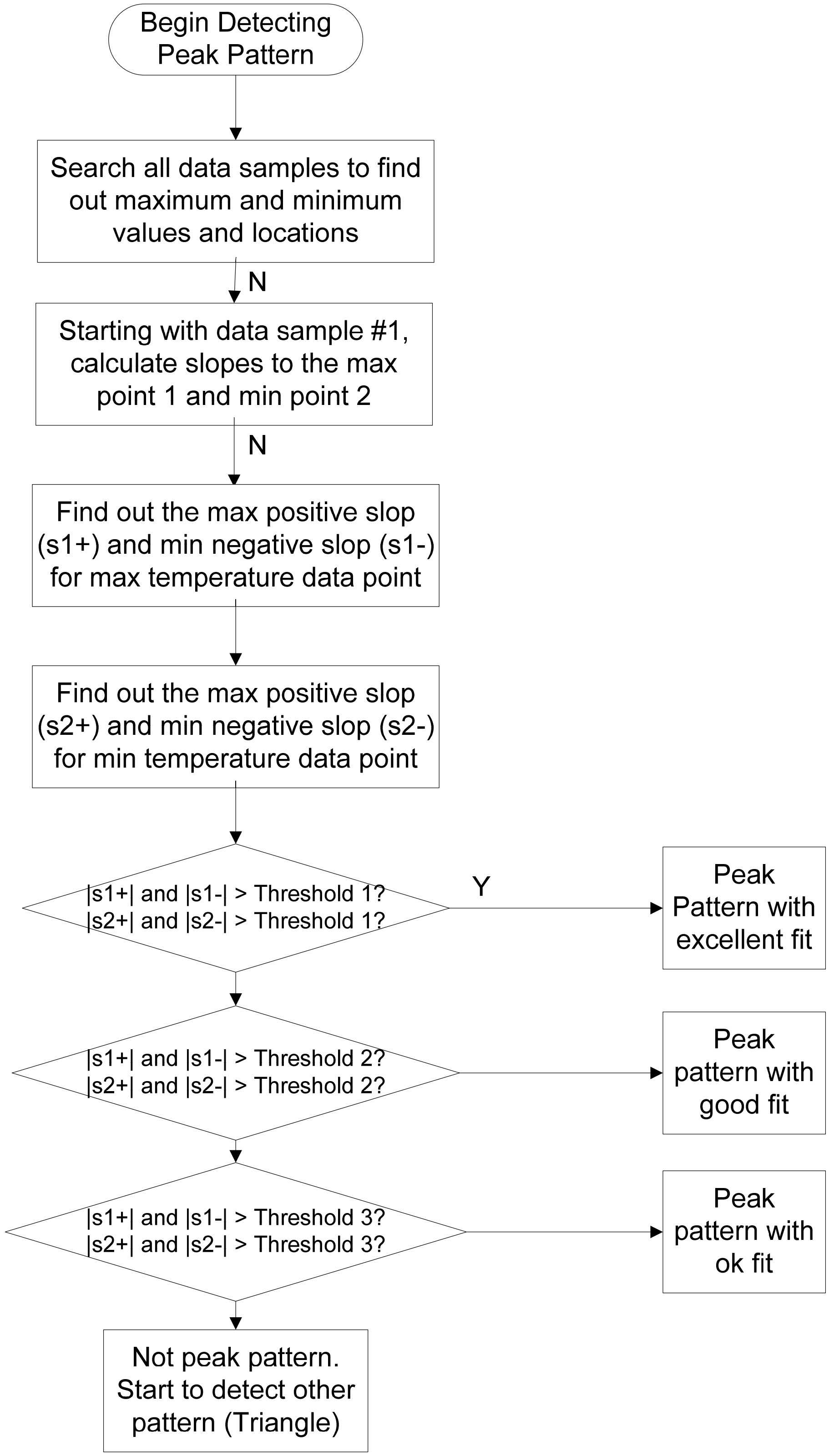



Figure 40. Workflow in detecting peak pattern

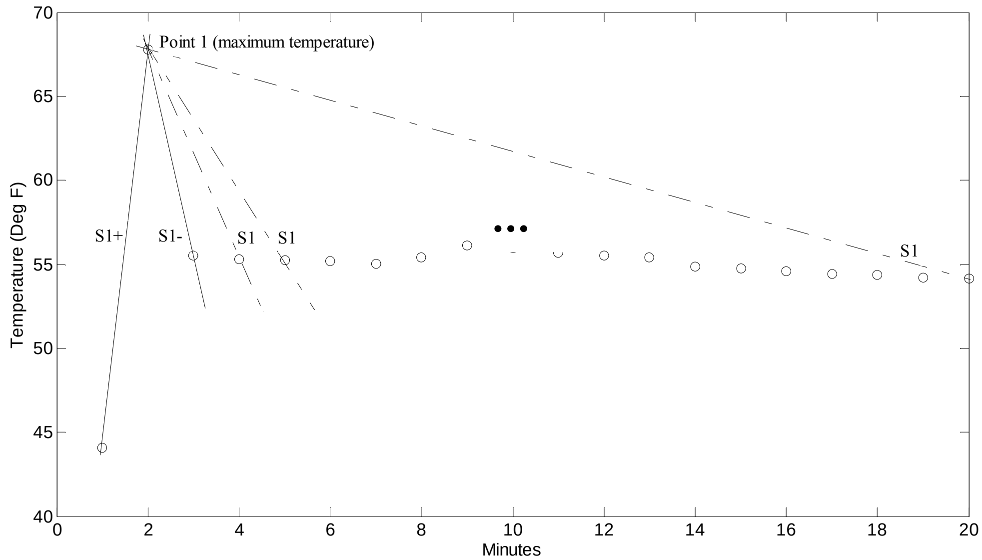



Figure 41. An illustration of peak pattern (up) recognition process

### 5.5.6 Structure Detector for Triangle Pattern

Similar to the peak pattern, a triangle pattern can be regard as a combination of two straight line patterns, except that the slops of the lines may not be as steep, because the pattern is caused by the chiller start/stop in stages when the cooling load is light. Normally, in a 60 minutes period, the up trend and down trend may change up to the maximum of 4 times (considering that at stopped mode, a chiller need at least 5 minutes before it can restart again). Therefore, the structure detector for a triangle pattern will separate the period into separate uptrend and downtrend regions first and then use the linear pattern detector described in section 5.5.2 to find out if in those regions temperature patterns are linear. The workflow is illustrated in Figure 42, and an example of triangle pattern recognition is illustrated in Figure 43.

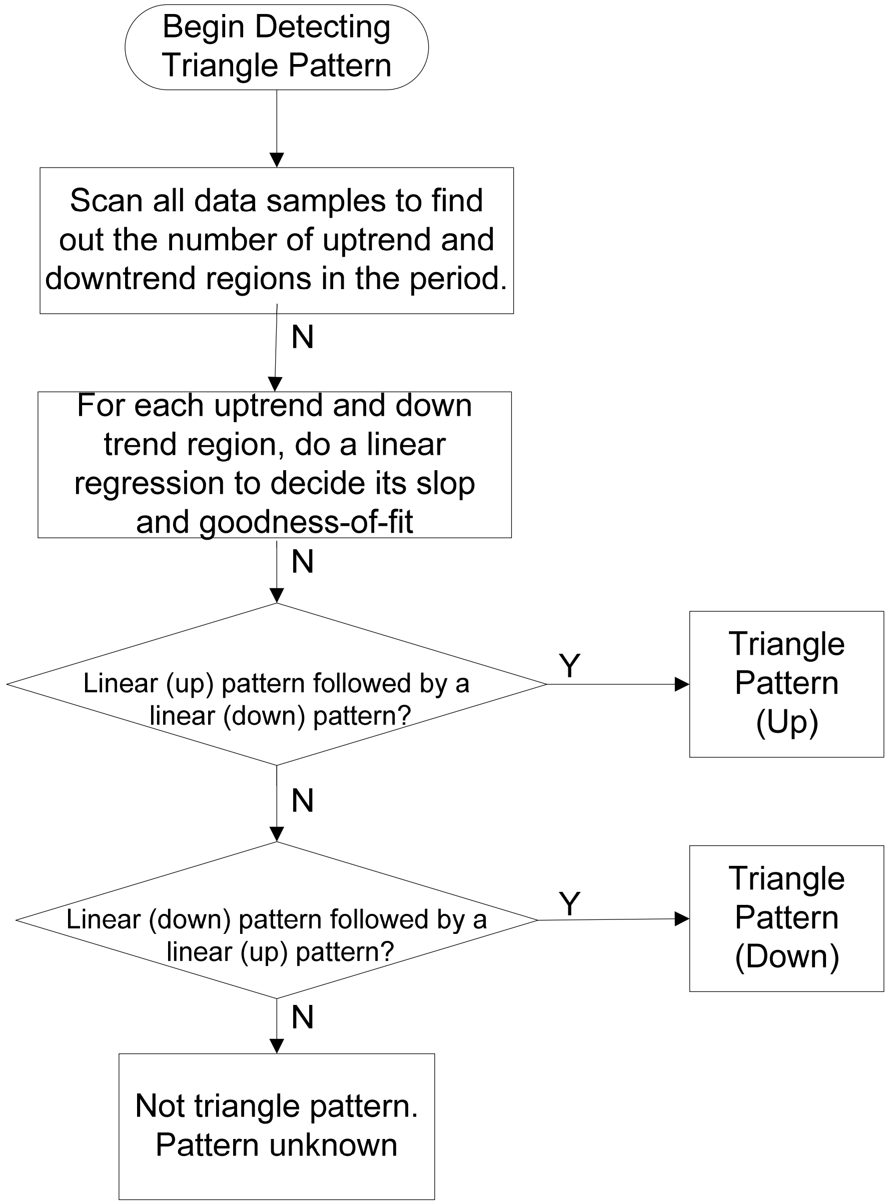



Figure 42. Workflow in Detecting Triangle Pattern

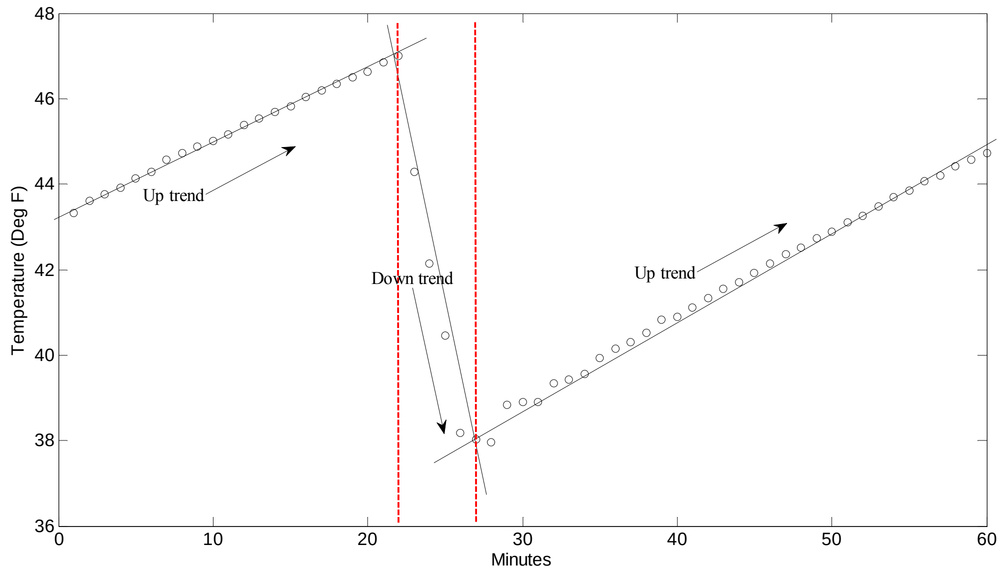



Figure 43. An example of triangle pattern recognition process

### 5.5.7 Coding Scheme for Temperature Patterns

A coding scheme is needed to describe the pattern detector outputs in a uniform way so they are easier to classify in the pattern recognition final step - classification. In this research, the pattern outputs *for each period* will be coded following the three digit number coding scheme listed in Tables 11 to 13. The reason for using numbers instead of characters for representing patterns is mainly for easier programming in a computer language:

Table 11. Coding scheme for AHU sensor pattern recognition for each period – 1

| Coding Scheme | First Digit - Pattern Type |
|---|---|
| Numbers | |
| **1** | Line |
| **2** | Exponential |
| **3** | Step |
| **4** | Peak |
| **5** | Triangle |

Table 12. Coding scheme for AHU sensor pattern recognition for each period – 2

| Coding Scheme | Second Digit - Sub-Pattern Type | | | | |
|---|---|---|---|---|---|
| Numbers | Line | Exponential | Step | Peak | Triangle |
| **1** | Constant | Exponential Growth Up | Up | Up | Up |
| **2** | Up | Exponential Decay Up | Down | Down | Down |
| **3** | Down | Exponential Growth Down | - | - | - |
| **4** | - | Exponential Decay Down | - | - | - |

Table 13. Coding scheme for AHU sensor pattern recognition for each period – 3

| Coding Scheme | Third Digit - Goodness-of-fit Description | | | | |
|---|---|---|---|---|---|
| Numbers | Line | Exponential | Step | Peak | Triangle |
| **1** | Excellent | Excellent | Excellent | Excellent | Ok |
| **2** | Good | Good | Good | Good | - |
| **3** | Ok | Ok | Ok | Ok | - |

Based on the above tables, an illustration of temperature patterns and their corresponding codes is shown in Figure 44, where "x" indicates the goodness of fit to real data. All other patterns or unrecognizable patterns will be assigned code “000”.

Since there are total of six periods in the designed sequence of operations, the overall temperature pattern will be a sequential addition of temperature pattern codes for the six periods. For each period, there may be up to two recognizable patterns including the transition and main regions. An example of overall temperature pattern code is shown in Figure 45.

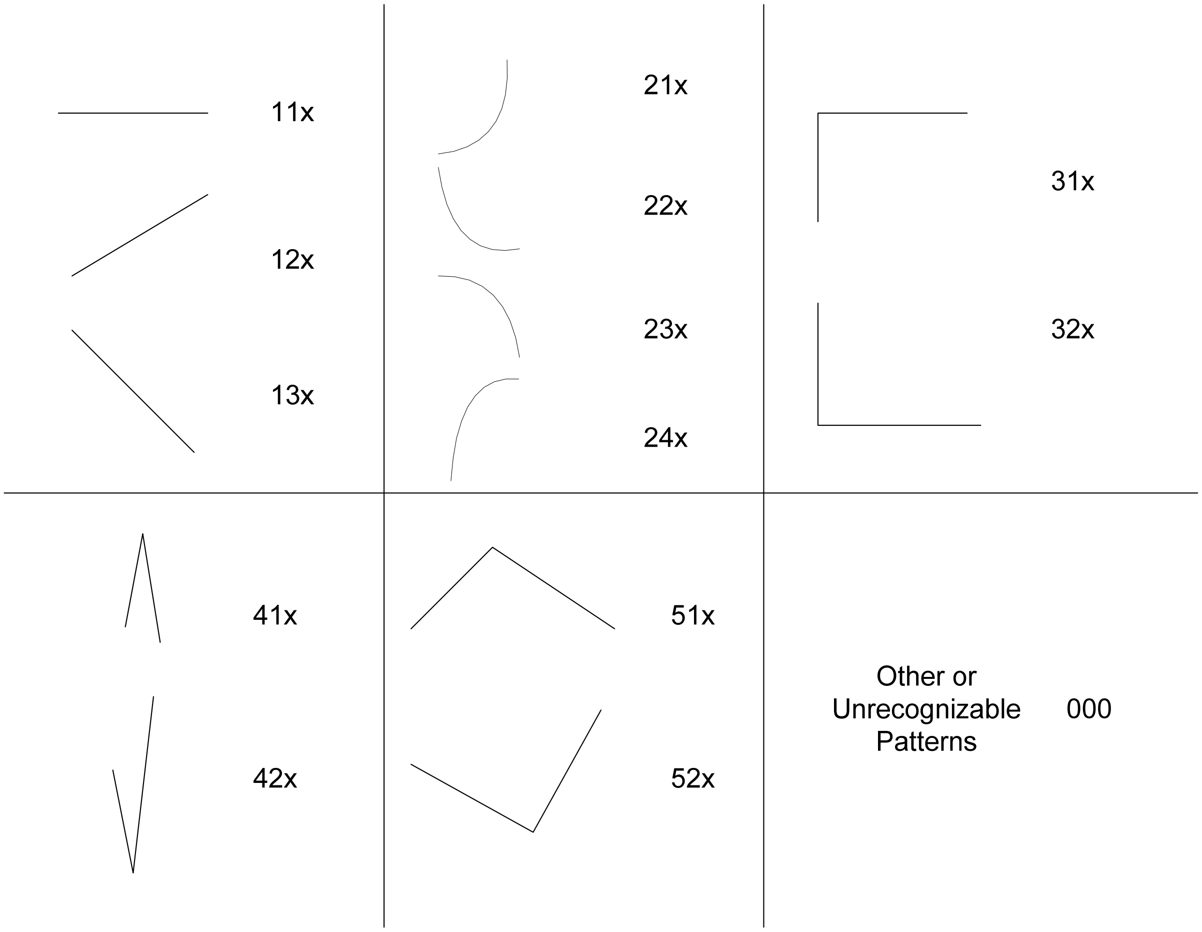



Figure 44. AHU temperature pattern coding scheme illustration

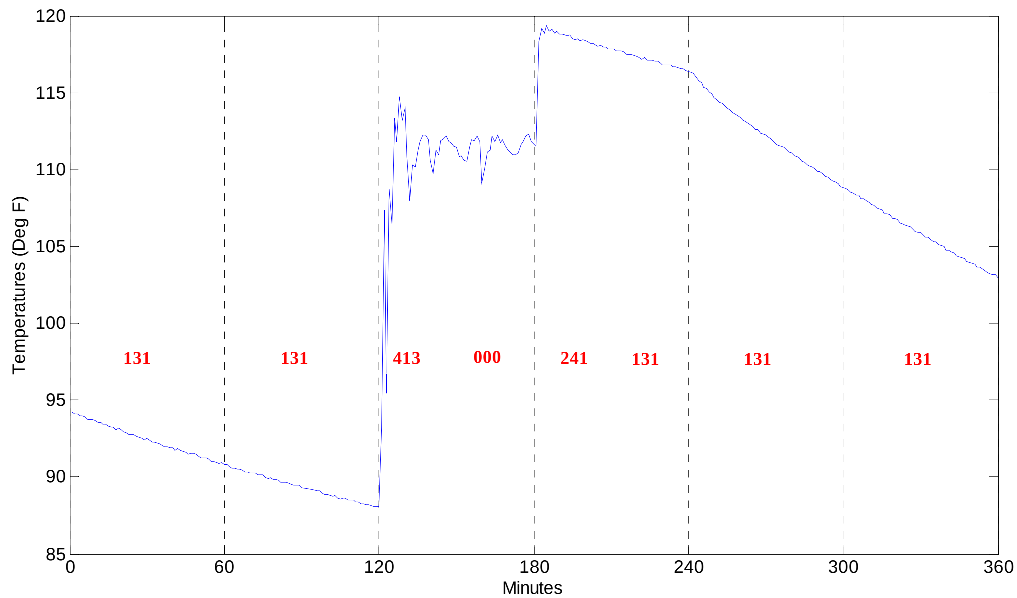



Figure 45. An example of a complete temperature pattern code

## 5.6 Pattern Feature Classification Using Template Matching

### 5.6.1 Template Matching

The classification is to recognize or categorize the pattern into specific categories. One of the most intuitive and simplest methods is to match the pattern code extracted from the temperature pattern data to a known template group with each template corresponding to a temperature sensor location. The feasibility of this approach is based on the major assumption in Chapter 4.3:

*Any distinct input/output point in an AHU serves a unique purpose (except redundant points used for reliability). Therefore, given a specified sequence of operation on the outputs, the inputs from different logical locations should display identifiable, unique,* *time-series patterns. The logical locations of these inputs/outputs can be recognized by studying the sequence of operations and the output patterns generated.*

A template for each AHU temperature sensor at a specific location is a table that lists all possible temperature pattern codes for each of the six periods with two pattern codes in each period (transition region and main region). An example of a template table is shown in Table 14. The creation of the template tables will be based on training data obtained in experimental testing, which will be described in detail in Chapter 6 and Chapter 7.

Table 14. An example of a template table for heating mixing water temperature

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | *2* | *1* | *2* | *1* | *2* | *1* | *2* | *1* | *2* | *1* | *2* |
| 999 | 111 | 999 | 111 | 999 | 000 | 999 | 000 | 999 | 131 | 999 | 131 |
| | 112 | | 112 | | 312 | | 131 | | 132 | | 132 |
| | 113 | | 113 | | 313 | | 132 | | | | |
| | 131 | | 131 | | 411 | | 133 | | | | |
| | 132 | | 132 | | 412 | | 221 | | | | |
| | 133 | | 133 | | 413 | | 222 | | | | |
| | | | | | 421 | | 223 | | | | |
| | | | | | 422 | | 412 | | | | |
| | | | | | 423 | | 413 | | | | |

*999 indicates that any pattern is ok for this pattern. Column *1* indicates transition region pattern (if detected) and column *2* the main region pattern.

Given a temperature pattern code and the template tables for all sensor locations, the template matching mechanism works as follows:

1. Select a template table at a new specific location (e.g. template table for Heating Mixing Water Temperature listed in Table 14)
2. Start with period 1, if the temperature pattern in period 1 includes a transition region pattern, compare the pattern code with the cells in table "period 1, column 1". If it matches any of the patterns, then continue to compare the main region pattern code with the cells in table "period 1, column 2". If both find matches, go to step 3. If not,

this temperature pattern does not belong to this location. Select a new template table and start over from step 1.

3. Continue the same comparison for periods 2 to 6, until the temperature pattern codes find matches in all six periods. The temperature pattern is then assigned to this location.
4. Select next template table in another location, redo step 1 to 3.
5. If the temperature pattern matches with multiple temperature locations, use some special heuristic rules (described in the next section) to eliminate the wrong one.

The temperature pattern code illustrated in Figure 46: “131” “131” “414 000” “241 131” “131” “131” is a match for template Table 14, therefore, this pattern is a possible output from the heating water mixing temperature (HWC-MWT”) sensor.

### 5.6.2 Special Rules

The AHU temperature sensor pattern recognition algorithm is supposed to be applicable to various outside air and environmental conditions. However, in some special conditions, one temperature pattern may match two or multiple sensor location template tables. In this case, the following rules will be applied trying to single out the true temperature sensor location. These rules are based on air handling unit common operation conditions and characteristics, and are not restricted to specific configuration, size of components and air flow, water flow rate, etc.:

- If the mean temperature of the six-period pattern is below 55 Deg F, then it is not one of the heating water temperatures or air temperatures; if the mean temperature is above 90 Deg F, it is one of the heating water temperatures. If it is in-between, it can only be one of the air temperature sensors or the cooling coil leaving water temperature (CHWC-LWT).

- To distinguish SA-TEMP and other temperature sensors (e.g. CHWC-DAT). Check the transition period pattern in period 6. If there is a peak (down) or linear (down) pattern, the pattern is an output from the supply air temperature (SA-TEMP). Otherwise, it is not.
- To distinguish RA-TEMP and MA-TEMP, check the end of period 4 and the start of period #5. If there is a smooth continuation of trend in data, then it is RA-TEMP, otherwise it is MA-TEMP.
- To distinguish CHWC-DAT and HWC-DAT, evaluate the slope and magnitude of temperature drop in the transition region in period 4. If it is a sharp down linear pattern, it is a HWC-DAT; otherwise, it is a CHWC-DAT.
- To distinguish CHWC-LWT and CHWC-MWT, evaluate the slope of temperature pattern in the transition region of period 4. If it is a sharp down linear pattern, it is a CHWC-MWT; otherwise, it is a CHWC-LWT.
- To distinguish CHWC-EWT and CHWC-MWT, evaluate the slope and magnitude of the temperature pattern in the transition region of period 4. If it is a sharp down linear pattern, it is a CHWC-MWT; otherwise, it is a CHWC-EWT.
- To distinguish HWC-EWT, HWC-MWT, and HEC-LWT, evaluate the period 4 transition patterns. If it is not a peak pattern and the first temperature is the highest in period 4, then it is HWC-LWT. If it is not a peak pattern and the first temperature is the lowest in period 4, then it is HWC-MWT.

# CHAPTER 6. FACILITY DESCRIPTION AND TEST SETUP

A prototype of a plug and play AHU control system was built to test the AHU temperature sensor auto recognition algorithm. The prototype is not a fully functional BAS control system, as many input/output “smart” transducer components are not commercially available yet. The main purpose of the test is to provide a proof of concept for the plug and play AHU control system framework, and to generate training data for constructing the group of template tables mentioned in Chapter 5.6.1. The prototype will be tested on real air handling units in a real building, and under various outside air and environmental conditions in the mechanical room where the AHUs are located.

## 6.1 Facility Layout

All tests are conducted at the Iowa Energy Center's Energy Resource Station (ERS) located in Ankeny, Iowa. The ERS is a full-scale building HVAC system test facility. The ERS combines laboratory testing capabilities with real building characteristics. The facility is equipped with three air handling units. AHU-1 serves the common areas of the building including two classrooms. The remaining two AHUs (AHU-A and AHU-B) serve the identical A- and B- Test Systems, with each system composed of four zones – one zone in each of East, South, West, and North orientation (the north oriented rooms do not have exterior windows and are called Interior Test Rooms) (Figure 46)[14]. A commercial building energy management and control system is used to control the ERS HVAC systems A and B. This system configuration allows ERS to do side-by-side simultaneous real world building HVAC system comparison testing.

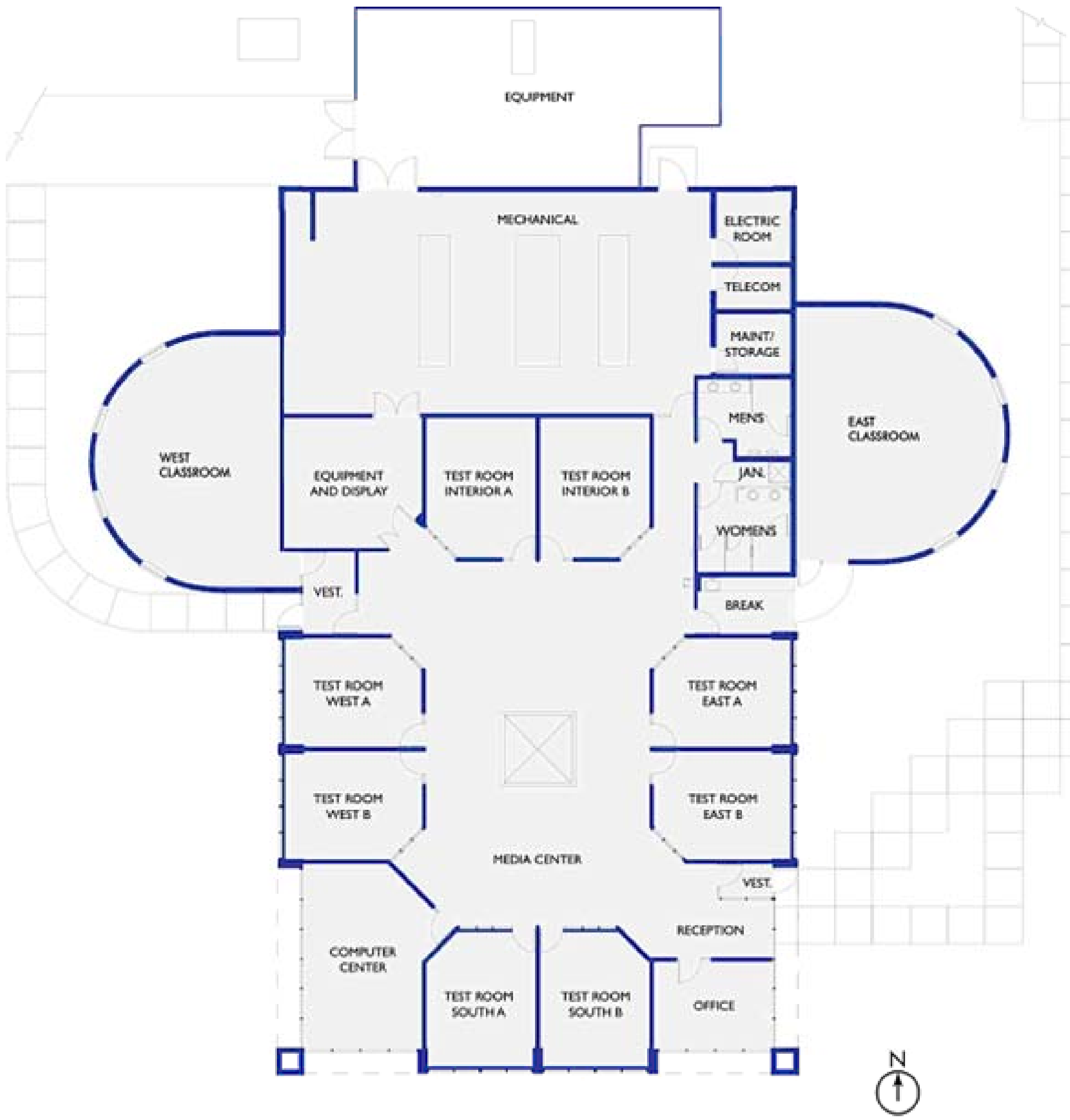



Figure 46. General floor plan at energy resource station

The test room floor area sizes and window sizes are listed in Table 15. The exterior walls have summer and winter thermal resistances of 12.90 and 13.18 $hft^{2o}F/Btu$. The windows in the Test Rooms are double-glazed 1/4 in. clear insulating glass with a 1/2 in. air space, measure 5 ft high by 14.8 ft wide, have aluminum frames with thermal breaks, have no exterior shading devices, have summer and winter overall U-values of 0.55 and 0.48 Btu/hft$^2$°F, and a shading coefficient (SC) of 0.85 [36].

Table 15. ERS test room dimensions

| Room | Net Floor Area (sq. ft) | Ceiling Height (ft) | Plenum Height (ft) | Exterior Wall (sq. ft) | Exterior Window (sq. ft) |
|---|---|---|---|---|---|
| Exterior | 267 | 8.5 | 5.5 | 137 | 74 |
| Interior | 267 | 8.5 | 5.5 | 0 | 0 |

The mechanical room is where the three air handling units are located. It is usually maintained around 65~70 Deg F by air handling unit AHU-1 and general service VAV box terminal unit.

## 6.2 Mechanical System Description

Each ERSTEST mechanical system consists of a variable-air-volume (VAV) type air handling unit (AHU-A or AHU-B), four variable-air-volume terminal units (one in each test room), and AHU supply air duct and return air duct distribution systems. There is a central heating plant (located in the mechanical room) and cooling plant (located outside the building) providing heating water and chilled water for all AHUs and VAVs.

The ERSTEST air handling units (Figure 15, Figure 47 [14]) are manufactured by TRANE. They are built from modular components that enable alternate components to be inserted as needed by the tests to be performed. Each AHU has designed supply air flow rate of 3200 CFM (Table 16). The AHUs have eight modular sections: mixed air section, filter section, air blender section, heating coil section, cooling coil section, supply air fan section, return air fan section, and economizer section (Figure 47). The major components includes supply and return fans, heating and cooling coils and their control valves, and outside air, return air and exhaust air dampers.

The supply fan and return fan designed data are listed in Table 17 and Table 18 respectively. Both fans are controlled by a VFD with minimum speed at 20% (12 HZ) and maximum at 100% (60 HZ).

Table 16. AHU general data

| | |
|---|---|
| Air Handling Unit Type | Central Station VAV |
| Total Design Supply Air Flow | 3200 CFM |
| Total Design Outside Air Flow | 1200 CFM Max |
| Economizer Mixed Air Flow | 0 - 100% |
| Supply Air Total Static Pressure | 3.20 Inch WG |
| Supply Air Motor Horsepower | 5.0 MHP |
| Return Air Total Static Pressure | 1.25 Inch WG |
| Return Air Motor Horsepower | 2.0 MHP |
| Cooling Coil | Chilled Water 135 MBH |
| Heating Coil | Hot Water 208 MBH |
| Manufacturer | Trane |
| Mixed Air Section | 14 x 30 OA Damper - Opposed Blade |
| | 14 x 30 RA Damper - Opposed Blade |
| Heating Coil Section | Hot Water - 2 Row (6.0 Sq. Ft. Face Area) |
| Cooling Coil Section | Chilled Water - 6 Row (6.0 Sq. Ft. Face Area) |
| Supply Air Fan Section | Double Width Centrifugal, Vertical Up Discharge |
| Return Air Fan Section | Double Width Centrifugal, Horizontal Discharge |
| Economizer Section | 14 x 40 EA Damper - Opposed Blade |

Table 17. AHU-A, AHU-B supply fan design data

| | |
|---|---|
| Fan Type | Forward Curve Double Width Centrifugal |
| Total Design Supply Air Flow | 3200 CFM |
| SA Fan Total Static Pressure | 3.20 Inch WG |
| SA Fan External Static Pressure | 1.75 Inch WG |
| SA Fan Efficiency | 55% |
| SA Fan Motor Horsepower | 5.0 MHP |
| SA Fan Brake Horsepower | 3.0 BHP |
| SA Fan Motor Speed Control | Variable Frequency Drive |
| Electrical Characteristics | 460 Volt / 3 Phase / 60 Hertz |

Table 18. AHU-A, AHU-B return fan design data

| | |
|---|---|
| Fan Type | Forward Curve Double Width Centrifugal |
| Total Design Return Air Flow | 3200 CFM |
| RA Fan Total Static Pressure | 1.25 Inch WG |
| RA Fan External Static Pressure | 0.25 Inch WG |
| RA Fan Efficiency | 70% |
| RA Fan Motor Horsepower | 2.0 MHP |
| RA Fan Brake Horsepower | 1.2 BHP |
| RA Fan Motor Speed Control | Variable Frequency Drive |
| Electrical Characteristics | 460 Volt / 3 Phase / 60 Hertz |

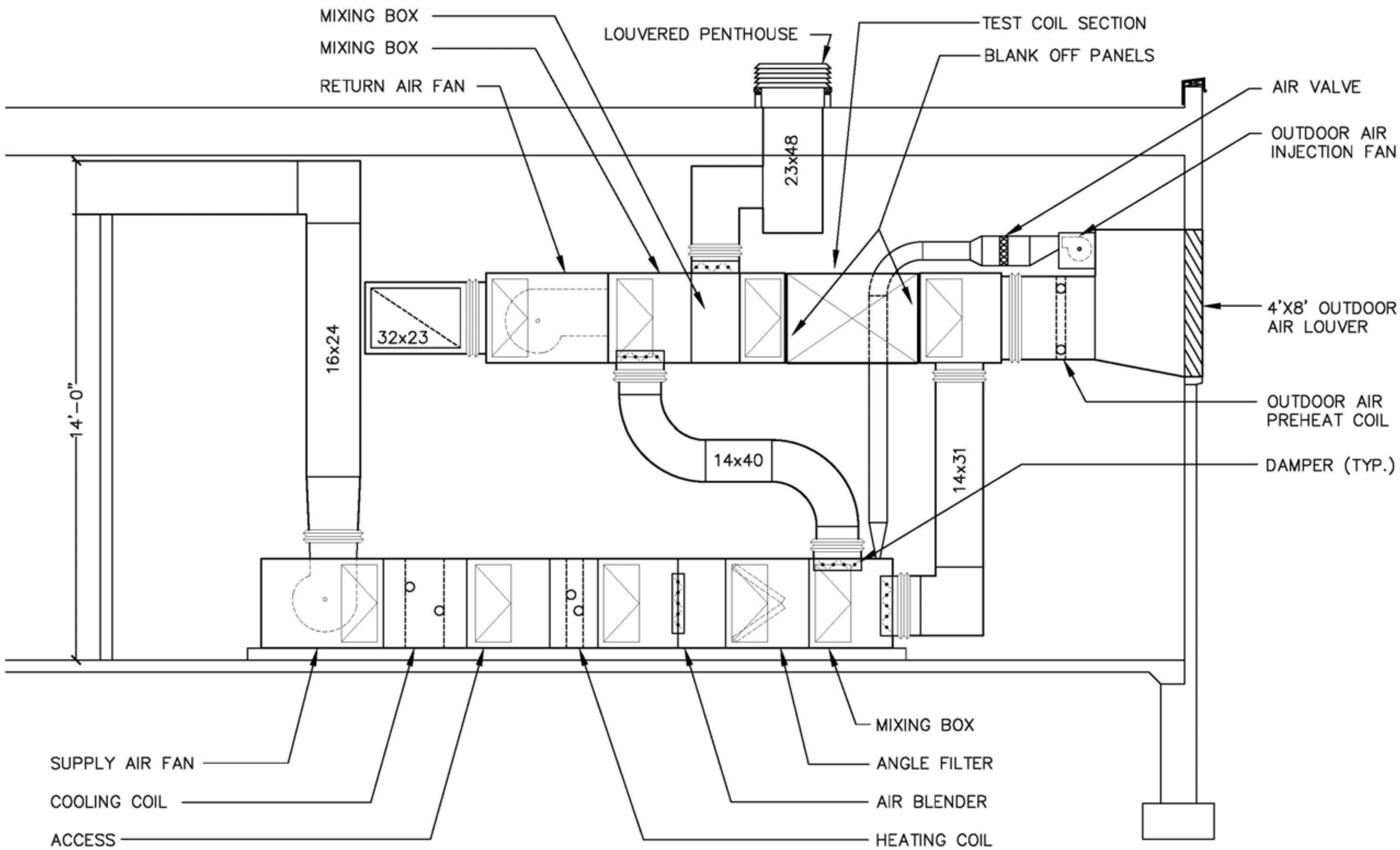



Figure 47 . ERSTEST AHU section details

The heating coil data is listed in Table 19, and the cooling coil data is listed in Table 20. Both coils are controlled through Johnson Controls VG 7842NT + 926 HGA 1" 3-way mixing globe valve with *linear* flow characteristics and M9216-HGA-2 actuator. The actuators are powered by 24VAC, accept 0~10VDC control output which corresponds to 0~100% valve open position, and has 0~10VDC feedback signals available. The control valve flow coefficient *Cv* values for both control valves are 11.6. The actuator rotation time ranges from 70 to 130 seconds for 0 to 140 lb·in, 90 seconds nominal at 50% rated load.

Table 19. AHU-A, AHU-B heating coil design data

| | |
|---|---|
| Manufacturer | Trane |
| Heating Coil Model Number | Trane Type "UW" Coil |
| Heating Coil Type | Copper Tube / Aluminum Plate Fin |
| Total Heating Capacity | 208,200 BTU/H |
| Entering Air Temp - Dry Bulb | 40.0°F db |
| Leaving Air Temp - Dry Bulb | 100.0°F db |
| Air Pressure Drop | 0.20 Inch WG |
| Water Flow Rate | 21.0 GPM |
| Entering Water Temp | 180.0°F |
| Leaving Water Temp | 160.20°F |

Table 20. AHU-A, AHU-B cooling coil design data

| | |
|---|---|
| Manufacturer | Trane |
| Cooling Coil Model Number | Trane Type "UW" coil |
| Cooling Coil Type | Copper Tube / Aluminum Plate Fin |
| Total Cooling Capacity | 122,100 BTU/H |
| Entering Air Temp - Dry Bulb | 82.0°F db |
| Entering Air Temp - Wet Bulb | 66.5°F wb |
| Leaving Air Temp - Dry Bulb | 54.5°F db |
| Leaving Air Temp - Wet Bulb | 54.0°F wb |
| Air Pressure Drop | 0.78 Inch WG |
| Water Flow Rate | 28.0 GPM |
| Entering Water Temp | 44.0°F |
| Leaving Water Temp | 53.7°F |

For water coils, the flow rate and the coil capacity (therefore the heat transfer output) is nonlinear and based on several factors [17]. A typical coil characteristic is non-linear and shown in Figure 48. Since the control valves used have *linear* characteristics – the percentage of flow rate is proportional to the percentage of valve stroke, the overall percent of coil capacity to the percentage of valve stroke will be similar shape as the coil characteristic in Figure 48. Even with other control valve types (equal percentage and quick opening), the temperature pattern for the first 10 minutes will probably be similar to the linear control valves. This is because the sampling rate of AHU temperature auto recognition algorithm is 1 minute, and the control valves take two minutes to go from fully closed to fully open. So it takes about 2 minutes for the coils to start transferring full capacity.

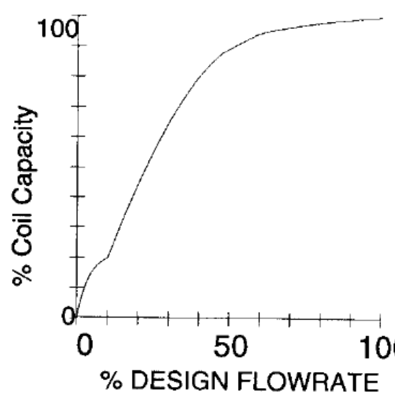



Figure 48. Typical coil characteristics

The three AHU dampers are used for economizer control to bring in fresh outside air if needed. Normally the outside air damper percentage open position, exhaust air damper percentage open position, and return air damper percentage close position are the same during normal operations to keep the outside, mixed air, and exhaust air in balance for a

AHU and the building. The outside air and return air dampers are Ruskin model CD60 14 x 30 3-opposed blade dampers, and the exhaust air dampers are 14 x 40 3-opposed blade dampers. The actuators for these dampers are Belimo model AF24-SR electrical damper actuator, which are powered by 24 volts (AC or DC) and damper outputs are proportional to 2~10 VDC signal (0~100%). They also have feedback signals of 2~10VDC corresponding to 0~100%. The running time for these actuators is 150 seconds from 0% to 100% open, independent of load. Therefore for damper operations in AHU temperature auto recognition algorithm step 6, the changeover of these dampers should be finished within 3 minutes.

The VAV unit in each test room (Figure 49, Table 21) distributes AHU supply air into the zone and controls the zone temperature by changing the cooled air (usually around 55 Deg F) volume or by changing the discharge air temperature via adjusting hydronic coil valve positions or enabling electric reheat coil 3 stages in the VAV. The designed air flow rate of each exterior VAV box is 10000 CFM, and 400 CFM for the interior VAV.

Table 21. VAV boxes design data

| Manufacturer | Titus | Titus |
|---|---|---|
| Test Rooms Served | East A & B / South A & B / West A & B | Interior A & B |
| VAV Box Type | Single Duct, Pressure Independent | Single Duct, Pressure Independent |
| CFM Range | 0-1050 CFM | 0-650 CFM |
| Design Airflow - Minimum | 200 CFM | 200 CFM |
| Design Airflow - Maximum | 1000 CFM | 400 CFM |

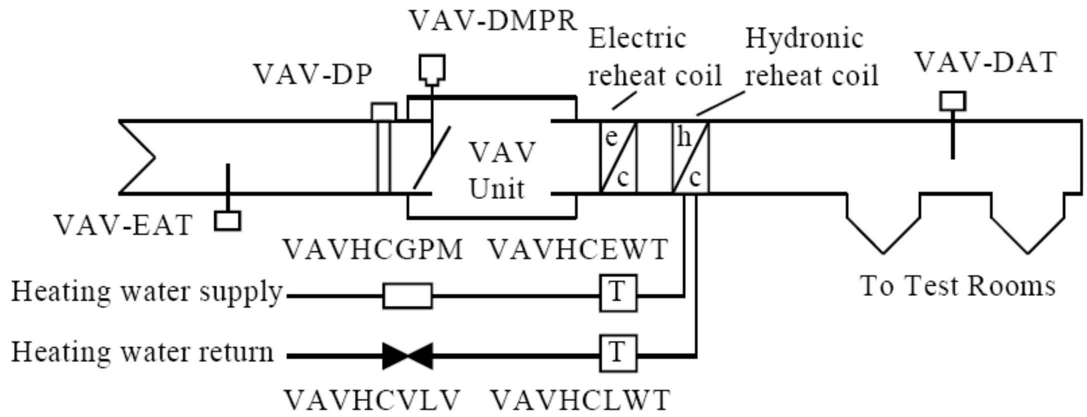



Figure 49. Test room VAV box schematic diagram

The heating plant in the mechanical system (Figure 51) at the ERS consists of a natural gas fired boiler, three fixed speed heating water pumps (one for each AHU heating water coil), two variable speed heating loop pumps for test room VAV hydronic reheat coils (not shown in the schematic diagram), and heating water distribution piping system. The boiler general data is listed in Table 22. The efficiency curve for the boiler is illustrated in Figure 50 [14]. It is normally operated in automatic control mode so that the leaving water temperature is maintained at a fixed setpoint (usually set between 120 Deg F ~ 180 Deg F for HVAC applications). The heating water pumps for AHU-A and AHU-B are 0.5 horsepower Bell & Gossett series 60 in-line centrifugal pump and the rated water flow rate is 21 GPM each.

Table 22. Boiler data

| | |
|---|---|
| Manufacturer | Aerco International |
| Boiler Unit Model | KC-1000-GWB |
| Boiler Type | Natural Gas Fired Hot Water |
| Fuel Consumption | 1,000 CFH Gas @ 1,000 BTU/CF |
| Maximum Capacity | 930,000 BTU/H |
| Water Volume | 23 Gallons |
| Control Range | 50° To 220° F |
| Rated GPM | 100 GPM |
| Water Temperature Rise @ Rated GPM | 17.2 / 18.3 |
| Minimum Flow, GPM | 25 GPM |
| Maximum Flow, GPM | 150 GPM |

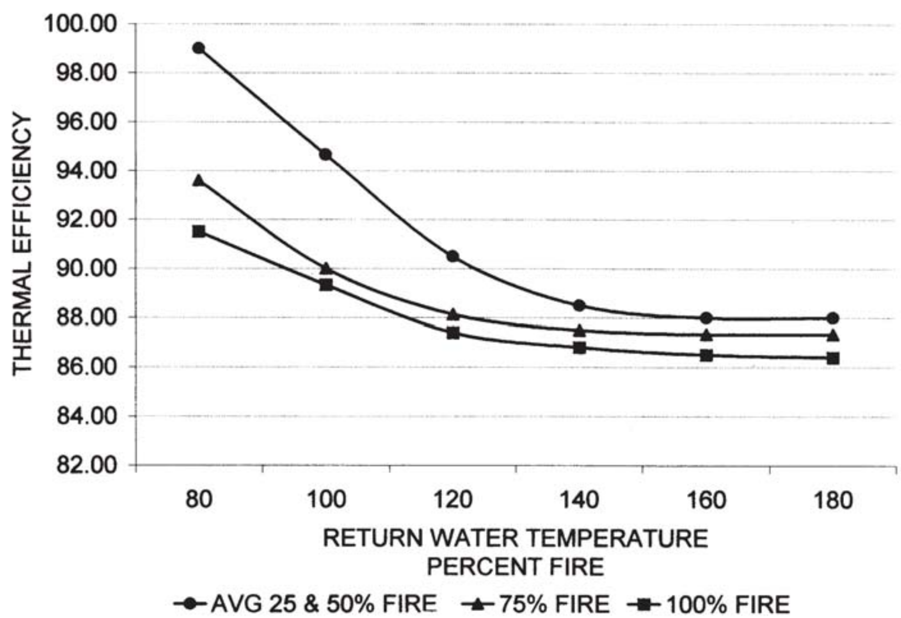



Figure 50. Thermal efficicney curve of the ERS boiler

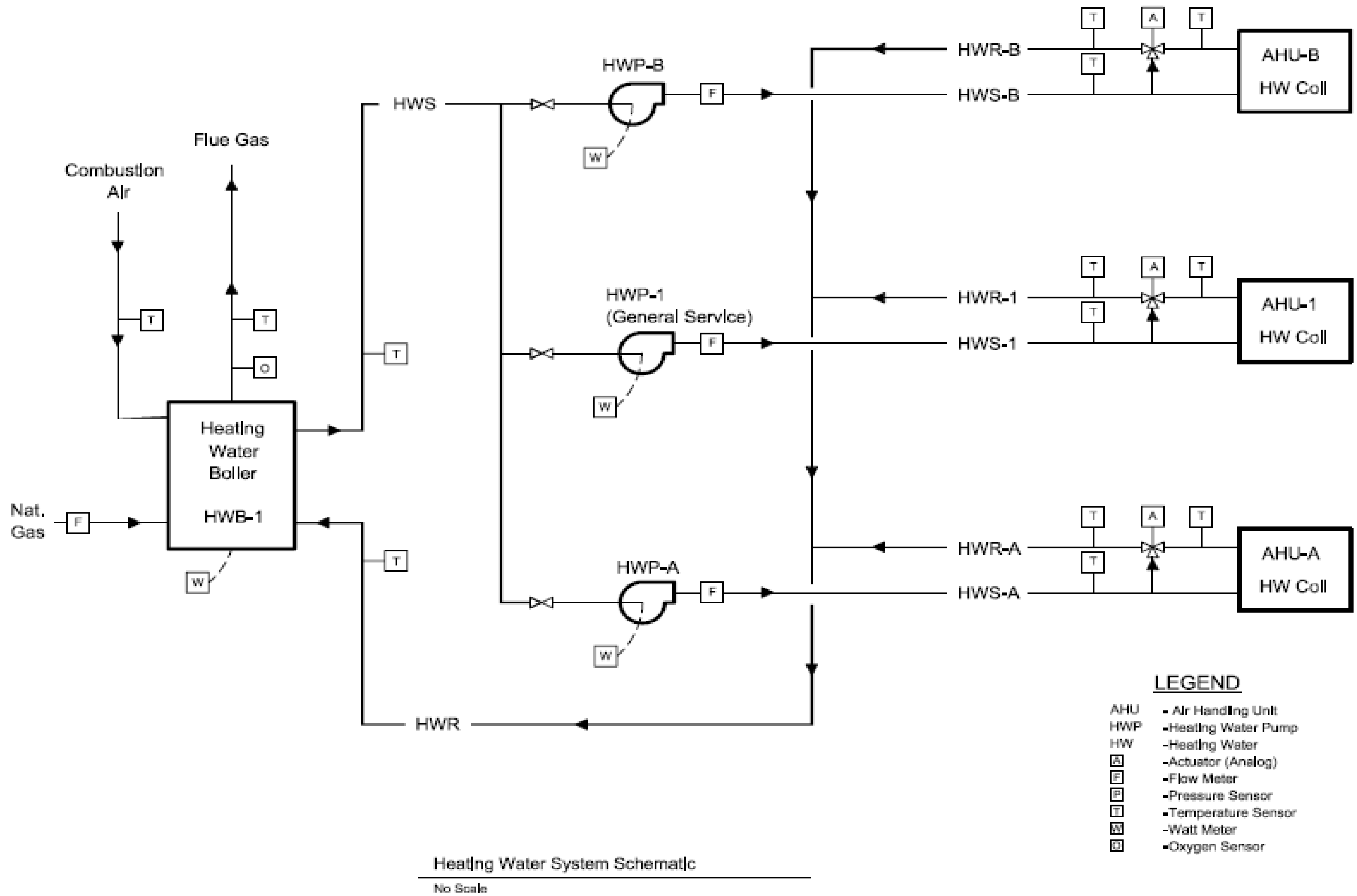



Figure 51. Heating water system schematic diagram

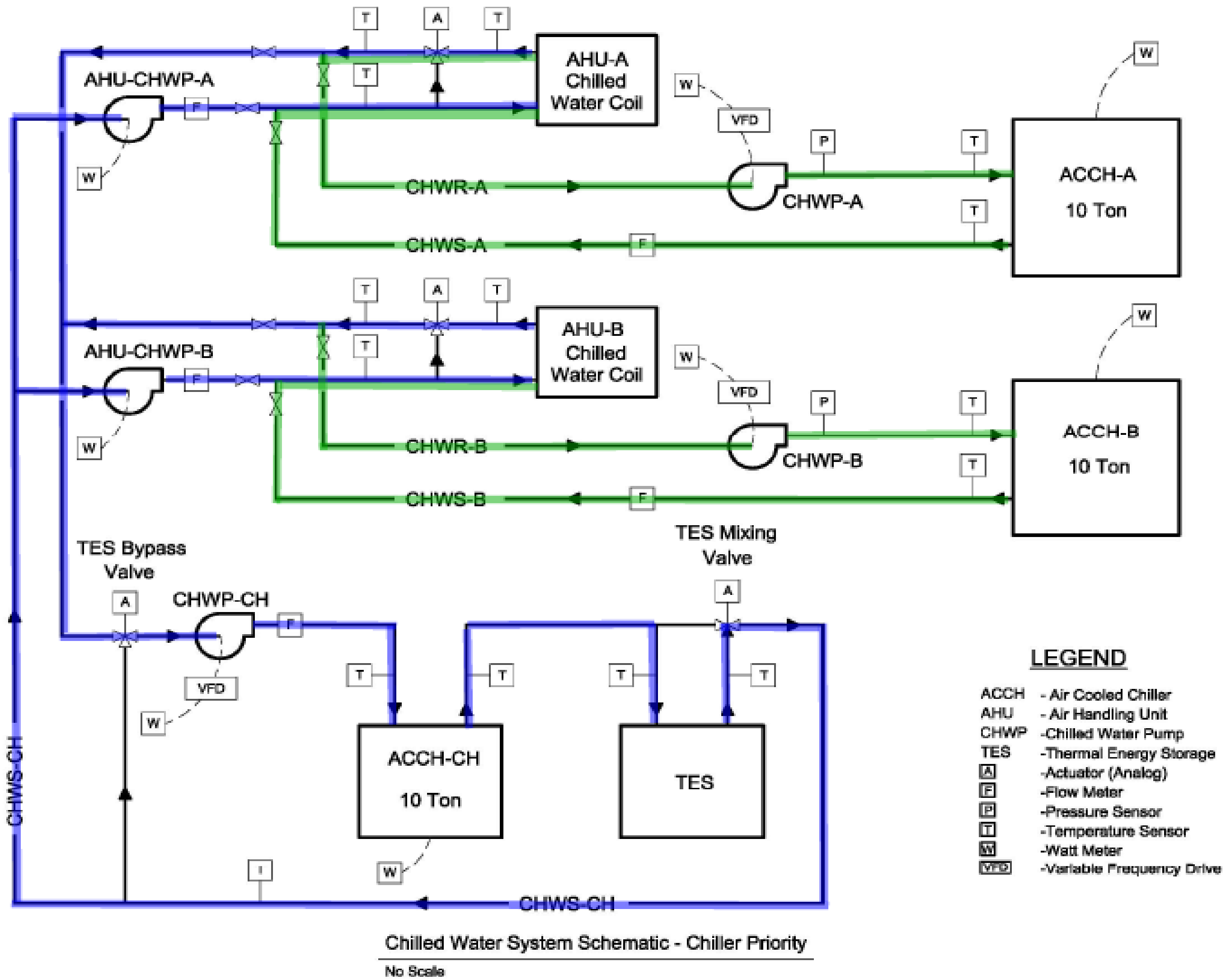



Figure 52. Chilled water system schematic diagram

The chilled water plant (Figure 52) at the ERS consists of three nominal 10 ton air-cooled chillers, a 149 ton·hour thermal energy storage (TES) unit, five chilled water pumps for circulating water through the HVAC components and necessary manual and automatic control valves for different system configurations. There are mainly two different system configurations for providing chilled water to the ERS air handling units: 1) Primary-Secondary pumping configuration (blue lines) with the combination of using "ACCH-CH" chiller and thermal storage to provide smooth chilled water supply temperature; and 2) Single pumping configuration (green lines), which use "ACCH-A" and "CHWP-A" to provide chilled water for AHU-A cooling coil, and "ACCH-A" and "CHWP-A" to provide chilled water for AHU-A cooling coil. The primary-secondary configuration also uses "CHWP-CH" as primary and "AHU-CHWP-A" and "AHU-CHWP-B" as secondary pumps. The two secondary pumps are fixed speed pumps while all others chilled water pumps are variable speed controlled.

The chillers' general data are listed in Table 23 (ACCH-CH) and Table 24 (ACCH-A and ACCH-B). The thermal storage data are listed in Table 25. All three chillers are installed outside the building, and the thermal storage is buried under the ground. The chilled water pumps general data is listed in Table 26. It is worth to mention that for the primary-secondary chilled water system with thermal storage configuration, the actual chilled water flow rate through each AHU coil is around 15 GPM if the both primary and secondary pumps are running, and about 11 GPM if only the primary pump (ACCH-CH) is running. For single pump system configuration, the chilled water flow rate to AHU cooling coil is around 28 GPM (when CHWP-A or CHWP-B runs at full speed).

Table 23. Chiller ACCH-CH general data

| | |
|---|---|
| Manufacturer | McQuay International |
| Chiller Type | Air Cooled Liquid Chiller |
| Nominal Unit @ ARI Conditions | 95°F Entering Air Temperature |
| Capacity | 9.6 Tons (33.8 KW) |
| Flow Rate | 24.0 GPM |
| Leaving Water Temp | 44.0°F |
| Full Load EER | 10.6 BTU/H per Watt |
| Integrated Part Load EER | 10.5 BTU/H per Watt |
| Heat Transfer Fluid | 25% Propylene Glycol |
| Electrical Characteristics | 460 Volt / 3 Phase / 60 Hertz |
| Chiller Performance (25% Propylene Glycol Application): | |
| Percent of Rated Capacity | 100% |
| Tons | 9.6 |
| Unit KW Input | 10.9 |
| EER - BTU/H per Watt | 10.6 |
| Entering Liquid Temp - °F | 54.0 |
| Leaving Liquid Temp - °F | 44.0 |
| Liquid Flow - GPM | 24.0 |
| Entering Air Temp - °F | 95.0 |

Table 24. Chiller ACCH-A, ACCH-B general data

| | |
|---|---|
| Manufacturer | McQuay International |
| Chiller Type | Air Cooled Liquid Chiller |
| Nominal Unit @ ARI Conditions | 95°F Entering Air Temperature |
| Capacity | 9.8 Tons (34.3 KW) |
| Flow Rate | 24.0 GPM |
| Leaving Water Temp | 44.0°F |
| Full Load EER | 9.7 BTU/H per Watt |
| Integrated Part Load EER | 12.2 BTU/H per Watt |
| Heat Transfer Fluid | 25% Propylene Glycol |
| Electrical Characteristics | 460 Volt / 3 Phase / 60 Hertz |
| Chiller Performance (25% Propylene Glycol Application): | |
| Percent of Rated Capacity | 100% |
| Tons | 9.6 |
| Unit KW Input | 12.0 |
| EER - BTU/H per Watt | 9.6 |
| Entering Liquid Temp - °F | 54.0 |
| Leaving Liquid Temp - °F | 44.0 |
| Liquid Flow - GPM | 24.0 |
| Entering Air Temp - °F | 95.0 |

Table 25. Thermal storage tank general data

| | |
|---|---|
| Manufacturer | FAFCO |
| Model | #140 |
| Dimension | 96” (L) x 66” (W) x 82” (H) |
| Nominal Storage | 149 ton hours |
| Latent Storage | 125 ton hours |
| Sensible Storage | 24 ton hours |

Table 26. Chilled water pumps general data

| Designation | AHU-CHWP-A, B | CHWP-A, B | CHWP-CH |
|---|---|---|---|
| Chilled Water Flow - GPM | 28.0 | 24.0 | 24.0 |
| Pump Head Press. - Feet WG | 26.0 | 50.0 | 50.0 |
| - PSI | 11.3 | 21.7 | 21.7 |
| Pump Efficiency | 48% | 37% | 36% |
| Pump Motor Horsepower - HP | 0.50 | 1.50 | 1.00 |
| Pump Motor Speed Control | Fixed | VFD | VFD |
| Pump Minimum Speed | 100% | 20% | 20% |

## 6.3 Smart Temperature Sensor Description

The original temperature sensors used for controlling the AHUs are platinum 1000 ohm RTD sensors from Weed Instruments (now Ultra Electronics, Nuclear Sensors & Process Instrumentation). These sensors are calibrated periodically to make sure they are within +/-0.25 Deg F compared with a high accuracy reference sensor throughout the applicable ranges. The sensors measure 1000 ohm resistance at 0 Deg C and have 0.00385055 TCR (Temperature Coefficient of Resistance). The water temperature sensors are fixed length, while the air temperature sensors are a field cuttable type.

To build the prototype of a plug and play AHU control system, all temperature sensors used will be IEEE 1451 compatible smart temperature sensors. Specifically, Weed Instruments now provides commercially available IEEE1451.4 compatible smart TEDS sensors. As introduced in Chapter 2.4, the IEEE1451.4 standard describes a mixed-mode interface for analog transducers with analog and digital operating modes. A TEDS was added to a traditional two-wire sensor, as illustrated in Figure 53. The addition of TEDS brings the benefits of faster set up time, increased reliability, improved accuracy, and open standard interoperability, etc.

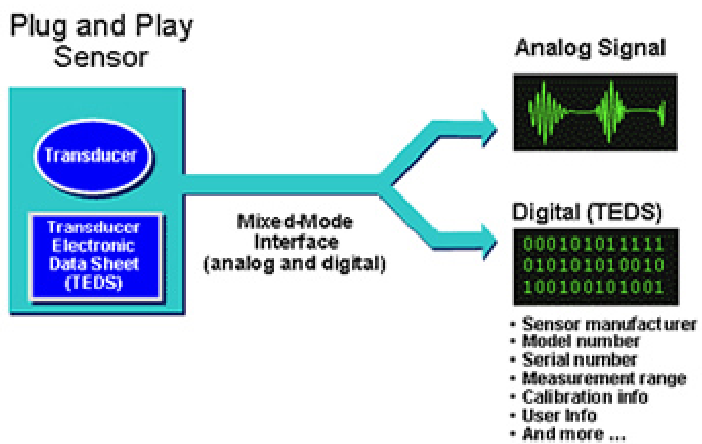



Figure 53. Illustration of IEEE 1451.4 compatible temperature sensors

Eleven smart temperature sensors were purchased from Weed Instrument for this research project, each is assigned to one AHU location (see Table 9 in Chapter 5.2 for location information). The specification for these sensors is listed in Table 27. A sensor photos are shown in Figure 54. As an example, some TEDS information is shown in Figures 55 and 56.

Table 27. Smart temperature sensor specification

| | |
|---|---|
| Manufacturer | Weed Instruments |
| Model | SP101-BH-D-4-C-010.0-Z024-W-TEDS |
| Type | 1000 ohm Platinum RTD with TEDS chip |
| Length | 10 inches |
| Diameter | 0.25 inch |
| Construction | Wire-wound |
| TEDS Protocol | IEEE 1451.4 |
| # Wires for Analog Signal | 4 |
| # Wires for Digital Signal | 2 |

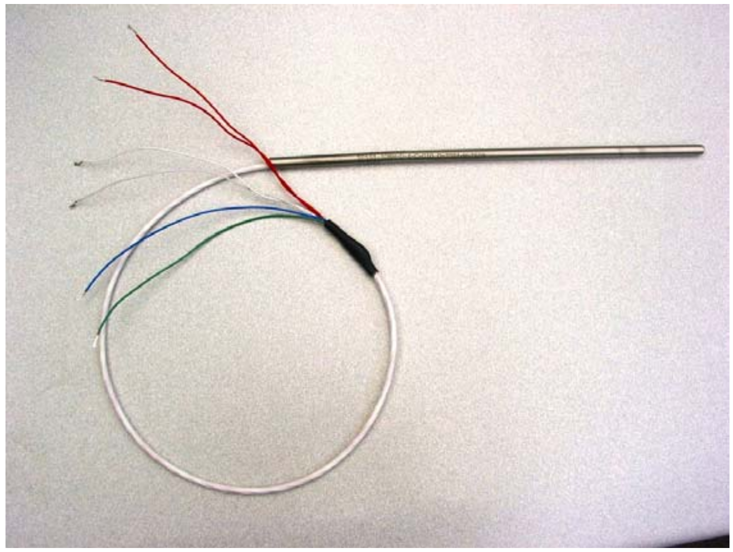
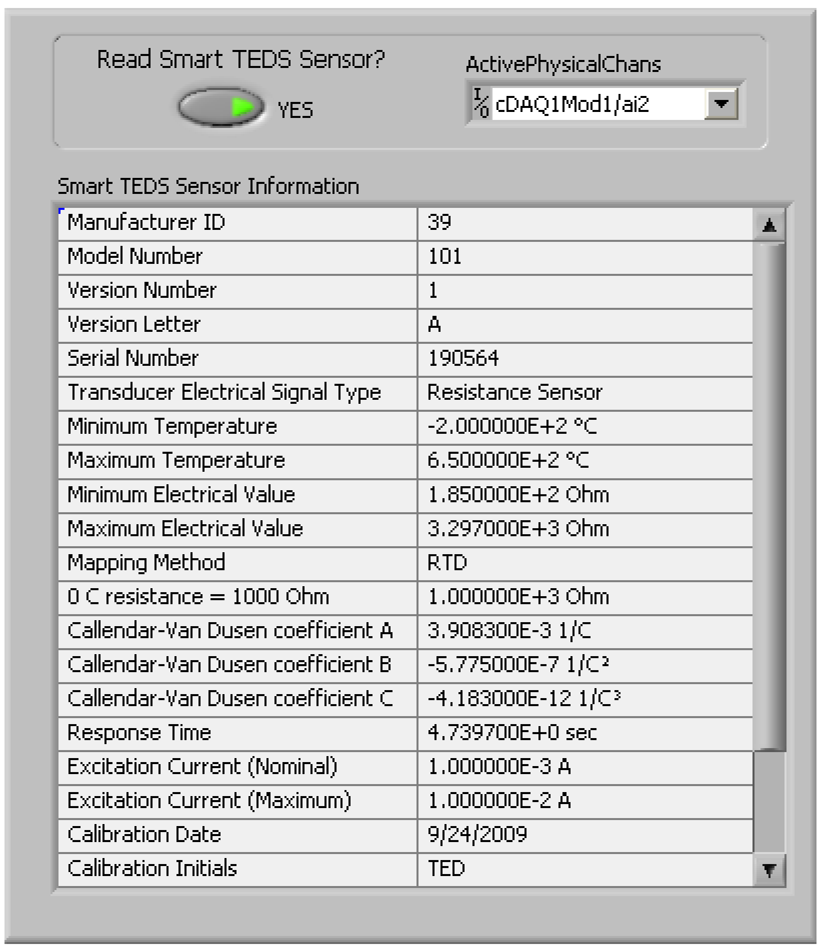
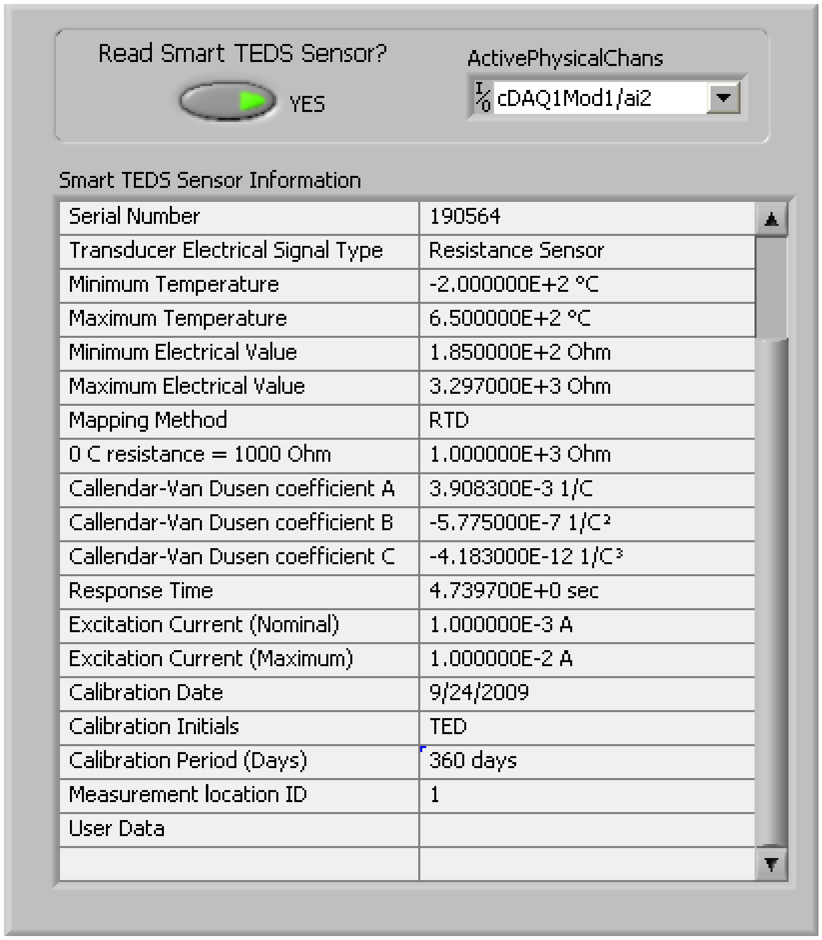


Figure 54. Photo of an IEEE1451.4 smart temperature sensor




| | |
|---|---|
| Manufacturer ID | 39 |
| Model Number | 101 |
| Version Number | 1 |
| Version Letter | A |
| Serial Number | 190564 |
| Transducer Electrical Signal Type | Resistance Sensor |
| Minimum Temperature | -2.000000E+2 °C |
| Maximum Temperature | 6.500000E+2 °C |
| Minimum Electrical Value | 1.850000E+2 Ohm |
| Maximum Electrical Value | 3.297000E+3 Ohm |
| Mapping Method | RTD |
| 0 C resistance = 1000 Ohm | 1.000000E+3 Ohm |
| Callendar-Van Dusen coefficient A | 3.908300E-3 1/C |
| Callendar-Van Dusen coefficient B | -5.775000E-7 1/C² |
| Callendar-Van Dusen coefficient C | -4.183000E-12 1/C³ |
| Response Time | 4.739700E+0 sec |
| Excitation Current (Nominal) | 1.000000E-3 A |
| Excitation Current (Maximum) | 1.000000E-2 A |
| Calibration Date | 9/24/2009 |
| Calibration Initials | TED |

Figure 55. A sample TEDS table for smart temperature sensor - 1




| | |
|---|---|
| Serial Number | 190564 |
| Transducer Electrical Signal Type | Resistance Sensor |
| Minimum Temperature | -2.000000E+2 °C |
| Maximum Temperature | 6.500000E+2 °C |
| Minimum Electrical Value | 1.850000E+2 Ohm |
| Maximum Electrical Value | 3.297000E+3 Ohm |
| Mapping Method | RTD |
| 0 C resistance = 1000 Ohm | 1.000000E+3 Ohm |
| Callendar-Van Dusen coefficient A | 3.908300E-3 1/C |
| Callendar-Van Dusen coefficient B | -5.775000E-7 1/C² |
| Callendar-Van Dusen coefficient C | -4.183000E-12 1/C³ |
| Response Time | 4.739700E+0 sec |
| Excitation Current (Nominal) | 1.000000E-3 A |
| Excitation Current (Maximum) | 1.000000E-2 A |
| Calibration Date | 9/24/2009 |
| Calibration Initials | TED |
| Calibration Period (Days) | 360 days |
| Measurement location ID | 1 |
| User Data | |
| | |

Figure 56. A sample TEDS table for smart temperature sensor – 2

As can be seen from the photo (Figure 54), the smart sensor has a small chip (TEDS) at the end of the sensor lead and a total of six wires (two red and two white wires are for 4-wire RTD connection and the blue and green wires are for digital connection). The 4-wire analog signals can be connected to a data acquisition system or control system the normal way a RTD sensor is connected (2-wire, 3-wire, or 4-wire connections). The two wires for the digital signal have to connect to an IEEE 1451 compatible data acquisition or measurement system to be able to read/write information from/to this sensor. Figures 55 and 56 show the information available from one of the eleven smart temperature sensors purchased. The values on the table are default values from the manufacture and stored on the

TEDS chips. It can be seen that besides the manufacture ID, model number, version number, version letter, serial number and transducer type, this sensor also provides minimum/maximum values for the resistance and temperature, as well as calibration information such as Callendar-Van Dusen coefficients for converting temperature to actual measured resistance. The equation can be used to generate a resistance-temperature table or reverse calculate temperature from measured resistance. The Callendar-Van Dusen equation [11] is listed in equation 6.3.1:

$$R(T) = R0[1 + AT + BT^2 + CT^3(T - 100)]; T < 0$$
$$R(T) = R0[1 + AT + BT^2]; T \geq 0$$

-200°C <T<650 °C     eq. 6.3.1

where

*R(T)* = Resistance at temperature T°C

*R(0)* = Resistance at temperature 0°C (given)

T = Temperature measured in °C

It is worth to mention that the Callendar-Van Dusen coefficients (A, B, and C values) in Figure 56 and Figure 57 correspond to the same resistance-temperature curve that expressed using TCR of 0.00385055 [11].

## 6.4 Control System Description

The original HVAC control system for the ERSTEST system uses METASYS building automation and control system (BAS) from Johnson Controls. The BAS consists of necessary hardware and software to be a full blown HVAC control system, and monitor and control all major inputs and outputs points of the system including AHUs, VAV units, chilled water and heating water plant, and lighting, etc. Advanced control algorithms are built in the local field controllers and network control modules. More than 800 data points are collected and stored in one minute intervals, 24 hours per day, 365 days per year. All data points are periodically calibrated to maintain its accuracy.

However, for a plug and play HVAC control system based on the framework from Chapter 4.3 and Figure 16, the communication protocol of the system needs to be able to read smart sensor information and execute commands (write) to smart actuators. The METASYS uses a proprietary communication protocol (*N1* for automation level and *N2* for field level) and does not have the capability to communicate with IEEE 1451 compatible smart sensors. Unfortunately, there is no commercially available HVAC control system yet to be able to communicate directly with IEEE 1451 compatible smart transducers.

The plug and play control system chosen in the prototype for this research is National Instruments' CompactDAQ USB data acquisition system (Figure 57). It "provides the plug-and-play simplicity of USB to sensor and electrical measurements" and "flexibility of modular instrumentation", for "fast, accurate measurements in a small, simple, and affordable system" [31]. This is a modular system with the flexibility of over 40 National Instrument measurement modules including temperature (RTD, thermocouple), voltage, current, and various other types of analog inputs as well as digital inputs and outputs. The chassis can hold up to 8 separate I/O modules with 24 bit analog resolution for different applications, and the interface from the chassis to a PC (or laptop) is a high speed USB (2.0) port. The main feature for this system is the capability to communicate with IEEE 1451.4 smart temperature sensors using a NI 9219 24-bit universal analog input module.

The NI 9219 module (Figure 58) is a 4-channel universal C Series module designed for multipurpose testing in any NI CompactDAQ or CompactRIO chassis. With the NI 9219, signals such as strain gages, RTDs, thermocouples, load cells, and other powered sensors can be measured. Each channel can be individually configured to different types of sensors and has 6 terminals for connections. For IEEE 1451.4 smart temperature sensors, 2 terminals will be used for the digital signal connection and the other 4 can be used for the RTD signal connections (2-wire, 3-wire, or 4-wire connection mode).

Figure 57. A National Instruments CompactDAQ data acquisition system


Figure 58. A NI 9219 module to measure IEEE1451.4 Smart temperature sensor

For the prototype control system to test AHU temperature auto recognition algorithm, the required points are listed in Table 9 in Chapter 5.2.1. The total number of smart temperature sensors that need to be recognized is 11. The total number of analog outputs includes: 2 for fan speeds, 3 for damper positions, and 2 for water control valves. The total number of digital outputs includes: 2 for fan start/stop and 2 for chilled water / heating water pump start/stop. It is worth mentioning that for all these points, only the temperature sensors need to be recognized as IEEE 1451 compatible smart transducers because all other types do not exist yet. Due to research budget limitation, the actual system configuration is listed as follows in Table 28:

Table 28. National Instruments hardware configuration for the prototype

| Model | Description | Quantity |
|---|---|---|
| NI 9481 | NI 9481 4-Ch 30 V, 60 V, 250 VAC EM Form A SPST Relay | 1 |
| NI 9263 | NI 9263 4 ch,16-bit, +/-10 V, 100 kS/s/Ch, AO Module | 1 |
| NI 9219 | NI 9219 4 Ch-Ch Isolated, 24-bit, ±60V, 100S/s Universal AI Module | 2 |
| NI cDAQ-9172 | cDAQ-9172 8-slot USB 2.0 Chassis for CompactDAQ, US (120 VAC) | 1 |

The above configuration can generate data for (and detect) up to 8 (instead of 11) smart temperature sensors at one time. Since in the designed sequence of operations the supply fan and return fan speed will be always 100% speed when started, the 2 analog output points can be eliminated in the prototype (just fixed the speed at the variable frequency drive to 60 HZ). For the three analog outputs used for controlling outside air, return air, and exhaust air dampers, since they open/close at the same time and the magnitude are the same (all 100% open or close), only 2 outputs are used (one output was parallel connected to both return and exhaust damper outputs to the actuators). The system configuration is also illustrated in Figure 59.

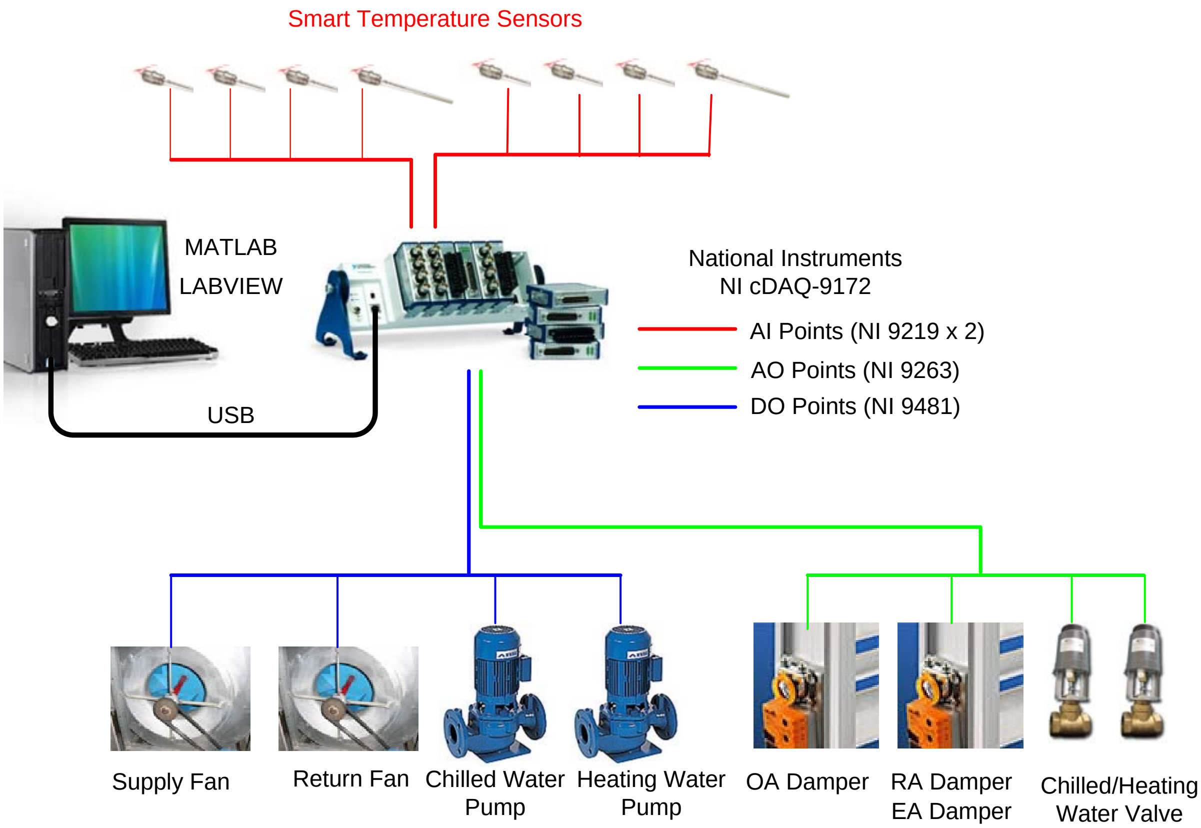



Figure 59. The prototype system configuration illustration

## 6.5 Software Description

The software used for data collection and execution of sequence of operations on this prototype is National Instruments' LABVIEW [48] - a graphical programming environment to develop sophisticated measurement, test, and control systems. The software used for execution of the pattern recognition algorithm developed in Chapter 5 is MathWorks' MATLAB [28], a very powerful software for scientific computing. The schematic of the software structure is illustrated in Figure 60. Both LABVEIW and MATLAB are installed on the same computer. LABVIEW communicates with the National Instruments hardware using a USB port. A LABVIEW program invokes the designed sequence of operations first

(1) and sends the command to the CompactDAQ system for execution (2). The corresponding fans, pumps, and dampers operate according to the sequence and the temperature data at eight different locations are recorded in ASCII format data files at 1 minute sampling rate (3) and (4). After all sequence of operations are finished and data collected, the LABVIEW program will call the MATLAB program to import the data set (5) and run temperature recognition algorithms to determine the logical locations for each of the eight analog channels. The result will be send back to the LABVIEW program (6) and then the location information is written on the smart temperature sensors' TEDS (7).

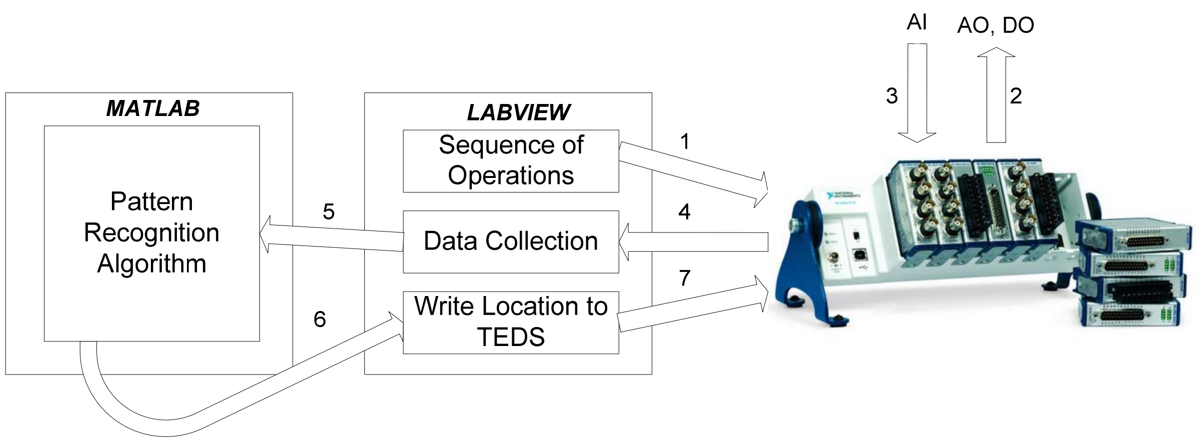



Figure 60. Software structure and program flow chart

# CHAPTER 7. TEST CASES, RESULTS AND ANALYSIS

## 7.1 Different Test Cases

In this research, there are two major categories of test cases: A) Test cases to generate a temperature pattern template table for each AHU temperature sensor location; and B) Test cases for verification of AHU temperature sensor auto recognition algorithm. In the following two subsections, the test cases and their testing conditions is discussed in details.

### 7.1.1 Test Cases for Pattern Training

Test cases for temperature training do not necessarily need to be implemented using the plug and play prototype for the AHU control system because the purpose is to collect temperature data patterns generated by AHUs according to the designed control sequences described in Chapter 5. Therefore, the AHUs and the control system used for data collection on these cases are the ERSTEST system AHU-A and AHU-B and their Johnson Controls' METASYS building automation system. The designed control sequences (fan, pump, valve, and damper operations) are scheduled via METASYS. These original temperature sensors are common general purpose platinum RTD temperature sensors (without TEDS chips) from Weed Instruments.

For the purpose of collecting data as a training data set for the temperature pattern recognition algorithm, test cases in this category will consider various outside air conditions, internal load conditions, and different chilled water supply configuration schemes. The test cases are implemented at the following conditions:

1. Different seasons: Tests are done in the summer period (August, September) as well as winter period (December, January). This is to provide data sets so the algorithm can be applicable all year long.
2. Different time of day: Tests are done starting at midnight (00:00), morning (08:00), and afternoon (16:00). Because of solar condition changes throughout the day and seasons, the internal loads of the zones will also change. This will generate data sets that cover various weather conditions.
3. Different chilled water supply configurations: Tests are done under single pumping configuration as well as primary-secondary pumping configurations. In the single pumping scheme, AHU-A chilled water is supplied by air cooled chiller A (ACCH-A) and AHU-B chilled water is supplied by air cooled chiller B (ACCH-B). In the primary-secondary pumping configuration, both AHU-A and AHU-B chilled water are supplied by air cooled chiller CH (ACCH-CH).
4. Different AHUs: Tests are done at AHU-A and AHU-B. This generates more data sets for training purposes, even though the two AHUs are identical in design.

A total of 129 successful tests (Table 29) are implemented and data collected at a 1 minute sampling rate from the original temperature sensors at each AHU sensor location. For each test, the effective testing duration is 6 hours, followed by a 2-hour period idling time before the next test starts. The test case numbers and their corresponding dates, start times, and AHU unit are listed in Table 29. In these test cases, the outside air temperature was as low as 26.7 Deg F and as high as 81.9 Deg F. The weather condition also ranges from cloudy, rainy days to clear sunny days. It is worth mentioning that due to ERS heating water system piping configuration (Figure 51), the thermosiphon effect (longer heating water piping therefore colder temperature in the pipe for AHU-B) causes a small water flow (0.5 ~ 1 GPM) going through AHU-B heating water pipe even without the heating water pump started in Step 1 and 2. Therefore the heating water temperatures for AHU-B are randomly affected by the boiler start/stop - these bad data are ignored. Therefore the total number of valid heating water temperature data sets is 70.

Table 29. Category A test case numbers and test conditions

| Outside Air Temperature Range (Deg F) | Case Number / Date | Start Time for AHU-A | | | Start Time for AHU-B | | |
|---|---|---|---|---|---|---|---|
| | | 0:00 | 8:00 | 16:00 | 0:00 | 8:00 | 16:00 |
| 61.4 – 79.0 | 8/19/2009# | **1** | **2** | **3** | **4*** | **5*** | **6** |
| 60.5 – 73.4 | 8/20/2009# | **7** | **8** | **9** | **10** | **11** | **12*** |
| 60.0 – 69.5 | 8/21/2009# | **13** | **14** | **15** | **16*** | **17** | **18*** |
| 54.8 – 76.3 | 8/22/2009# | **19** | **20** | **21** | **22** | **23** | **24*** |
| 61.8 – 81.9 | 8/25/2009# | **25** | **26** | **27** | **28** | **29** | **30** |
| 60.7 – 67.0 | 8/27/2009 | **31** | **32** | **33** | **34** | **35*** | **36*** |
| 62.5 – 76.9 | 8/28/2009 | **37** | **38** | **39** | **40*** | **41*** | **42*** |
| 54.6 – 70.4 | 8/29/2009 | **43** | **44** | **45** | **46*** | **47*** | **48*** |
| 47.9 – 66.7 | 8/30/2009 | **49** | **50** | **51** | **52*** | **53*** | **54*** |
| 52.1 – 73.2 | 9/2/2009 | **55** | **56** | **57** | **58*** | **59*** | **60*** |
| 39.9 – 63.9 | 10/30/2009 | - | - | **61** | - | - | **62*** |
| 35.5 – 51.6 | 10/31/2009 | **63** | **64** | **65** | **66*** | **67*** | **68*** |
| 38.5 – 67.5 | 11/1/2009 | **69** | **70** | **71** | **72*** | **73*** | **74*** |
| 38.3 – 58.3 | 11/2/2009# | **75** | - | **76** | **77*** | - | **78*** |
| 29.7 – 49.6 | 11/3/2009# | **79** | **80** | **81** | **82*** | **83*** | **84*** |
| 34.5 – 53.3 | 11/4/2009# | **85** | **86** | **87** | **88*** | **89*** | **90*** |
| 30.7 – 59.5 | 11/5/2009# | **91** | - | **92** | **93*** | - | **94*** |
| 40.2 – 61.6 | 11/12/2009 | **95** | **96** | **97** | **98*** | **99*** | **100*** |
| 47.9 – 59.9 | 11/13/2009 | **101** | **102** | **103** | **104*** | **105*** | **106*** |
| 45.2 – 56.1 | 11/23/2009 | - | - | - | - | - | **107*** |
| 42.0 – 49.5 | 11/24/2009 | - | - | - | **108** | **109*** | **110*** |
| 34.3 – 42.3 | 11/25/2009 | - | - | - | **111** | **112*** | **113*** |
| 28.2 – 34.9 | 11/26/2009 | - | - | - | **114*** | **115** | **116*** |
| 27.0 – 48.7 | 11/27/2009 | - | - | - | **117*** | **118*** | **119** |
| 31.2 – 56.0 | 11/28/2009 | - | - | - | **120*** | **121*** | **122** |
| 33.6 – 40.0 | 11/29/2009 | - | - | - | **123*** | **124*** | **125** |
| 27.6 – 52.1 | 11/30/2009 | - | - | - | **126*** | **127*** | **128** |
| 26.7 – 36.8 | 12/2/2009# | - | - | - | - | - | **129*** |

#The single pumping configuration is used for chilled water supply to AHU-A and AHU-B on these days; All other cases the primary-secondary pumping configuration is used.
*The three heating water temperature data for these cases are ignored.

### 7.1.2 Test Cases for Prototype Testing

Category B test cases are implemented on the plug and play AHU control system prototype described on Chapter 6. These cases are used to test the quality and feasibility of the plug and play framework and the AHU temperature sensor auto recognition algorithm. The temperature sensors used are IEEE 1451.4 smart temperature sensors described in Chapter 6.3. The end of each temperature sensor is connected to a terminal connector that can be plugged into any one of the eight analog channels of the plug and play prototype hardware (CompactDAQ system by National Instruments) (Figure 61). During these test cases, the original METASYS control system is disabled. The necessary digital and analog outputs from the hardware output module are connected to the actual AHU-A supply/return fan start/stop relay, three air dampers actuators, and two control valves actuators. The designed control sequences are programmed using LABVIEW. The software for the prototype also do data logging at a 1 minute sampling rate for each of the eight temperature channels and display all the temperature patterns on the screen (Figure 62). At the end of each test case, the LABVIEW software will invoke a MATLAB program to auto identify temperature location that is corresponding to each channel (Figure 63).

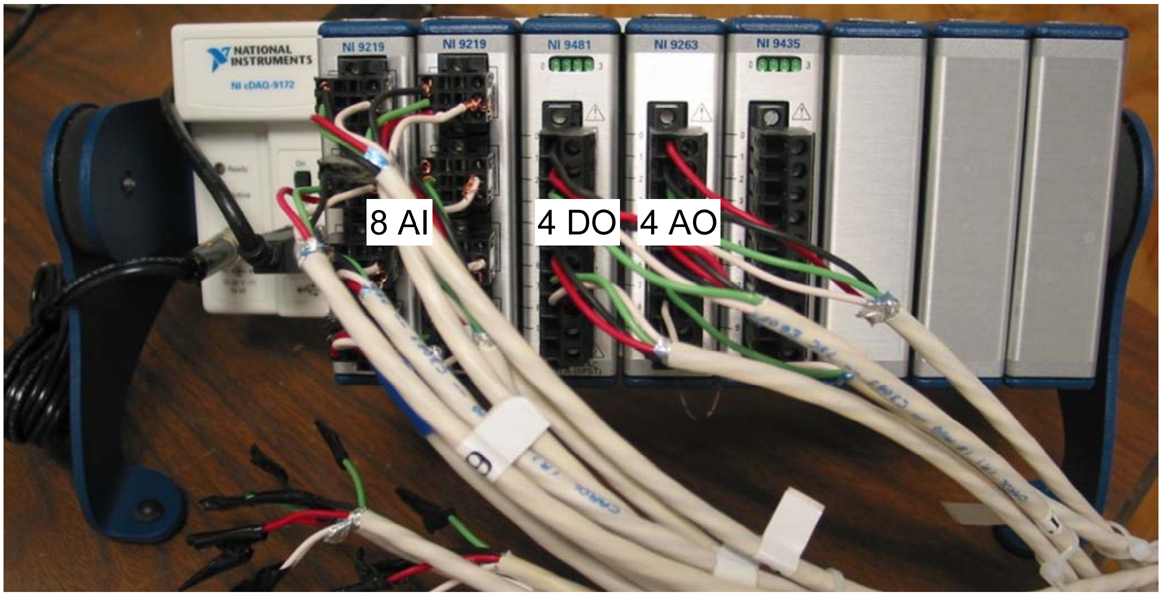



Figure 61. Plug and play prototype hardware

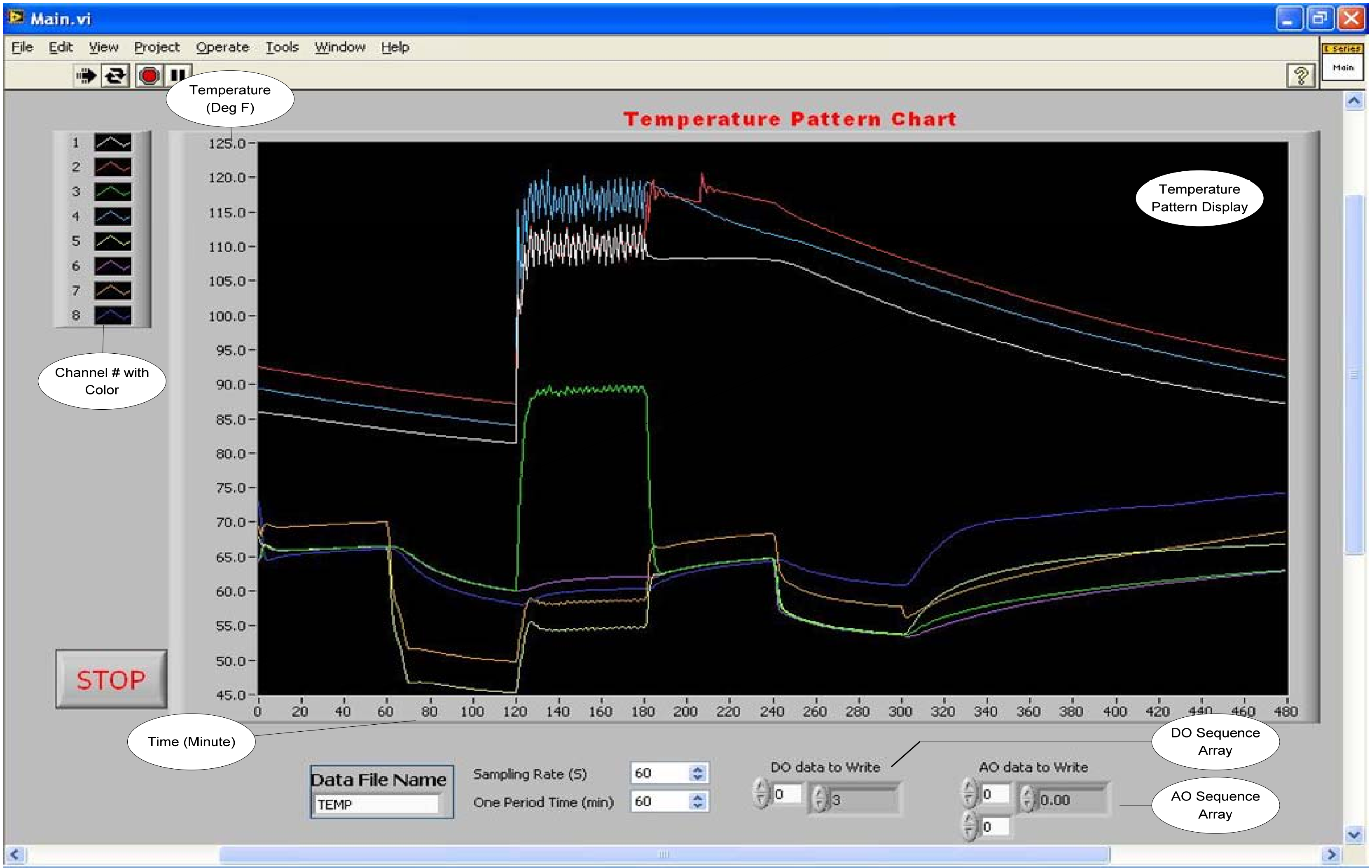



Figure 62. Plug and play prototype software screen shot 1 of 2

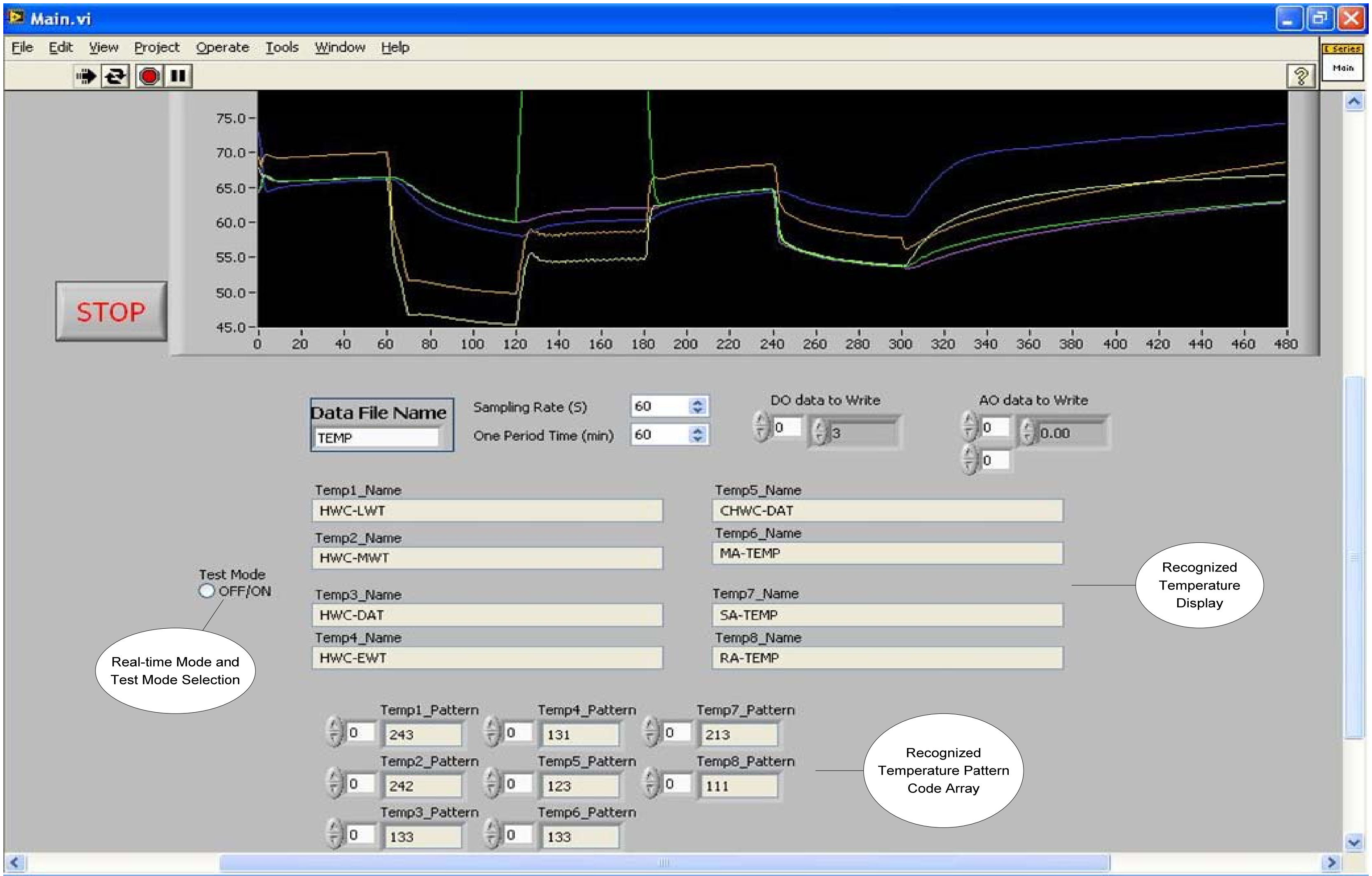



Figure 63. Plug and play prototype software screen shot 2 of 2

A total of 40 tests are implemented and data collected at a 1 minute sampling rate from the smart temperature sensors at each AHU sensor location. All tests are done on AHU-A, and a maximum of three tests are done in one day. For each test case, the prototype program is started manually at a random time and then everything is automatic. The test case numbers and their corresponding date are listed in Table 30.

Table 30. Category B test case numbers and test conditions

| | | AHU-A | | |
|---|---|---|---|---|
| Outside Air Temperature Range (Deg F) | **Case Number / Date** | 1 | 2 | 3 |
| 31.9 – 53.5 | 11/21/2009 | **1** | **-** | **-** |
| 46.9 – 52.8 | 11/22/2009 | **2** | **3** | **-** |
| 45.2 – 56.1 | 11/23/2009 | **4** | **5** | **-** |
| 42.0 – 49.5 | 11/24/2009 | **6** | **7** | **-** |
| 34.3 – 42.3 | 11/25/2009 | **8** | **9** | **-** |
| 28.2 – 34.9 | 11/26/2009 | **10** | **-** | **-** |
| 27.0 – 48.7 | 11/27/2009 | **11** | **12** | **-** |
| 31.2 – 56.0 | 11/28/2009 | **13** | **14** | **-** |
| 33.6 – 40.0 | 11/29/2009 | **15** | **16** | **-** |
| 27.6 – 52.1 | 11/30/2009 | **17** | **-** | **-** |
| 35.5 – 60.4 | 12/1/2009 | **18** | **-** | **-** |
| 18.8 – 28.1 | 12/3/2009# | **19** | **20** | |
| 14.7 – 24.7 | 12/4/2009# | **21** | **-** | **-** |
| 16.6 – 41.2 | 12/5/2009# | **22** | **23** | |
| 19.5 – 29.0 | 12/6/2009# | **24** | **-** | **-** |
| 15.0 – 22.3 | 12/7/2009# | **25** | **26** | |
| 19.2 – 28.3 | 12/8/2009# | **27** | **-** | **-** |
| 0.3 – 24.4 | 12/9/2009# | **28** | **29** | |
| -9.1 – 7.5 | 1/1/2010# | **30** | **31** | **32** |
| -19.5 – -1.7 | 1/2/2010# | **33** | **-** | **-** |
| 1.2 – 9.6 | 1/28/2010# | **34** | **-** | **-** |
| 0.3 – 12.5 | 1/29/2010# | **35** | **36** | **-** |
| 3.8 – 21.4 | 1/30/2010# | **37** | **38** | **-** |
| 10.8 – 18.9 | 1/31/2010# | **39** | **40** | **-** |

#The single pumping configuration is used for chilled water supply to AHU-A and AHU-B on these days; For other cases without the “#”, the primary-secondary pumping configuration is used.

Since there are total of 11 temperature locations and only up to eight smart temperature sensors can be connected to the prototype hardware at one time, the number of data sets for each location is equal to or less than the total number of 40 test cases. The availability of the smart temperature sensor for each test case in category B is listed in Table 31.

The temperature channel assignment for these cases may or may not be the same. The channel assignment of each available temperature sensors is listed in Table 32. The Case #40 temperature sensor channels was randomly changed via plug and play using the same temperature sensors from Case #30-39.

In the following sections 7.2 to 7.12, the temperature pattern statistics for each different temperature sensor in Category A cases will be studied in detail, and then a template table for the sensor is proposed based on the statistics. In section 7.13, the temperature pattern recognition results for both Category A and Category B cases will be discussed and analyzed.

Table 31. Smart sensor connections in Category B test cases

| Case # | RA-TEMP | MA-TEMP | HWC-DAT | CHWC-DAT | SA-TEMP | HWC-EWT | HWC-LWT | HWC-MWT | CHWC-EWT | CHWC-LWT | CHWC-MWT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **1** | **1** | **1** | **1** | **1** | | **1** | | **1** | | **1** |
| 2 | **1** | **1** | **1** | **1** | **1** | | **1** | | **1** | | **1** |
| 3 | **1** | **1** | **1** | **1** | **1** | | **1** | | **1** | | **1** |
| 4 | **1** | **1** | **1** | **1** | **1** | | **1** | | **1** | | **1** |
| 5 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 6 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 7 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 8 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 9 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 10 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 11 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 12 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 13 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 14 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 15 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 16 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 17 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 18 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 19 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 20 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 21 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 22 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 23 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 24 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 25 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 26 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 27 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 28 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 29 | **1** | **1** | **1** | **1** | **1** | | | | **1** | **1** | **1** |
| 30 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 31 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 32 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 33 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 34 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 35 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 36 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 37 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 38 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 39 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| 40 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | | | |
| Total # | ***40*** | ***40*** | ***40*** | ***40*** | ***40*** | ***21*** | ***25*** | ***21*** | ***19*** | ***15*** | ***19*** |

Table 32. Temperature sensor channel assignment for Category B test cases

| Channel# | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Case 1~4 | RA-TEMP | SA-TEMP | MA-TEMP | CHWC-DAT | HWC-DAT | CHWC-MWT | CHWC-EWT | HWC-LWT |
| Case 5-12/ 23-29 | RA-TEMP | SA-TEMP | MA-TEMP | CHWC-DAT | HWC-DAT | CHWC-MWT | CHWC-EWT | CHWC-LWT |
| Case 13-22/ 30-39 | RA-TEMP | SA-TEMP | MA-TEMP | CHWC-DAT | HWC-DAT | HWC-EWT | HWC-LWT | HWC-MWT |
| Case 40 | HWC-LWT | HWC-MWT | HWC-DAT | HWC-EWT | CHWC-DAT | MA-TEMP | SA-TEMP | RA-TEMP |

## 7.2 Return Air Temperature

As discussed in Chapter 5.2, the return air temperature pattern will be influenced by the supply air temperature, the thermal capacitance of all the zones, the internal/external load of all the zones, and the air flow rate of the AHU supply and return air. Because of the thermal capacitance of all the zones, the return air temperature pattern often shown in straight line (1xx) or exponential patterns (2xx). The statistics of 129 temperature patterns for the return air is listed in Table 33. The percentage of occurrence for each pattern in each period is calculated, and the most observed pattern is shown in red.

The statistics shows that, as estimated, the most commonly observed pattern combinations for the six periods are line and exponential patterns (121-221-242-241-221-241). There is almost no transition period sudden temperature change for all periods due to thermal capacitance of the zones. An example of a return air temperature pattern is shown in Figure 64. For this figure and all similar figures, the red dots separate the test periods. The temperature main patterns for this test case are: 121-221-241-241-222-241.

Table 33. Statistics on RA-TEMP pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 8 | **6.2%** | 1 | 111 |
| | | 2 | **1.6%** | | 112 |
| | | 112 | **86.8%** | | 121 |
| | | 4 | **3.1%** | | 122 |
| | | 3 | **2.3%** | | 241 |
| | | 128 | **99.2%** | 2 | 221 |
| | | 1 | **0.8%** | | 222 |
| | | 1 | **0.8%** | 3 | 0 |
| | | 8 | **6.2%** | | 111 |
| | | 15 | **11.6%** | | 112 |
| | | 10 | **7.8%** | | 113 |
| | | 44 | **34.1%** | | 241 |
| | | 48 | **37.2%** | | 242 |
| | | 1 | **0.8%** | | 243 |
| | | 2 | **1.6%** | | 313 |
| 4 | **3.1%** | | | | 423 |
| | | 2 | **1.6%** | 4 | 121 |
| | | 118 | **91.5%** | | 241 |
| | | 9 | **7.0%** | | 242 |
| | | 1 | **0.8%** | 5 | 0 |
| | | 20 | **15.5%** | | 111 |
| | | 5 | **3.9%** | | 112 |
| | | 5 | **3.9%** | | 113 |
| | | 2 | **1.6%** | | 121 |
| | | 2 | **1.6%** | | 131 |
| | | 3 | **2.3%** | | 132 |
| | | 57 | **44.2%** | | 221 |
| | | 29 | **22.5%** | | 222 |
| | | 3 | **2.3%** | | 241 |
| | | 1 | **0.8%** | | 242 |
| 1 | **0.8%** | | | | 243 |
| | | 1 | **0.8%** | | 323 |
| | | 15 | **11.6%** | 6 | 111 |
| | | 5 | **3.9%** | | 112 |
| | | 2 | **1.6%** | | 113 |
| | | 1 | **0.8%** | | 121 |
| | | 2 | **1.6%** | | 222 |
| | | 90 | **69.8%** | | 241 |
| | | 14 | **10.9%** | | 242 |

To create the temperature template, all observed temperature patterns listed in the above table are included. In addition, some temperature patterns may be added for different periods because based on experience, some testing conditions did not occur in these testing cases but it is very likely to happen in the real world (other geological location, etc.) For example, higher initial RA-TEMP and lower zone temperature (or cooling load in the zone) may cause the first period pattern to show linear down patterns (13x), therefore 131~133 are added in the template table. The final template table for return air temperature is listed in Table 34.

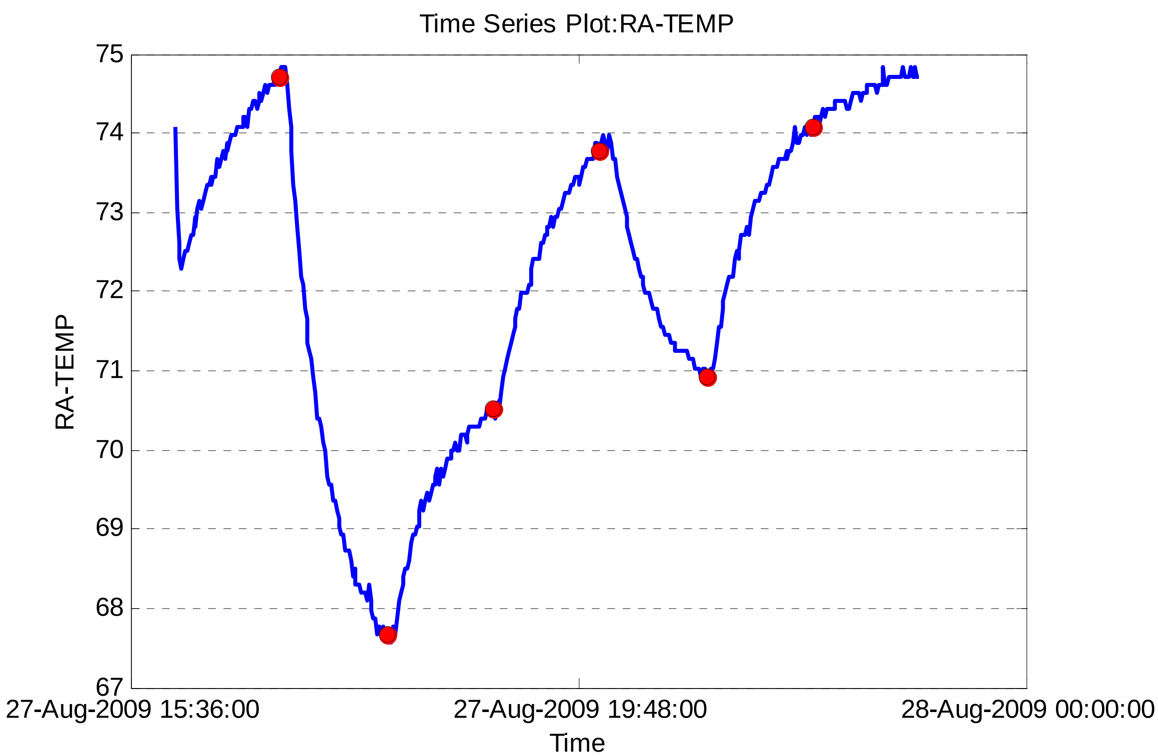



Figure 64. A typical temperature pattern for RA-TEMP

Table 34. Template table for RA-TEMP

| Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 131 | 999 | 111 | 999 | 111 | 999 | 111 | 999 | 111 |
| | 112 | | 132 | | 112 | | 112 | | 112 | | 112 |
| | 113 | | 133 | | 113 | | 113 | | 113 | | 113 |
| | 121 | | 221 | | 121 | | 121 | | 121 | | 121 |
| | 122 | | 222 | | 122 | | 122 | | 122 | | 122 |
| | 123 | | 223 | | 123 | | 123 | | 123 | | 123 |
| | 131 | | | | 241 | | 241 | | 131 | | 131 |
| | 132 | | | | 242 | | 242 | | 132 | | 132 |
| | 133 | | | | 243 | | 243 | | 133 | | 133 |
| | 221 | | | | | | | | 221 | | 221 |
| | 222 | | | | | | | | 222 | | 222 |
| | 223 | | | | | | | | 223 | | 223 |
| | 241 | | | | | | | | 241 | | 241 |
| | 242 | | | | | | | | 242 | | 242 |
| | 243 | | | | | | | | 243 | | 243 |

## 7.3 Mixing Air Temperature

Based on the control sequence, the mixed air temperature patterns will be similar to the return air, except that in period 5 the outside air is introduced and directly affect the mixed air temperature but not the return air temperature. The statistics of 129 temperature patterns for the mixed air is listed in Table 35. The percentage of occurrence for each pattern in each period is calculated, and the most observed pattern is shown in red.

From the statistics table it can be seen the most commonly observed pattern combinations for the six periods are: 121-221-241-241-323-121. The transition period patterns mostly happened in period 5 when the outside air damper starts to open fully from a closed position. All other patterns are similar to the return air temperature. An example of a mixed air temperature pattern is shown in Figure 65. The temperature main patterns for this test case are: 121-221-241-241-323-121.

Table 35. Statistics on MA-TEMP pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 11 | **8.5%** | 1 | 111 |
| | | 2 | **1.6%** | | 112 |
| | | 103 | **79.8%** | | 121 |
| | | 5 | **3.9%** | | 122 |
| | | 7 | **5.4%** | | 241 |
| | | 1 | **0.8%** | | 242 |
| | | 1 | **0.8%** | 2 | 131 |
| | | 2 | **1.6%** | | 132 |
| | | 1 | **0.8%** | | 133 |
| | | 124 | **96.1%** | | 221 |
| | | 1 | **0.8%** | | 222 |
| | | 1 | **0.8%** | 3 | 0 |
| | | 18 | **14.0%** | | 111 |
| | | 11 | **8.5%** | | 112 |
| | | 9 | **7.0%** | | 113 |
| | | 54 | **41.9%** | | 241 |
| | | 36 | **27.9%** | | 242 |
| 1 | **0.8%** | | | | 423 |
| | | 1 | **0.8%** | 4 | 112 |
| | | 1 | **0.8%** | | 113 |
| | | 3 | **2.3%** | | 122 |
| | | 113 | **87.6%** | | 241 |
| | | 11 | **8.5%** | | 242 |
| 1 | **0.8%** | 8 | **6.2%** | 5 | 0 |
| | | 3 | **2.3%** | | 113 |
| | | 1 | **0.8%** | | 122 |
| | | 1 | **0.8%** | | 123 |
| | | 1 | **0.8%** | | 132 |
| 9 | **7.0%** | | | | 133 |
| | | 17 | **13.2%** | | 221 |
| | | 27 | **20.9%** | | 222 |
| 1 | **0.8%** | 7 | **5.4%** | | 223 |
| 3 | **2.3%** | | | | 231 |
| 10 | **7.8%** | 1 | **0.8%** | | 232 |
| 37 | **28.7%** | 1 | **0.8%** | | 233 |
| | | 2 | **1.6%** | | 242 |
| | | 1 | **0.8%** | | 313 |
| | | 52 | **40.3%** | | 323 |
| 3 | **2.3%** | 7 | **5.4%** | | 423 |

Table 35. (continued)

| | | | | | |
|---|---|---|---|---|---|
| | | 23 | **17.8%** | 6 | 111 |
| | | 3 | **2.3%** | | 112 |
| | | 54 | **41.9%** | | 121 |
| | | 6 | **4.7%** | | 122 |
| | | 2 | **1.6%** | | 221 |
| | | 2 | **1.6%** | | 222 |
| | | 37 | **28.7%** | | 241 |
| | | 2 | **1.6%** | | 242 |

All observed temperature patterns listed in the above table are included and some temperature patterns may be added in the template table for MA-TEMP. For period 5, since the outside temperature cannot be controlled and will directly affect the pattern, all patterns are allowed. The final template table for the mixed air temperature is listed in Table 36.

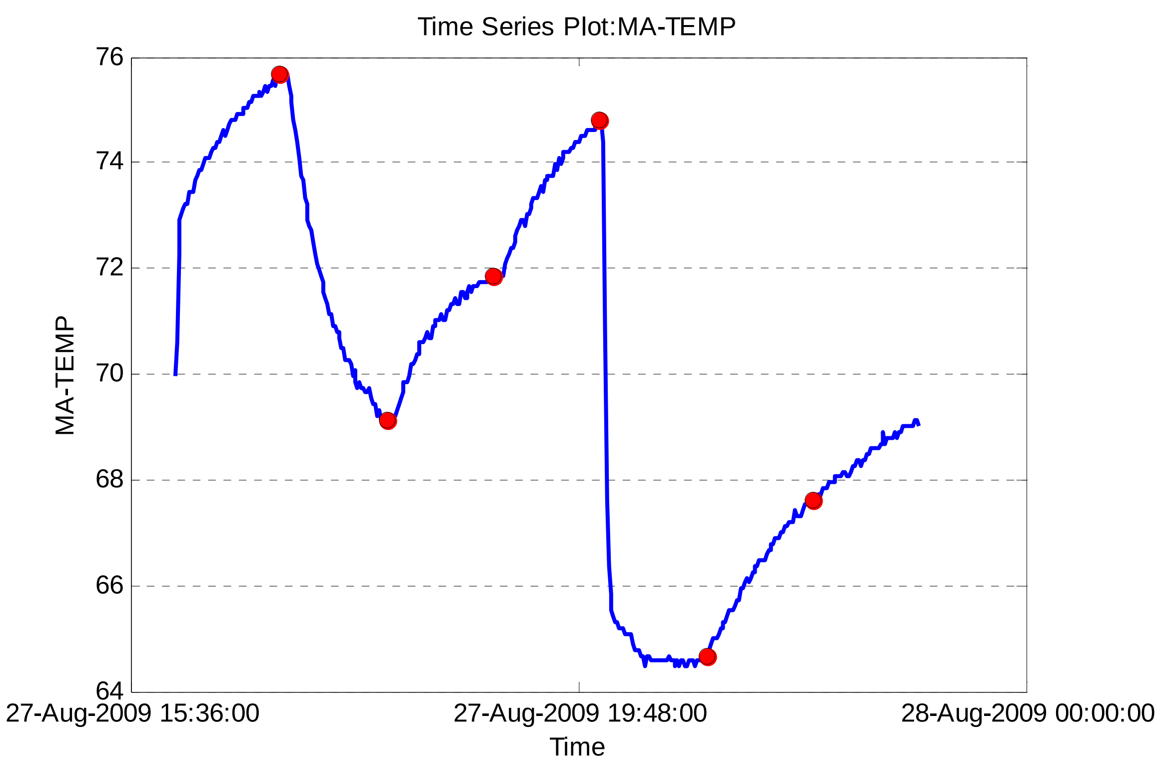



Figure 65. A typical temperature pattern for MA-TEMP

Table 36. Template table for MA-TEMP

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 131 | 999 | 111 | 999 | 111 | 999 | 999 | 999 | 111 |
| | 112 | | 132 | | 112 | | 112 | | | | 112 |
| | 113 | | 133 | | 113 | | 113 | | | | 113 |
| | 121 | | 221 | | 121 | | 121 | | | | 121 |
| | 122 | | 222 | | 122 | | 122 | | | | 122 |
| | 123 | | 223 | | 123 | | 123 | | | | 123 |
| | 131 | | | | 241 | | 241 | | | | 131 |
| | 132 | | | | 242 | | 242 | | | | 132 |
| | 133 | | | | 243 | | 243 | | | | 133 |
| | 221 | | | | | | | | | | 221 |
| | 222 | | | | | | | | | | 222 |
| | 223 | | | | | | | | | | 223 |
| | 241 | | | | | | | | | | 241 |
| | 242 | | | | | | | | | | 242 |
| | 243 | | | | | | | | | | 243 |

## 7.4 Heating Water Coil Discharge Air Temperature

The heating water coil discharge air temperature is greatly affected by the heat transfer from the AHU heating coil. Therefore the main characteristics for this temperature pattern is that, in period 3 when the heating water control valve opens and heating water pumps starts, the temperature will follow a step up pattern. The statistics of 129 temperature patterns for the heating water coil discharge air temperature is listed in Table 37. The percentage of occurrence for each pattern in each period is calculated, and the most observed pattern is shown in red.

Table 37. Statistics on HWC-DAT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 10 | **7.8%** | 1 | 111 |
| | | 2 | **1.6%** | | 112 |
| | | 100 | **77.5%** | | 121 |
| | | 6 | **4.7%** | | 122 |
| | | 10 | **7.8%** | | 241 |
| | | 1 | **0.8%** | | 242 |
| | | 1 | **0.8%** | 2 | 131 |
| | | 3 | **2.3%** | | 132 |
| | | 122 | **94.6%** | | 221 |
| | | 3 | **2.3%** | | 222 |
| | | 2 | **1.6%** | 3 | 0 |
| 1 | **0.8%** | | | | 211 |
| | | 28 | **21.7%** | | 312 |
| | | 99 | **76.7%** | | 313 |
| 1 | **0.8%** | | | | 413 |
| | | 14 | **10.9%** | 4 | 122 |
| | | 39 | **30.2%** | | 123 |
| 17 | **13.2%** | | | | 132 |
| 60 | **46.5%** | | | | 133 |
| 2 | **1.6%** | | | | 222 |
| 20 | **15.5%** | | | | 232 |
| 28 | **21.7%** | | | | 233 |
| | | 14 | **10.9%** | | 241 |
| | | 48 | **37.2%** | | 242 |
| | | 12 | **9.3%** | | 243 |
| | | 2 | **1.6%** | | 323 |
| | | 6 | **4.7%** | 5 | 0 |
| | | 2 | **1.6%** | | 113 |
| | | 2 | **1.6%** | | 122 |
| 1 | **0.8%** | 2 | **1.6%** | | 132 |
| 5 | **3.9%** | | | | 133 |
| | | 2 | **1.6%** | | 221 |
| | | 13 | **10.1%** | | 222 |
| | | 24 | **18.6%** | | 223 |
| 5 | **3.9%** | | | | 231 |
| 14 | **10.9%** | | | | 232 |
| 8 | **6.2%** | | | | 233 |
| | | 2 | **1.6%** | | 242 |
| | | 5 | **3.9%** | | 322 |
| | | 60 | **46.5%** | | 323 |
| 1 | **0.8%** | 11 | **8.5%** | | 423 |

Table 37. (continued)

| | | | | | |
|---|---|---|---|---|---|
| | | 18 | **14.0%** | | 111 |
| | | 5 | **3.9%** | | 112 |
| | | 3 | **2.3%** | | 122 |
| | | 1 | **0.8%** | | 131 |
| | | 1 | **0.8%** | 6 | 133 |
| | | 1 | **0.8%** | | 221 |
| | | 1 | **0.8%** | | 222 |
| | | 93 | **72.1%** | | 241 |
| | | 6 | **4.7%** | | 242 |

From the statistics table it can be seen the most commonly observed pattern combinations for the six periods are: 121-221-313-242-323-241. The transition period patterns are mostly happened in early period 4 and 5 when heating valve close and when the outside air damper starts to open. An example of a heating water discharge air pattern is shown in Figure 66. The temperature patterns are: 121-221-313-132/123-323-241.

For period 5, all patterns are allowed due to the same reason discussed in section 7.3. The final template table for the heating coil discharge air temperature is listed in Table 38.

Table 38. Template table for HWC-DAT

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 131 | 999 | 0 | 999 | 111 | 999 | 999 | 999 | 111 |
| | 112 | | 132 | | 311 | | 112 | | | | 112 |
| | 113 | | 133 | | 312 | | 113 | | | | 113 |
| | 121 | | 221 | | 313 | | 121 | | | | 121 |
| | 122 | | 222 | | | | 122 | | | | 122 |
| | 123 | | 223 | | | | 123 | | | | 123 |
| | 131 | | | | | | 241 | | | | 131 |
| | 132 | | | | | | 242 | | | | 132 |
| | 133 | | | | | | 243 | | | | 133 |
| | 221 | | | | | | 321 | | | | 221 |
| | 222 | | | | | | 322 | | | | 222 |
| | 223 | | | | | | 323 | | | | 223 |
| | 241 | | | | | | | | | | 241 |
| | 242 | | | | | | | | | | 242 |
| | 243 | | | | | | | | | | 243 |

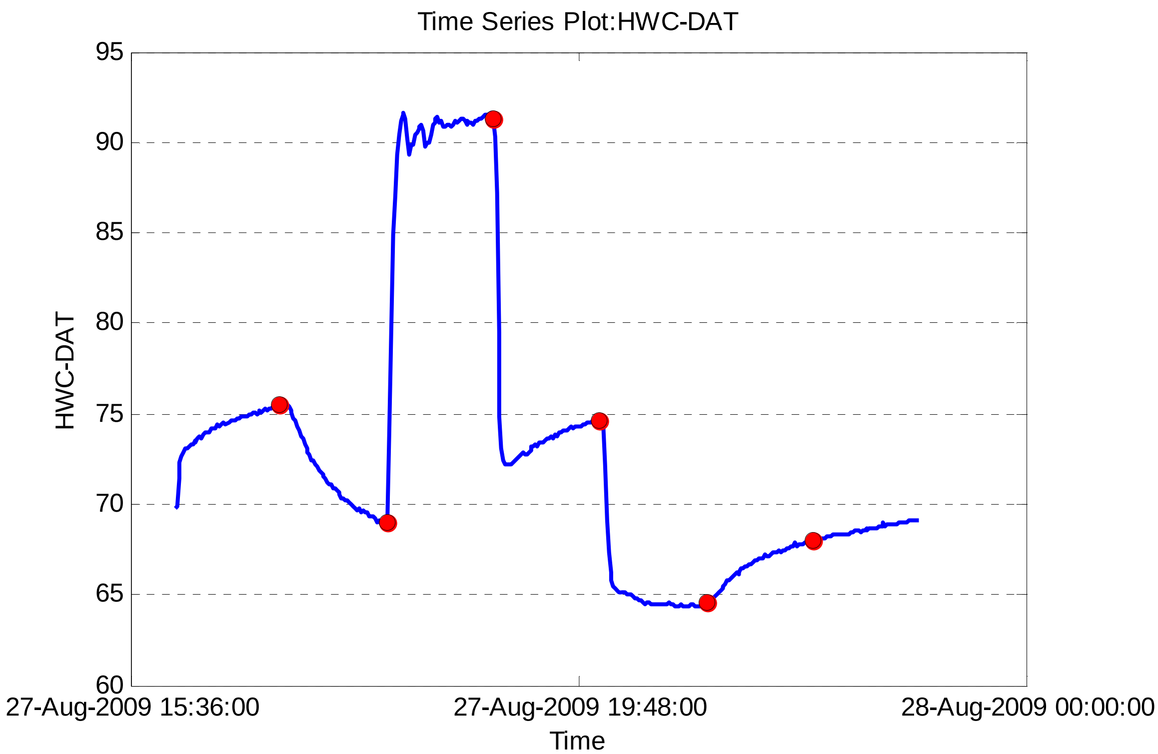



Figure 66. A typical temperature pattern for HWC-DAT

## 7.5 Chilled Water Coil Discharge Air Temperature

The chilled water coil discharge air temperature is greatly affected by the heat transfer from the AHU cooling coil during period 2 (when the chilled water passes the coil). For different chilled water pumping configurations (single pumping vs. primary-secondary pumping configurations) the temperature patterns may be different due to different chilled water entering water temperature pattern. In addition, because the cooling coil is after the heating coil in the air flow direction, its pattern will also change significantly during period 3 when the heating water valve is open. Therefore the main characteristics for this temperature pattern are a step down pattern in period 2 and a step up pattern in period 3. Depending on the cooling coil capacity and water flow rate, the step down pattern in period 2 can be detected as a exponential down type pattern (22x). The statistics of 129 temperature patterns for the chilled water coil discharge air temperature are listed in Table 39. The percentage of occurrence for each pattern in each period is calculated, and the most observed pattern is shown in red.

The most commonly observed pattern combinations for the six periods in this case are: 121-222-313-241-223-241. An example of a chilled water discharge air temperature pattern for primary-secondary chilled water system configuration is shown in Figure 67. The temperature patterns for this test case are: 121-133/222-243-123/241-323-241. An example of a single pumping chilled water system configuration is shown in Figure 68. The temperature patterns for this test case are: 121-323-213/243-123/241-232/423-243. In this case, the period 2 pattern shows small partial triangle pattern due to chilled water temperature cycling (refer to section 7.7) but is still detected as a rough step down pattern (323). In period 5 due to the effect of outside air temperature drifting, the pattern also seems kind of random. Therefore, in finalizing the template table for this temperature, an undetectable pattern (code: 000) is added in both periods 2 and 3 since the chilled water affect both periods. For period 5 all patterns are allowed due to the same reason discussed in section 7.3. The final template table for the chilled water coil discharge air temperature is listed in Table 40.

Table 39. Statistics on CHWC-DAT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 9 | **7.0%** | 1 | 111 |
| | | 1 | **0.8%** | | 112 |
| | | 98 | **76.0%** | | 121 |
| | | 6 | **4.7%** | | 122 |
| | | 14 | **10.9%** | | 241 |
| | | 1 | **0.8%** | | 242 |
| 41 | **31.8%** | 2 | **1.6%** | 2 | 0 |
| 30 | **23.3%** | | | | 133 |
| | | 24 | **18.6%** | | 221 |
| 1 | **0.8%** | 45 | **34.9%** | | 222 |
| 14 | **10.9%** | 10 | **7.8%** | | 223 |
| 12 | **9.3%** | | | | 233 |
| | | 20 | **15.5%** | | 323 |
| | | 23 | **17.8%** | | 423 |
| | | 3 | **2.3%** | | 511 |
| | | 2 | **1.6%** | | 521 |
| | | 12 | **9.3%** | 3 | 0 |
| 4 | **3.1%** | | | | 122 |
| 7 | **5.4%** | | | | 123 |
| 3 | **2.3%** | | | | 212 |
| 6 | **4.7%** | | | | 213 |
| | | 2 | **1.6%** | | 223 |
| 1 | **0.8%** | 1 | **0.8%** | | 241 |
| 1 | **0.8%** | 8 | **6.2%** | | 242 |
| 8 | **6.2%** | 35 | **27.1%** | | 243 |
| | | 2 | **1.6%** | | 312 |
| | | 67 | **51.9%** | | 313 |
| | | 1 | **0.8%** | | 423 |
| | | 1 | **0.8%** | | 521 |
| 22 | **17.1%** | | | 4 | 0 |
| 2 | **1.6%** | 16 | **12.4%** | | 122 |
| 41 | **31.8%** | 15 | **11.6%** | | 123 |
| 3 | **2.3%** | | | | 212 |
| 21 | **16.3%** | | | | 213 |
| | | 64 | **49.6%** | | 241 |
| 10 | **7.8%** | 13 | **10.1%** | | 242 |
| 9 | **7.0%** | 21 | **16.3%** | | 243 |

Table 39. (continued)

| | | | | | |
|---|---|---|---|---|---|
| 1 | **0.8%** | 4 | **3.1%** | 5 | 0 |
| | | 2 | **1.6%** | | 113 |
| | | 1 | **0.8%** | | 122 |
| | | 2 | **1.6%** | | 132 |
| 2 | **1.6%** | | | | 133 |
| | | 1 | **0.8%** | | 212 |
| | | 15 | **11.6%** | | 222 |
| | | 50 | **38.8%** | | 223 |
| 5 | **3.9%** | | | | 231 |
| 10 | **7.8%** | | | | 232 |
| 3 | **2.3%** | 1 | **0.8%** | | 233 |
| | | 2 | **1.6%** | | 242 |
| | | 14 | **10.9%** | | 322 |
| | | 29 | **22.5%** | | 323 |
| | | 8 | **6.2%** | | 423 |
| | | 3 | **2.3%** | 6 | 113 |
| | | 114 | **88.4%** | | 241 |
| | | 4 | **3.1%** | | 242 |
| | | 7 | **5.4%** | | 243 |
| | | 1 | **0.8%** | | 313 |
| 1 | **0.8%** | | | | 423 |

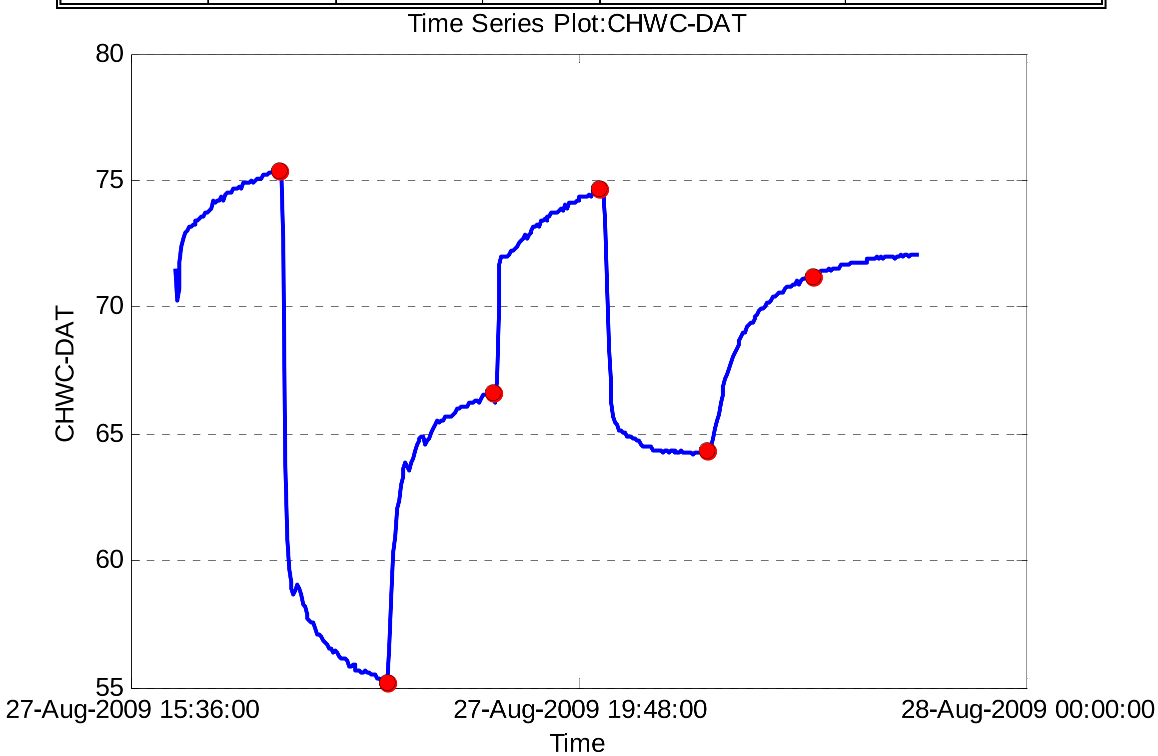



Figure 67. A typical temperature pattern for CHWC-DAT, single pumping

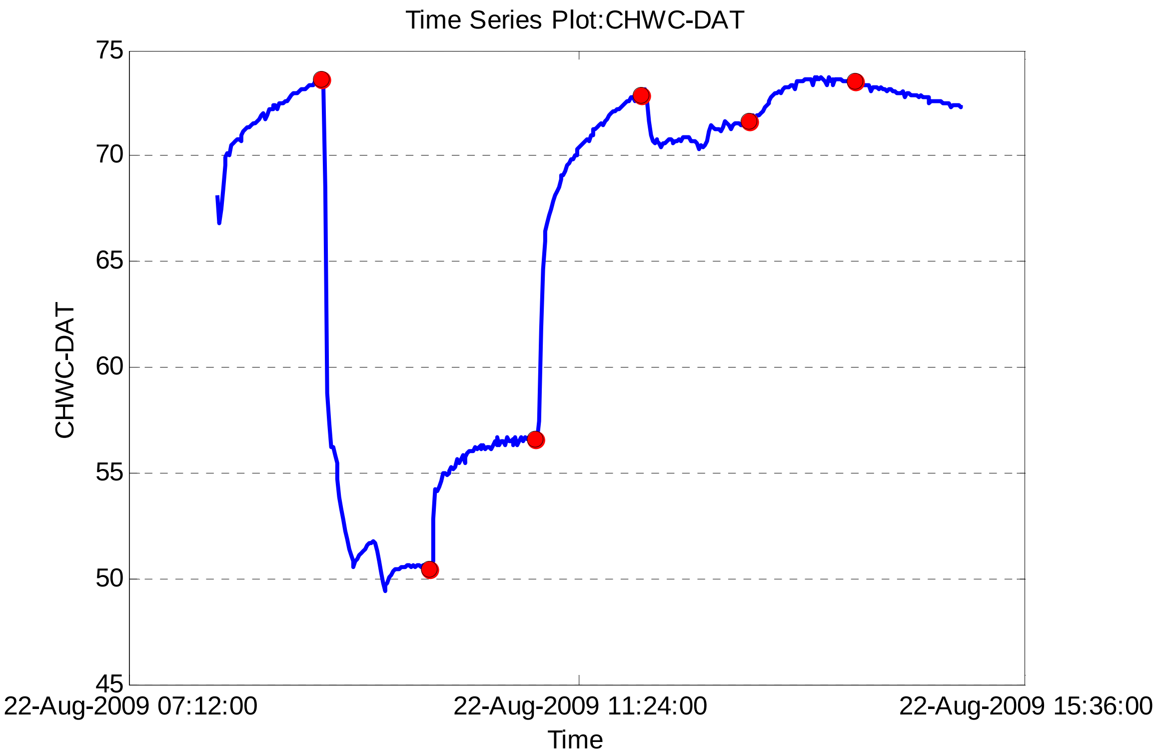



Figure 68 . A typical temperature pattern for CHWC-DAT, primary-secondary pumping

Table 40. Template table for CHWC-DAT

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 0 | 999 | 0 | 999 | 121 | 999 | 999 | 999 | 111 |
| | 112 | | 221 | | 121 | | 122 | | | | 112 |
| | 113 | | 222 | | 122 | | 123 | | | | 113 |
| | 121 | | 223 | | 123 | | 241 | | | | 221 |
| | 122 | | 321 | | 211 | | 242 | | | | 222 |
| | 123 | | 322 | | 212 | | 243 | | | | 223 |
| | 131 | | 323 | | 213 | | 311 | | | | 241 |
| | 132 | | 421 | | 221 | | 312 | | | | 242 |
| | 133 | | 422 | | 222 | | 313 | | | | 243 |
| | 221 | | 423 | | 223 | | | | | | 311 |
| | 222 | | 511 | | 241 | | | | | | 312 |
| | 223 | | 512 | | 242 | | | | | | 313 |
| | 241 | | 513 | | 243 | | | | | | |
| | 242 | | 521 | | 311 | | | | | | |
| | 243 | | 522 | | 312 | | | | | | |
| | | | 523 | | 313 | | | | | | |

## 7.6 Supply Air Temperature

The supply air temperature is downstream of the chilled water discharge air temperature. The main characteristics for this temperature pattern are mostly very similar to that of the discharge air temperature. The only distinguishable difference in patterns is that in the first 10 minutes of period 6, there will be a quick down pattern in temperature when the heat generated by the full speed supply fan is removed. The statistics of 129 temperature patterns for the supply air temperature is listed in Table 41. The percentage of occurrence for each pattern in each period is calculated, and the most observed pattern is shown in red.

The most commonly observed pattern combinations for the six periods in this case are: 121-221-243-241-222-123. An example of a supply air temperature pattern for primary-secondary chilled water system configuration is shown in Figure 69. The temperature patterns for this test case are: 121-133/221-242-212/241-222-123. An example of a single pumping chilled water system configuration is shown in Figure 70. The temperature patterns for this test case are: 241-323-243-243-232/423-112. In both cases there is a small temperature dip in early period 6 (marked by green circle). They are not detected directly in the pattern detection algorithm due to relatively small magnitude but it was reprocessed using the special rules (see section 5.6.2). In finalizing the template table, some temperature patterns are added for the same reason discussed in the previous section. The final template table for the supply air temperature is listed in Table 42.

Table 41. Statistics on SA-TEMP pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 3 | **2.3%** | 1 | 111 |
| | | 57 | **44.2%** | | 121 |
| | | 12 | **9.3%** | | 122 |
| | | 2 | **1.6%** | | 123 |
| | | 50 | **38.8%** | | 241 |
| | | 5 | **3.9%** | | 242 |
| 2 | **1.6%** | 2 | **1.6%** | 2 | 0 |
| 19 | **14.7%** | | | | 133 |
| | | 39 | **30.2%** | | 221 |
| | | 30 | **23.3%** | | 222 |
| 20 | **15.5%** | 30 | **23.3%** | | 223 |
| 35 | **27.1%** | | | | 233 |
| | | 1 | **0.8%** | | 322 |
| | | 23 | **17.8%** | | 323 |
| | | 3 | **2.3%** | | 423 |
| | | 1 | **0.8%** | | 511 |
| | | 5 | **3.9%** | 3 | 0 |
| 1 | **0.8%** | | | | 122 |
| | | 1 | **0.8%** | | 123 |
| 1 | **0.8%** | | | | 212 |
| 1 | **0.8%** | | | | 213 |
| | | 1 | **0.8%** | | 223 |
| | | 2 | **1.6%** | | 241 |
| | | 12 | **9.3%** | | 242 |
| 3 | **2.3%** | 68 | **52.7%** | | 243 |
| | | 16 | **12.4%** | | 312 |
| | | 24 | **18.6%** | | 313 |
| 2 | **1.6%** | | | | 423 |
| 29 | **22.5%** | | | 4 | 0 |
| 5 | | 16 | **12.4%** | | 122 |
| 25 | **19.4%** | 4 | **3.1%** | | 123 |
| 5 | **3.9%** | | | | 212 |
| 21 | **16.3%** | | | | 213 |
| | | 64 | **49.6%** | | 241 |
| 6 | **4.7%** | 16 | **12.4%** | | 242 |
| 6 | **4.7%** | 28 | **21.7%** | | 243 |
| | | 1 | **0.8%** | | 313 |

Table 42. (continued)

| | | | | | |
|---|---|---|---|---|---|
| 1 | | 5 | **3.9%** | | 0 |
| | | 3 | **2.3%** | | 113 |
| 1 | **0.8%** | 2 | **1.6%** | | 132 |
| 2 | **1.6%** | | | | 133 |
| | | 2 | **1.6%** | | 212 |
| | | 80 | **62.0%** | | 222 |
| | | 18 | **14.0%** | 5 | 223 |
| 4 | **3.1%** | | | | 231 |
| 5 | **3.9%** | | | | 232 |
| | | 2 | **1.6%** | | 242 |
| | | 6 | **4.7%** | | 322 |
| | | 6 | **4.7%** | | 323 |
| | | 4 | **3.1%** | | 423 |
| | | 1 | **0.8%** | | 511 |
| | | 14 | **10.9%** | | 112 |
| | | 21 | **16.3%** | | 113 |
| | | 1 | **0.8%** | | 121 |
| | | 13 | **10.1%** | | 122 |
| | | 46 | **35.7%** | 6 | 123 |
| | | 6 | **4.7%** | | 132 |
| | | 1 | **0.8%** | | 241 |
| | | 27 | **20.9%** | | 242 |

Table 43. Template table for SA-TEMP

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 0 | 999 | 0 | 999 | 121 | 999 | 999 | 999 | 111 |
| | 112 | | 221 | | 121 | | 122 | | | | 112 |
| | 113 | | 222 | | 122 | | 123 | | | | 113 |
| | 121 | | 223 | | 123 | | 241 | | | | 121 |
| | 122 | | 321 | | 211 | | 242 | | | | 122 |
| | 123 | | 322 | | 212 | | 243 | | | | 123 |
| | 131 | | 323 | | 213 | | 311 | | | | 131 |
| | 132 | | 421 | | 221 | | 312 | | | | 132 |
| | 133 | | 422 | | 222 | | 313 | | | | 133 |
| | 221 | | 423 | | 223 | | | | | | 221 |
| | 222 | | 511 | | 241 | | | | | | 222 |
| | 223 | | 512 | | 242 | | | | | | 223 |
| | 241 | | 513 | | 243 | | | | | | 241 |
| | 242 | | 521 | | 311 | | | | | | 242 |
| | 243 | | 522 | | 312 | | | | | | 243 |
| | | | 523 | | 313 | | | | | | |


Figure 69 . A typical temperature pattern for SA-TEMP, primary-secondary pumping

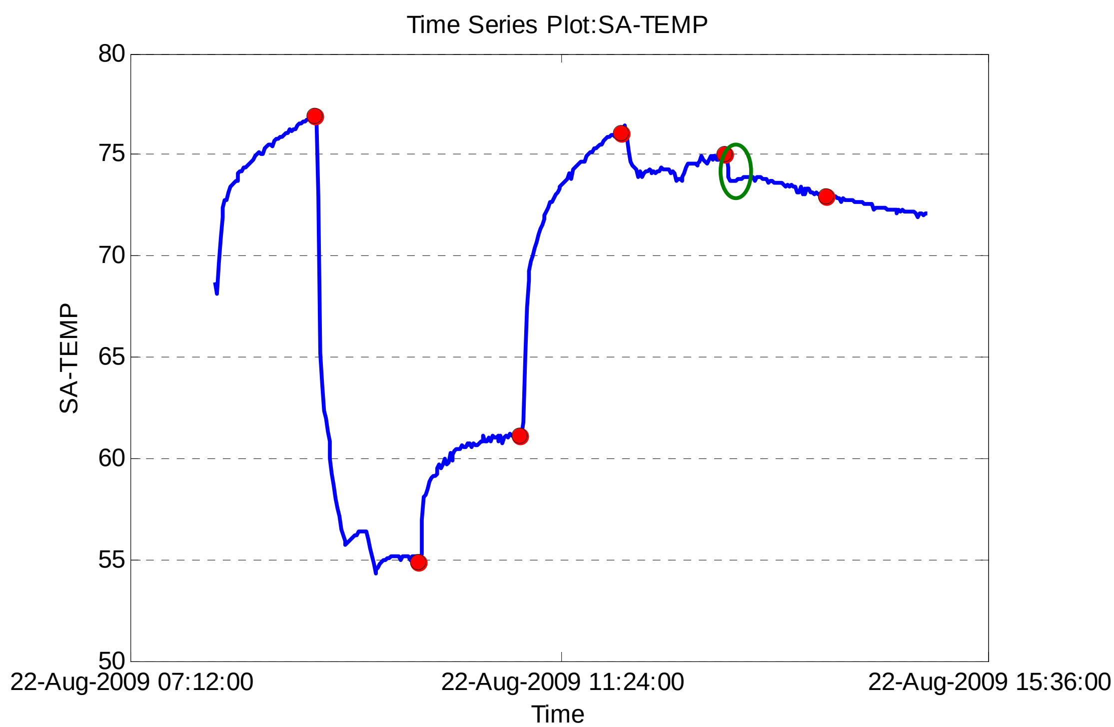



Figure 70. A typical temperature pattern for SA-TEMP, single pumping

## 7.7 Chilled Water Coil Entering Water Temperature

Water temperature patterns are different from air temperature patterns in that quicker change in temperatures may occur because water transfers heats much faster through conduction. Spikes are also common when control valves open and close, causing the residual water in the coil to mix with the chilled water. Therefore, peak and triangle patterns are common due to the two different chilled water pumping schemes.

For the primary-secondary pumping scheme, the chilled water entering temperature change will mostly depend on when the chiller starts and stops. Since the chiller start/stop times depend on its capacity, the overall load condition (there may be other cooling loads on the same chilled water system), and the chiller control settings (chiller water temperature setpoint, start/stop deadband, etc.), it is hard to determine the exact times for these operations. Sometimes the temperature patterns do not belong to any of the basic pattern categories.

For the single pumping scheme, since the chiller directly supplies the chilled water to the AHU chilled water coil, the temperature patterns in periods 1, 4, 5 and 6 more predictably resemble triangle shapes because there is no cooling load in the system, only the chilled water pump continuously runs to add heat to make the temperature rise, and the chiller will start when the temperature is higher than its trigger level.

The statistics of 129 temperature patterns for the chilled water entering temperature is listed in Table 43. The percentage of occurrence for each pattern in each period is calculated, and the most observed pattern is shown in red.

Table 44. Statistics on CHWC-EWT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| 9 | | 15 | **11.6%** | 1 | 0 |
| | | 37 | **28.7%** | | 111 |
| | | 1 | **0.8%** | | 112 |
| | | 2 | **1.6%** | | 113 |
| | | 1 | **0.8%** | | 121 |
| | | 2 | **1.6%** | | 123 |
| | | 3 | **2.3%** | | 243 |
| 6 | **4.7%** | 31 | **24.0%** | | 423 |
| | | 18 | **14.0%** | | 511 |
| | | 19 | **14.7%** | | 521 |
| 9 | **7.0%** | 59 | **45.7%** | 2 | 0 |
| | | 3 | **2.3%** | | 112 |
| | | 6 | **4.7%** | | 113 |
| 1 | **0.8%** | | | | 121 |
| | | 1 | **0.8%** | | 123 |
| | | 1 | **0.8%** | | 131 |
| | | 1 | **0.8%** | | 132 |
| | | 10 | **7.8%** | | 133 |
| 15 | **11.6%** | | | | 211 |
| 13 | **10.1%** | | | | 212 |
| 7 | **5.4%** | | | | 213 |
| | | 5 | **3.9%** | | 222 |
| | | 25 | **19.4%** | | 223 |
| 2 | **1.6%** | | | | 231 |
| 1 | **0.8%** | | | | 241 |
| | | 6 | **4.7%** | | 313 |
| | | 1 | **0.8%** | | 323 |
| 4 | **3.1%** | | | | 412 |
| 38 | **29.5%** | | | | 413 |
| 3 | **2.3%** | 8 | **6.2%** | | 423 |
| | | 2 | **1.6%** | | 511 |
| | | 1 | **0.8%** | | 521 |

Table 43. (continued)

| | | | | | |
|---|---|---|---|---|---|
| 5 | **3.9%** | 14 | **10.9%** | 3 | 0 |
| | | 3 | **2.3%** | | 111 |
| | | 3 | **2.3%** | | 112 |
| | | 17 | **13.2%** | | 113 |
| 2 | **1.6%** | | | | 122 |
| 1 | **0.8%** | 1 | **0.8%** | | 123 |
| 1 | **0.8%** | | | | 131 |
| 1 | **0.8%** | | | | 212 |
| 1 | **0.8%** | 1 | **0.8%** | | 213 |
| 1 | **0.8%** | | | | 221 |
| | | 2 | **1.6%** | | 222 |
| | | 5 | **3.9%** | | 223 |
| 4 | **3.1%** | | | | 233 |
| 2 | **1.6%** | 50 | **38.8%** | | 242 |
| | | 27 | **20.9%** | | 243 |
| | | 4 | **3.1%** | | 313 |
| | | 1 | **0.8%** | | 323 |
| 13 | **10.1%** | | | | 413 |
| 10 | **7.8%** | | | | 423 |
| | | 1 | **0.8%** | | 521 |
| | | 31 | **24.0%** | 4 | 0 |
| | | 1 | **0.8%** | | 112 |
| | | 14 | **10.9%** | | 113 |
| 4 | **3.1%** | 5 | **3.9%** | | 121 |
| | | 4 | **3.1%** | | 122 |
| 2 | **1.6%** | | | | 123 |
| 2 | **1.6%** | | | | 133 |
| 6 | **4.7%** | | | | 211 |
| 5 | **3.9%** | | | | 212 |
| 7 | **5.4%** | | | | 213 |
| | | 2 | **1.6%** | | 222 |
| | | 2 | **1.6%** | | 223 |
| 8 | **6.2%** | | | | 231 |
| 4 | **3.1%** | | | | 232 |
| 21 | **16.3%** | | | | 233 |
| 3 | **2.3%** | 7 | **5.4%** | | 241 |
| 1 | **0.8%** | | | | 242 |
| 7 | **5.4%** | 2 | **1.6%** | | 243 |
| 32 | **24.8%** | 60 | **46.5%** | | 423 |
| | | 1 | **0.8%** | | 511 |

Table 43. (continued)

| | | | | | |
|---|---|---|---|---|---|
| 8 | **6.2%** | 13 | **10.1%** | | 0 |
| | | 34 | **26.4%** | | 111 |
| | | 4 | **3.1%** | | 112 |
| | | 3 | **2.3%** | | 113 |
| | | 6 | **4.7%** | | 121 |
| 1 | **0.8%** | 3 | **2.3%** | | 122 |
| | | 1 | **0.8%** | | 123 |
| 1 | **0.8%** | | | | 131 |
| 1 | **0.8%** | | | | 132 |
| 2 | **1.6%** | | | | 133 |
| 2 | **1.6%** | | | | 211 |
| 3 | **2.3%** | | | 5 | 213 |
| 2 | **1.6%** | | | | 222 |
| 5 | **3.9%** | | | | 223 |
| 1 | **0.8%** | | | | 231 |
| 4 | **3.1%** | | | | 232 |
| 9 | **7.0%** | | | | 233 |
| 4 | **3.1%** | 3 | **2.3%** | | 241 |
| 1 | **0.8%** | | | | 242 |
| | | 4 | **3.1%** | | 243 |
| | | 1 | **0.8%** | | 313 |
| 4 | **3.1%** | 27 | **20.9%** | | 423 |
| | | 12 | **9.3%** | | 511 |
| | | 18 | **14.0%** | | 521 |

Table 43. (continued)

| | | | | | |
|---|---|---|---|---|---|
| 5 | **3.9%** | 12 | **9.3%** | 6 | 0 |
| | | 32 | **24.8%** | | 111 |
| | | 1 | **0.8%** | | 112 |
| | | 6 | **4.7%** | | 113 |
| 5 | **3.9%** | 6 | **4.7%** | | 121 |
| 2 | **1.6%** | | | | 122 |
| 1 | **0.8%** | 1 | **0.8%** | | 123 |
| 1 | **0.8%** | | | | 131 |
| 2 | **1.6%** | | | | 132 |
| 6 | **4.7%** | | | | 133 |
| 8 | **6.2%** | | | | 211 |
| 3 | **2.3%** | | | | 212 |
| 1 | **0.8%** | | | | 221 |
| 1 | **0.8%** | | | | 222 |
| 2 | **1.6%** | | | | 223 |
| 1 | **0.8%** | | | | 231 |
| 3 | **2.3%** | | | | 232 |
| 8 | **6.2%** | | | | 233 |
| 7 | **5.4%** | 3 | **2.3%** | | 241 |
| 2 | **1.6%** | | | | 242 |
| | | 4 | **3.1%** | | 243 |
| | | 2 | **1.6%** | | 313 |
| | | 2 | **1.6%** | | 323 |
| 4 | **3.1%** | 40 | **31.0%** | | 423 |
| | | 6 | **4.7%** | | 511 |
| | | 14 | **10.9%** | | 521 |

From the statistics, there is less percentage of common patterns in each period. In period 2 when the chilled valve opens, the unrecognizable pattern ("000") is observed 45.7% of the time. The common main patterns for the six periods in this case are: 111-000-242-423-111-423, which shows that the peak patterns and unrecognizable patterns happened quite often. An example pattern for primary-secondary chilled water system configuration is shown in Figure 71. The temperature patterns for this test case are: 423-231/000-242-423-423-133/423. An example of a single pumping chilled water system configuration pattern is shown in Figure 72. The temperature patterns for this test case are: 521-413/000-413/243-423/000-511-241/423. The final template table for the chilled water coil entering water temperature is listed in Table 44.

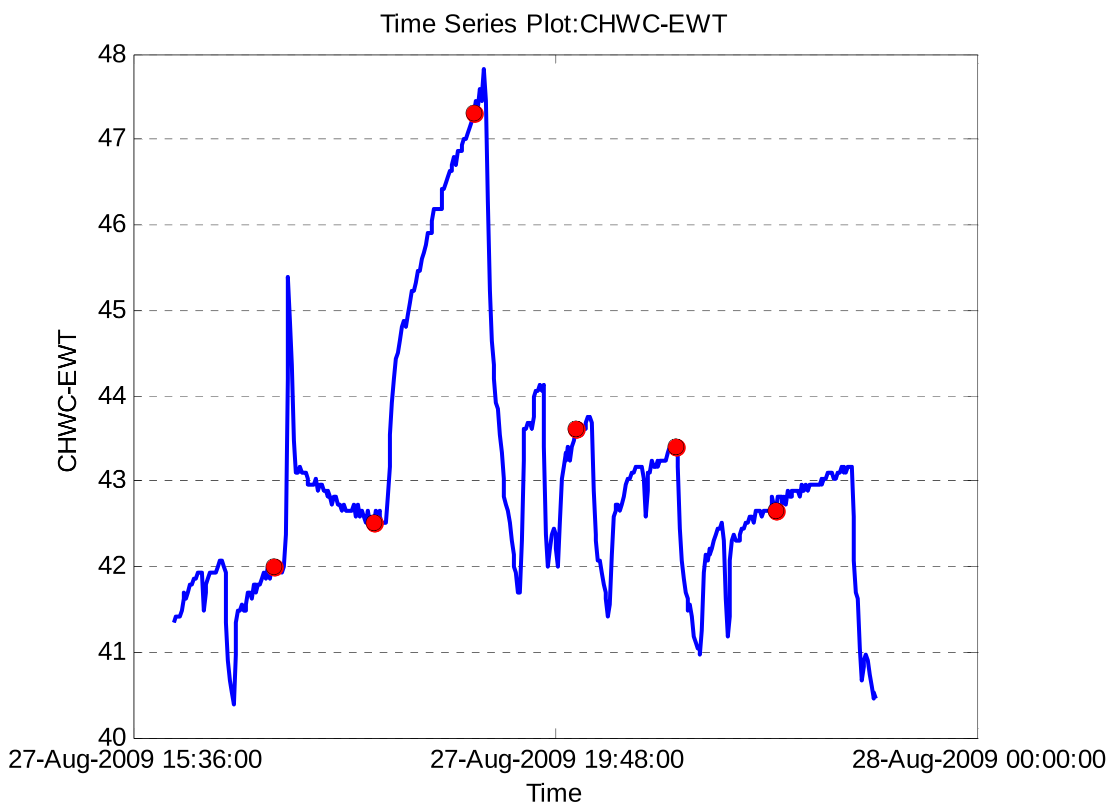



Figure 71. A typical temperature pattern for CHWC-EWT, primary-secondary pumping

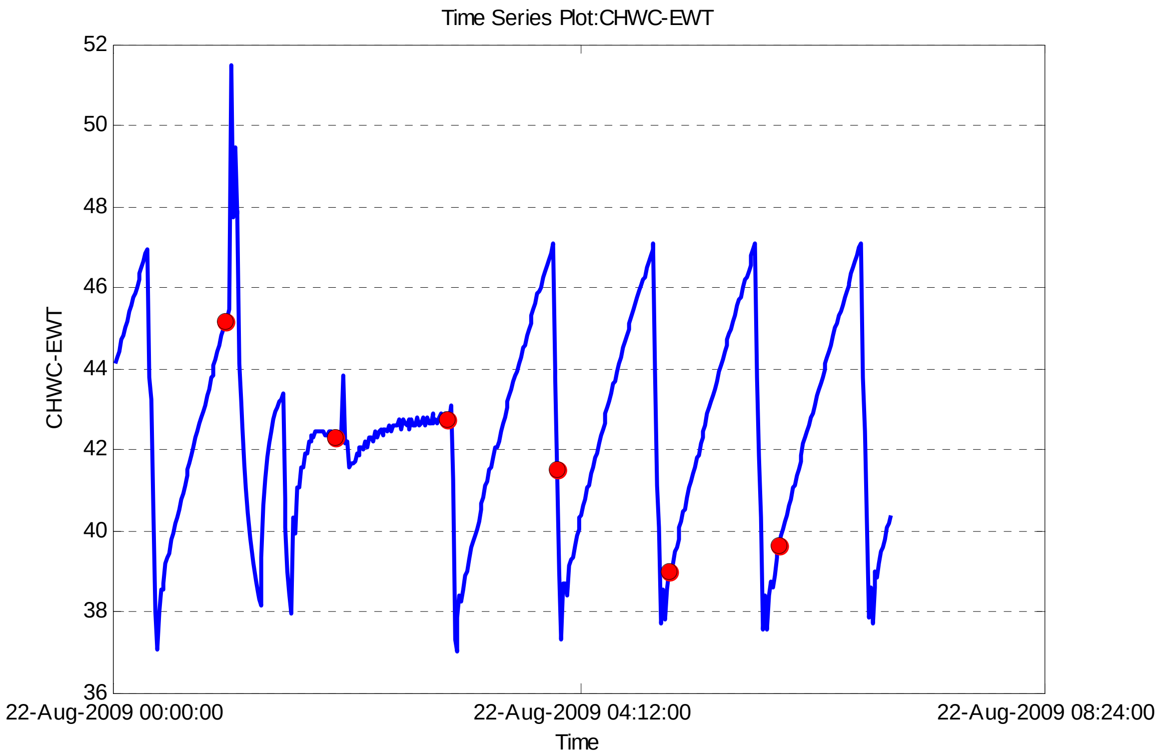



Figure 72. A typical temperature pattern for CHWC-EWT, single pumping

Table 45. Template table for CHWC-EWT

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 0 | 999 | 0 | 999 | 0 | 999 | 0 | 999 | 0 | 999 | 0 |
| | 111 | | 111 | | 111 | | 111 | | 111 | | 111 |
| | 112 | | 112 | | 112 | | 112 | | 112 | | 112 |
| | 113 | | 113 | | 113 | | 113 | | 113 | | 113 |
| | 121 | | 131 | | 121 | | 121 | | 121 | | 121 |
| | 122 | | 132 | | 122 | | 122 | | 122 | | 122 |
| | 123 | | 133 | | 123 | | 123 | | 123 | | 123 |
| | 131 | | 211 | | 211 | | 221 | | 231 | | 241 |
| | 132 | | 212 | | 212 | | 222 | | 232 | | 242 |
| | 133 | | 213 | | 221 | | 223 | | 233 | | 243 |
| | 222 | | 221 | | 222 | | 241 | | 241 | | 313 |
| | 241 | | 222 | | 223 | | 242 | | 242 | | 323 |
| | 242 | | 223 | | 241 | | 243 | | 243 | | 421 |
| | 243 | | 232 | | 242 | | 421 | | 313 | | 422 |
| | 421 | | 243 | | 243 | | 422 | | 323 | | 423 |
| | 422 | | 313 | | 311 | | 423 | | 421 | | 511 |
| | 423 | | 322 | | 312 | | 511 | | 422 | | 521 |
| | 511 | | 323 | | 313 | | 521 | | 423 | | |
| | 521 | | 412 | | 313 | | | | 511 | | |
| | | | 413 | | 413 | | | | 521 | | |
| | | | 423 | | 423 | | | | | | |
| | | | 511 | | | | | | | | |
| | | | 521 | | | | | | | | |

## 7.8 Chilled Water Coil Leaving Water Temperature

Chilled water coil leaving temperature is usually close to the air temperature in the AHU (but lower) when there is no chilled water passing through the coil (chilled water control valve is fully closed). When the control valve starts to open, it will quickly drop but will be higher than the entering water temperature due to heat transfer by the coil. The rate of drop and the pattern depends on multiple variables: coil capacity, water flow rate, air flow rate, and the stability of the entering chilled water. The statistics for the chilled water coil leaving temperature pattern is listed in Table 45.

Table 46. Statistics on CHWC-LWT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 93 | **72.1%** | 1 | 111 |
| | | 32 | **24.8%** | | 112 |
| | | 1 | **0.8%** | | 113 |
| | | 2 | **1.6%** | | 121 |
| | | 1 | **0.8%** | | 222 |
| 1 | **0.8%** | 13 | **10.1%** | 2 | 0 |
| | | 1 | **0.8%** | | 133 |
| 1 | **0.8%** | 20 | **15.5%** | | 221 |
| 3 | **2.3%** | 38 | **29.5%** | | 222 |
| 6 | **4.7%** | 17 | **13.2%** | | 223 |
| 52 | **40.3%** | | | | 411 |
| 24 | **18.6%** | | | | 412 |
| 11 | **8.5%** | | | | 413 |
| | | 39 | **30.2%** | | 423 |
| | | 1 | **0.8%** | | 511 |
| 23 | **17.8%** | 46 | **35.7%** | 3 | 0 |
| 2 | **1.6%** | | | | 121 |
| 3 | **2.3%** | | | | 122 |
| 17 | **13.2%** | 2 | **1.6%** | | 123 |
| 2 | **1.6%** | | | | 211 |
| 2 | **1.6%** | | | | 213 |
| | | 3 | **2.3%** | | 223 |
| 9 | **7.0%** | | | | 241 |
| 15 | **11.6%** | 12 | **9.3%** | | 242 |
| 23 | **17.8%** | 36 | **27.9%** | | 243 |
| | | 25 | **19.4%** | | 313 |
| 8 | **6.2%** | 5 | **3.9%** | | 413 |
| 1 | **0.8%** | | | | 423 |

Table 45. (continued)

| | | | | | |
|---|---|---|---|---|---|
| | | 1 | **0.8%** | 4 | 0 |
| | | 6 | **4.7%** | | 112 |
| | | 8 | **6.2%** | | 113 |
| | | 2 | **1.6%** | | 121 |
| | | 19 | **14.7%** | | 122 |
| | | 3 | **2.3%** | | 123 |
| | | 34 | **26.4%** | | 133 |
| | | 1 | **0.8%** | | 211 |
| | | 15 | **11.6%** | | 212 |
| | | 8 | **6.2%** | | 213 |
| | | 14 | **10.9%** | | 222 |
| | | 14 | **10.9%** | | 223 |
| 64 | **49.6%** | 1 | **0.8%** | | 241 |
| 7 | **5.4%** | 1 | **0.8%** | | 242 |
| 5 | **3.9%** | | | | 243 |
| | | 1 | **0.8%** | | 313 |
| | | 1 | **0.8%** | | 423 |
| | | 67 | **51.9%** | 5 | 111 |
| | | 51 | **39.5%** | | 112 |
| | | 5 | **3.9%** | | 113 |
| | | 5 | **3.9%** | | 122 |
| | | 1 | **0.8%** | | 123 |
| | | 95 | **73.6%** | 6 | 111 |
| | | 30 | **23.3%** | | 112 |
| | | 3 | **2.3%** | | 113 |
| | | 1 | **0.8%** | | 131 |

Statistics show that the common main patterns for the six periods in this case are: 111-423-000-133-111-111, which shows that in periods 1, 4, 5 and 6 are almost all linear patterns, while in the other two periods the patterns varies greatly. An example pattern for primary-secondary chilled water system configuration is shown in Figure 72. The temperature patterns for this test case are: 111-412/221-242/243-241/223-112-112. An example of a single pumping chilled water system configuration pattern is shown in Figure 73. The temperature patterns for this test case are: 112-223/423-123/000-241/212-112-112. It is noticed that the pattern in periods 2 and 3 for both cases are very different. The major reason is that in the primary-secondary pumping configuration (Figure 73), the entering water temperature is more stable but the flow rate is much lower than the designed rate of 27 GPM (only approximately 11 GPM going through the coil). So the cooling capability of the coil is not 100%. In the single pumping configuration, water flow is about 28 GPM, and the chiller start/stop in period 2 causes the small peak form. The reason there is a spike up in the first minute or two of period 2 in Figure 73 is that low water flow rate causes the warmer residual water in the cooling coil leaving pipe segment to be pushed slowly past the leaving water sensor. In the higher flow rate case (Figure 74) the leaving water temperature from high to low changes quickly within 1 minute and the data did not sample the high temperature point. The final template table for the chilled water coil leaving water temperature is listed in Table 46.

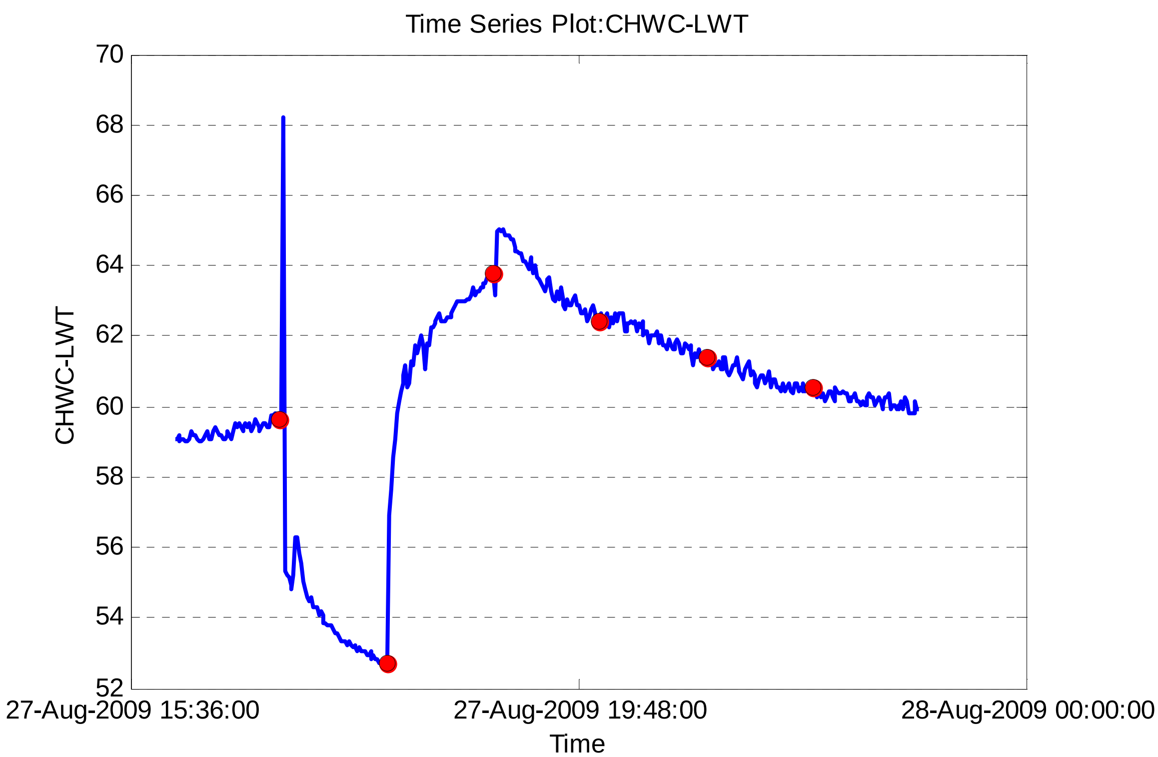



Figure 73. A typical temperature pattern for CHWC-LWT, primary-secondary pumping

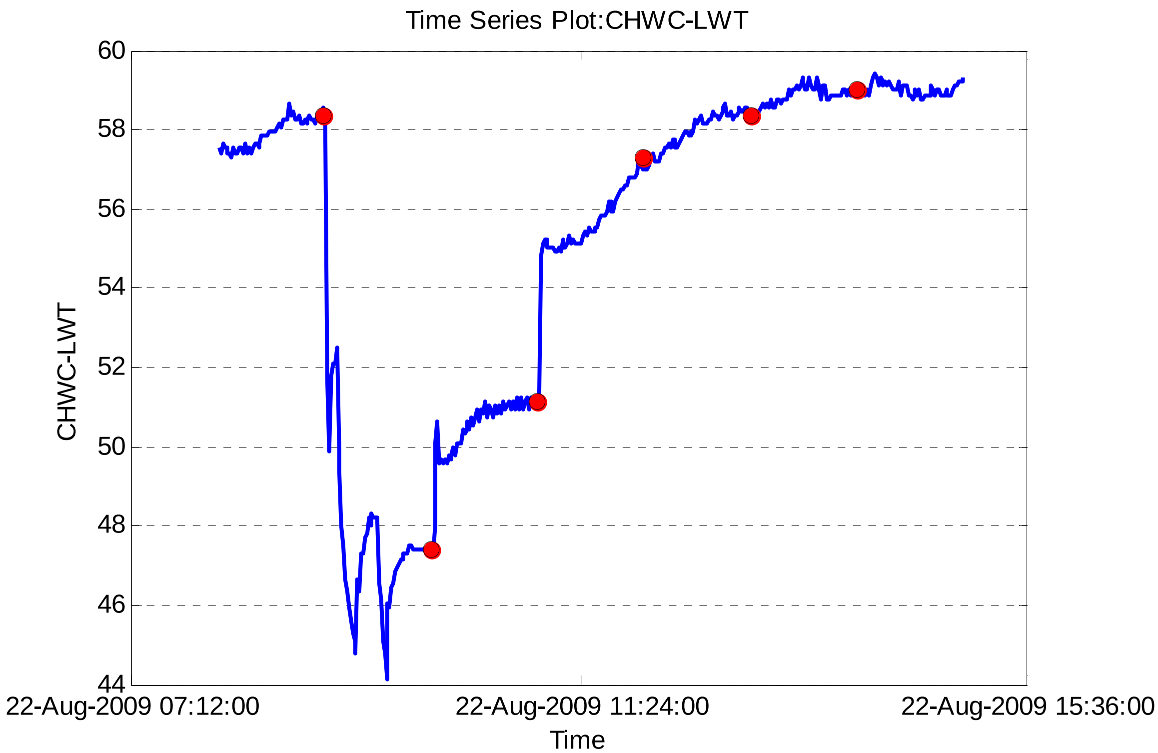



Figure 74. A typical temperature pattern for CHWC-LWT, single pumping

Table 47. Template table for CHWC-LWT

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 0 | 999 | 0 | 999 | 111 | 999 | 111 | 999 | 111 |
| | 112 | | 131 | | 121 | | 112 | | 112 | | 112 |
| | 113 | | 132 | | 122 | | 113 | | 113 | | 113 |
| | 121 | | 133 | | 123 | | 121 | | 121 | | 121 |
| | 122 | | 221 | | 211 | | 122 | | 122 | | 122 |
| | 123 | | 222 | | 212 | | 123 | | 123 | | 123 |
| | 211 | | 223 | | 213 | | 131 | | 241 | | 131 |
| | 212 | | 411 | | 221 | | 132 | | 242 | | 132 |
| | 213 | | 412 | | 222 | | 133 | | 243 | | 133 |
| | | | 413 | | 223 | | 211 | | | | |
| | | | 421 | | 241 | | 212 | | | | |
| | | | 422 | | 242 | | 213 | | | | |
| | | | 423 | | 243 | | 221 | | | | |
| | | | | | 311 | | 222 | | | | |
| | | | | | 312 | | 223 | | | | |
| | | | | | 313 | | 241 | | | | |
| | | | | | 411 | | 242 | | | | |
| | | | | | 412 | | 243 | | | | |
| | | | | | 413 | | 311 | | | | |
| | | | | | 421 | | 312 | | | | |
| | | | | | 422 | | 313 | | | | |
| | | | | | 423 | | | | | | |

## 7.9 Chilled Water Coil Mixing Water Temperature

The chilled water coil mixing temperature is the same as the entering temperature when the 3-way control valve is fully closed (and there is water flow). Once the valve starts to open, the temperature at the mixing location will initially mix the entering water with the residual water from the cooling coil, and then gradually convert to the same pattern as the leaving water temperature. The statistics of 129 cases for the chilled water mixing temperature is listed in Table 47.

Table 48. Statistics on CHWC-MWT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| 5 | **3.9%** | 12 | **9.3%** | 1 | 0 |
| | | 37 | **28.7%** | | 111 |
| | | 1 | **0.8%** | | 112 |
| | | 3 | **2.3%** | | 113 |
| | | 1 | **0.8%** | | 121 |
| | | 2 | **1.6%** | | 123 |
| | | 3 | **2.3%** | | 243 |
| 7 | **5.4%** | 35 | **27.1%** | | 423 |
| | | 20 | **15.5%** | | 511 |
| | | 15 | **11.6%** | | 521 |
| 1 | **0.8%** | 51 | **39.5%** | 2 | 0 |
| | | 35 | **27.1%** | | 221 |
| | | 30 | **23.3%** | | 222 |
| | | 11 | **8.5%** | | 223 |
| 3 | **2.3%** | | | | 241 |
| 5 | **3.9%** | | | | 243 |
| 29 | **22.5%** | | | | 411 |
| 41 | **31.8%** | | | | 412 |
| 49 | **38.0%** | | | | 413 |
| | | 2 | **1.6%** | | 423 |
| 31 | **24.0%** | 37 | **28.7%** | 3 | 0 |
| | | 1 | | | 113 |
| 7 | **5.4%** | 2 | **1.6%** | | 123 |
| 2 | **1.6%** | | | | 211 |
| 1 | **0.8%** | | | | 212 |
| 3 | **2.3%** | | | | 213 |
| | | 3 | **2.3%** | | 223 |
| 6 | **4.7%** | 1 | **0.8%** | | 241 |
| 15 | **11.6%** | 15 | **11.6%** | | 242 |
| 27 | **20.9%** | 40 | **31.0%** | | 243 |
| | | 29 | **22.5%** | | 313 |
| 6 | **4.7%** | 2 | **1.6%** | | 413 |
| 1 | **0.8%** | | | | 423 |

Table 47. (continued)

| | | | | | |
|---|---|---|---|---|---|
| | | 17 | **13.2%** | | 0 |
| | | 15 | **11.6%** | | 121 |
| 46 | **35.7%** | | | | 221 |
| 22 | **17.1%** | 3 | **2.3%** | | 222 |
| 5 | **3.9%** | | | | 223 |
| | | 1 | **0.8%** | 4 | 241 |
| | | 2 | **1.6%** | | 243 |
| | | 14 | **10.9%** | | 322 |
| | | 4 | **3.1%** | | 323 |
| 17 | **13.2%** | 52 | **40.3%** | | 423 |
| | | 14 | **10.9%** | | 511 |
| | | 7 | **5.4%** | | 521 |
| 13 | **10.1%** | 15 | **11.6%** | | 0 |
| | | 34 | **26.4%** | | 111 |
| | | 4 | **3.1%** | | 112 |
| | | 3 | **2.3%** | | 113 |
| 2 | **1.6%** | 7 | **5.4%** | | 121 |
| | | 5 | **3.9%** | | 122 |
| 1 | **0.8%** | | | | 123 |
| 1 | **0.8%** | | | | 131 |
| 2 | **1.6%** | | | | 133 |
| 2 | **1.6%** | | | | 212 |
| 4 | **3.1%** | | | | 213 |
| 1 | **0.8%** | | | | 221 |
| 1 | **0.8%** | | | 5 | 222 |
| 2 | **1.6%** | | | | 223 |
| 1 | **0.8%** | | | | 231 |
| 3 | **2.3%** | | | | 232 |
| 9 | **7.0%** | | | | 233 |
| 4 | **3.1%** | 1 | **0.8%** | | 241 |
| 3 | **2.3%** | | | | 242 |
| 1 | **0.8%** | 3 | **2.3%** | | 243 |
| | | 2 | **1.6%** | | 313 |
| | | | | | 323 |
| 3 | **2.3%** | 27 | **20.9%** | | 423 |
| | | 9 | **7.0%** | | 511 |
| | | 19 | **14.7%** | | 521 |

Table 47. (continued)

| | | | | | |
|---|---|---|---|---|---|
| 5 | **3.9%** | 14 | **10.9%** | 6 | 0 |
| 2 | **1.6%** | 32 | **24.8%** | | 111 |
| | | 1 | **0.8%** | | 112 |
| | | 8 | **6.2%** | | 113 |
| 6 | **4.7%** | 7 | **5.4%** | | 121 |
| 3 | **2.3%** | | | | 122 |
| 2 | **1.6%** | 1 | **0.8%** | | 123 |
| 1 | **0.8%** | | | | 131 |
| 5 | **3.9%** | | | | 132 |
| 1 | **0.8%** | | | | 133 |
| 2 | **1.6%** | | | | 211 |
| 1 | **0.8%** | | | | 212 |
| 2 | **1.6%** | | | | 213 |
| 2 | **1.6%** | | | | 221 |
| 1 | **0.8%** | | | | 222 |
| 2 | **1.6%** | | | | 231 |
| 4 | **3.1%** | | | | 232 |
| 7 | **5.4%** | | | | 233 |
| 5 | **3.9%** | 2 | **1.6%** | | 241 |
| 1 | **0.8%** | | | | 242 |
| 1 | **0.8%** | 4 | **3.1%** | | 243 |
| | | 2 | **1.6%** | | 323 |
| 5 | **3.9%** | 34 | **26.4%** | | 423 |
| | | 9 | **7.0%** | | 511 |
| | | 15 | **11.6%** | | 521 |

From above table, the common main patterns for the six periods are: 111-000-243-423-111-423. Besides periods 2 and 3, other period patterns are mostly linear or peak patterns, which are similar to that of the entering water temperature. An example pattern for primary-secondary chilled water system configuration is shown in Figure 75. The temperature patterns for this test case are: 423-411/221-242/242-221/423-241/423-232/423. An example of a single pumping chilled water system configuration pattern is shown in Figure 76. The temperature patterns for this test case are: 511-413/000-123/000-511-521-511. It is understandable that many patterns have a triangular shape because of the single pumping configuration. In both cases there is a spike up at the beginning of period 2 because of the switching from chilled entering water mixed with higher residual (and then leaving) water temperature from cooling coil leaving side. The final template table for the chilled water coil mixing water temperature is listed in Table 48. For simplicity, the periods 5 and 6 do not filter out any patterns.

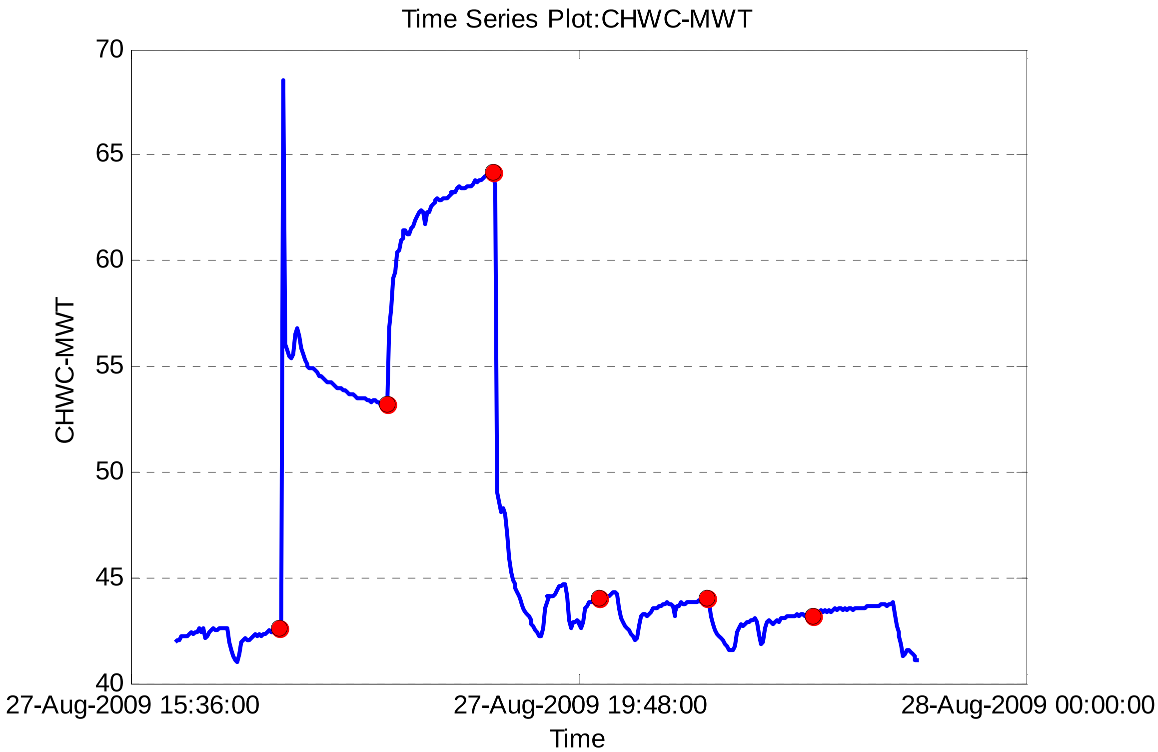



Figure 75 . A typical temperature pattern for CHWC-MWT, primary-secondary pumping

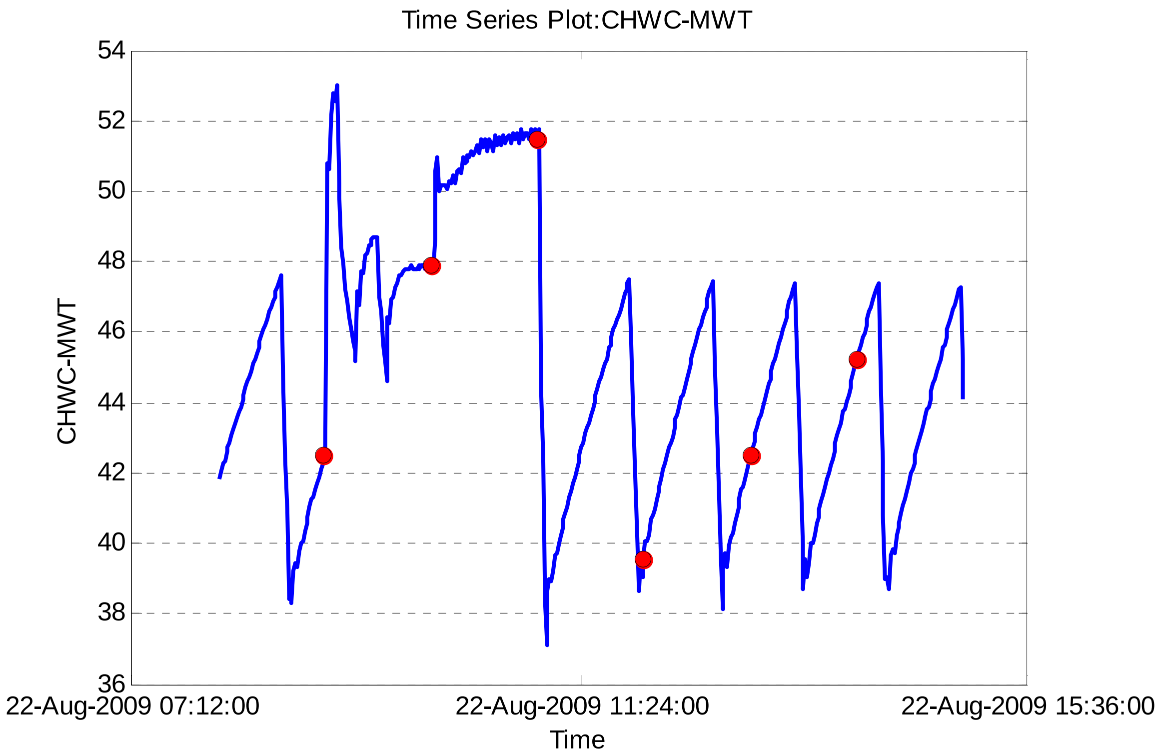



Figure 76. A typical temperature pattern for CHWC-MWT, single pumping

Table 49. Template table for CHWC-MWT

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 0 | 999 | 0 | 999 | 0 | 999 | 0 | 999 | 999 | 999 | 999 |
| | 111 | | 111 | | 121 | | 121 | | | | |
| | 112 | | 131 | | 122 | | 122 | | | | |
| | 113 | | 132 | | 123 | | 123 | | | | |
| | 121 | | 133 | | 221 | | 221 | | | | |
| | 122 | | 221 | | 222 | | 222 | | | | |
| | 123 | | 222 | | 223 | | 223 | | | | |
| | 131 | | 223 | | 241 | | 241 | | | | |
| | 132 | | 313 | | 242 | | 242 | | | | |
| | 133 | | 411 | | 243 | | 243 | | | | |
| | 222 | | 412 | | 311 | | 321 | | | | |
| | 241 | | 413 | | 312 | | 322 | | | | |
| | 242 | | 421 | | 313 | | 323 | | | | |
| | 243 | | 422 | | 412 | | 421 | | | | |
| | 421 | | 423 | | 413 | | 422 | | | | |
| | 422 | | | | 423 | | 423 | | | | |
| | 423 | | | | | | 511 | | | | |
| | 511 | | | | | | 521 | | | | |
| | 521 | | | | | | | | | | |

## 7.10 Heating Water Coil Entering Water Temperature

Heating water temperatures are easy to separate from other temperatures because of their high temperatures. However, to distinguish among them is not easy. Since the heating water pump is initially stopped and only runs during periods 2, 3 and 4, temperature patterns for other periods are almost always a linear pattern (drifted down). Detailed transition period characteristics of these temperature patterns in periods 2, 3 and 4 needs to be studied to effectively distinguish among these temperatures. For the heating water entering temperature, the characteristics mostly depend on the boiler control setting (setpoint, control deadband, etc.) and its capacity relative to the heating load needed. In most cases, if the boiler entering water temperature is lower than a certain level, the boiler will automatically start to raise the supply water temperature. This is the reason during period 3 when the heating water going through AHU heating coil, there is a quick rise in temperature and then oscillation around the setpoint (in all test cases, the boiler setpoint is 120 Deg F). The frequency of the oscillation may vary as load condition changes on the heating water system (the AHU under test may not be the only heating load in the system). The statistics table for heating water coil entering temperature is shown in Table 49.

Table 50. Statistics on HWC-EWT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| 1 | **1.4%** | 1 | **1.4%** | 1 | 0 |
| | | 5 | **7.1%** | | 111 |
| | | 61 | **87.1%** | | 131 |
| | | 1 | **1.4%** | | 132 |
| | | 1 | **1.4%** | | 133 |
| | | 1 | **1.4%** | | 232 |
| | | 5 | **7.1%** | 2 | 111 |
| | | 65 | **92.9%** | | 131 |
| 3 | **4.3%** | 42 | **60.0%** | 3 | 0 |
| | | 2 | **2.9%** | | 313 |
| 4 | **5.7%** | 18 | **25.7%** | | 412 |
| 35 | **50.0%** | 8 | **11.4%** | | 413 |
| 1 | **1.4%** | | | | 422 |
| 2 | **2.9%** | 13 | **18.6%** | 4 | 0 |
| | | 39 | **55.7%** | | 131 |
| | | 6 | **8.6%** | | 132 |
| | | 10 | **14.3%** | | 133 |
| 8 | **11.4%** | | | | 211 |
| 1 | **1.4%** | | | | 213 |
| | | 1 | **1.4%** | | 221 |
| 1 | **1.4%** | | | | 241 |
| 2 | **2.9%** | | | | 412 |
| 10 | **14.3%** | | | | 413 |
| 7 | **10.0%** | | | | 422 |
| 20 | **28.6%** | 1 | **1.4%** | | 423 |
| | | 66 | **94.3%** | 5 | 131 |
| | | 4 | **5.7%** | | 132 |
| | | 67 | **95.7%** | 6 | 131 |
| | | 3 | **4.3%** | | 132 |

For the 70 test cases, the common main patterns for the entering heating water are: 131-131-0-131-131-131. An example pattern for primary-secondary chilled water system configuration is shown in Figure 77. The temperature patterns for this test case are: 131-131-413/000-241/131-131-131. An example of a single pumping chilled water system configuration pattern is shown in Figure 78. The temperature patterns for this test case are: 131-131-413-423/131-131-131. Both patterns are very similar. A common characteristic for the entering water temperature is that during period 4, when the control valve is closed but the heating water pump is still running, the temperature will start to drop from close to the boiler setpoint level. The final template table for the heating water entering temperature is listed in Table 50.


Figure 77. A typical temperature pattern for HWC-EWT, primary-secondary pumping

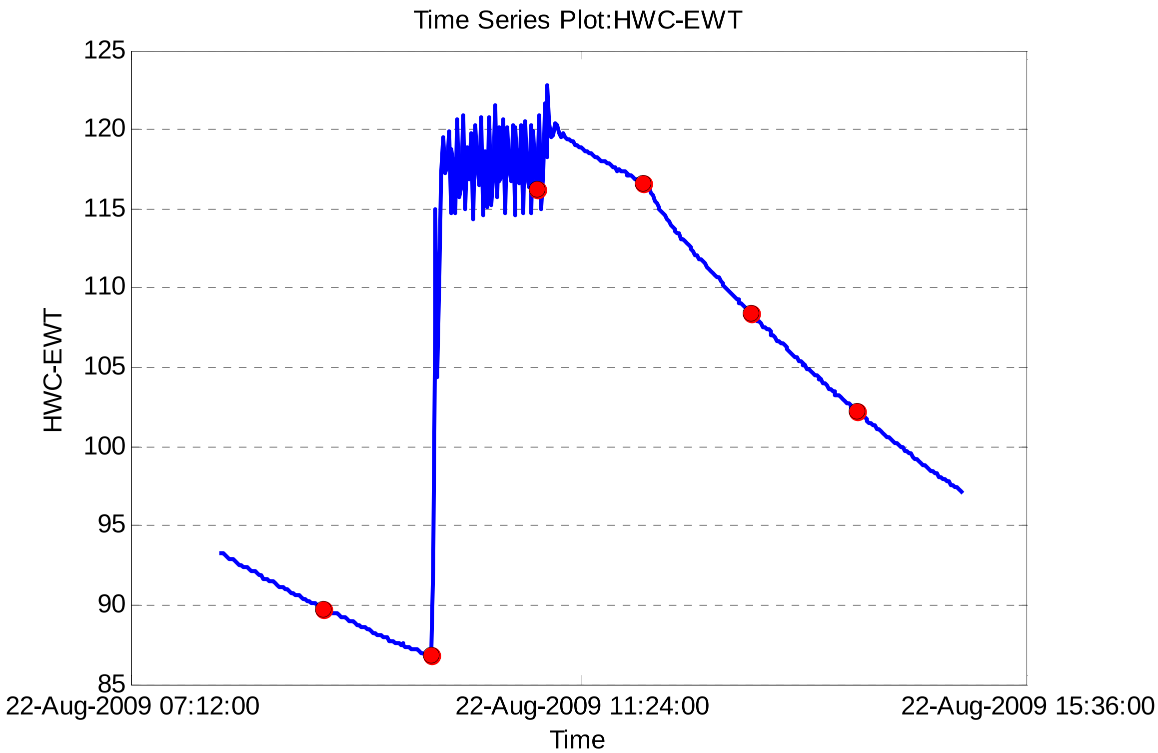



Figure 78. A typical temperature pattern for HWC-EWT, single pumping

Table 51. Template table for HWC-EWT

| **Period 1** | | **Period 2** | | **Period 3** | | **Period 4** | | **Period 5** | | **Period 6** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 111 | 999 | 0 | 999 | 0 | 999 | 131 | 999 | 131 |
| | 112 | | 112 | | 312 | | 131 | | 132 | | 132 |
| | 113 | | 113 | | 313 | | 132 | | 231 | | 521 |
| | 131 | | 131 | | 411 | | 133 | | 232 | | |
| | 132 | | 132 | | 412 | | 221 | | 233 | | |
| | 133 | | 133 | | 413 | | 222 | | 423 | | |
| | 423 | | 412 | | | | 411 | | | | |
| | | | | | | | 412 | | | | |
| | | | | | | | 413 | | | | |
| | | | | | | | 421 | | | | |
| | | | | | | | 422 | | | | |
| | | | | | | | 423 | | | | |

## 7.11 Heating Water Coil Leaving Water Temperature

The leaving water temperature has similar overall patterns compared to the entering and mixing water temperature. The only difference is the transition pattern in period 4. When the control valve start to close, the water flow going through the heating coil reduces gradually to 0, thus the leaving water temperature is affected by the entering water temperature (via conduction) and heat transfer from the airflow through heating coil. The pattern is normally a smooth V shape pattern. The statistics table for heating water coil entering temperature is shown in Table 51.

For the 70 test cases, the common main patterns for the entering heating water are: 131-131-0-243(or 323)-131-131. An example pattern for primary-secondary chilled water system configuration is shown in Figure 79. The temperature patterns for this test case are: 131-131-413/000-223/242-131-131. An example of a single pumping chilled water system configuration pattern is shown in Figure 80. The temperature patterns for this test case are: 131-131-423/000-223/242-131-131. The final template table for the heating water leaving temperature is listed in Table 52.

Table 52. Statistics on HWC-LWT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 5 | **7.1%** | 1 | 111 |
| | | 65 | **92.9%** | | 131 |
| | | 11 | **15.7%** | 2 | 111 |
| | | 59 | **84.3%** | | 131 |
| | | 55 | **78.6%** | 3 | 0 |
| 1 | **1.4%** | | | | 241 |
| 1 | **1.4%** | | | | 242 |
| 1 | **1.4%** | | | | 243 |
| | | 7 | **10.0%** | | 313 |
| 6 | **8.6%** | 2 | **2.9%** | | 412 |
| 31 | **44.3%** | 6 | **8.6%** | | 413 |
| 6 | **8.6%** | | | | 422 |
| 13 | **18.6%** | | | | 423 |
| | | 3 | **4.3%** | 4 | 0 |
| | | 5 | **7.1%** | | 113 |
| | | 1 | **1.4%** | | 133 |
| 33 | **47.1%** | | | | 221 |
| 3 | **4.3%** | 1 | **1.4%** | | 222 |
| 6 | **8.6%** | | | | 223 |
| | | 11 | **15.7%** | | 241 |
| | | 14 | **20.0%** | | 242 |
| | | 16 | **22.9%** | | 243 |
| | | 2 | **2.9%** | | 321 |
| | | 16 | **22.9%** | | 323 |
| 7 | **10.0%** | 1 | **1.4%** | | 423 |
| | | 53 | **75.7%** | 5 | 131 |
| | | 13 | **18.6%** | | 132 |
| | | 4 | **5.7%** | | 231 |
| | | 70 | **100.0%** | 6 | 131 |

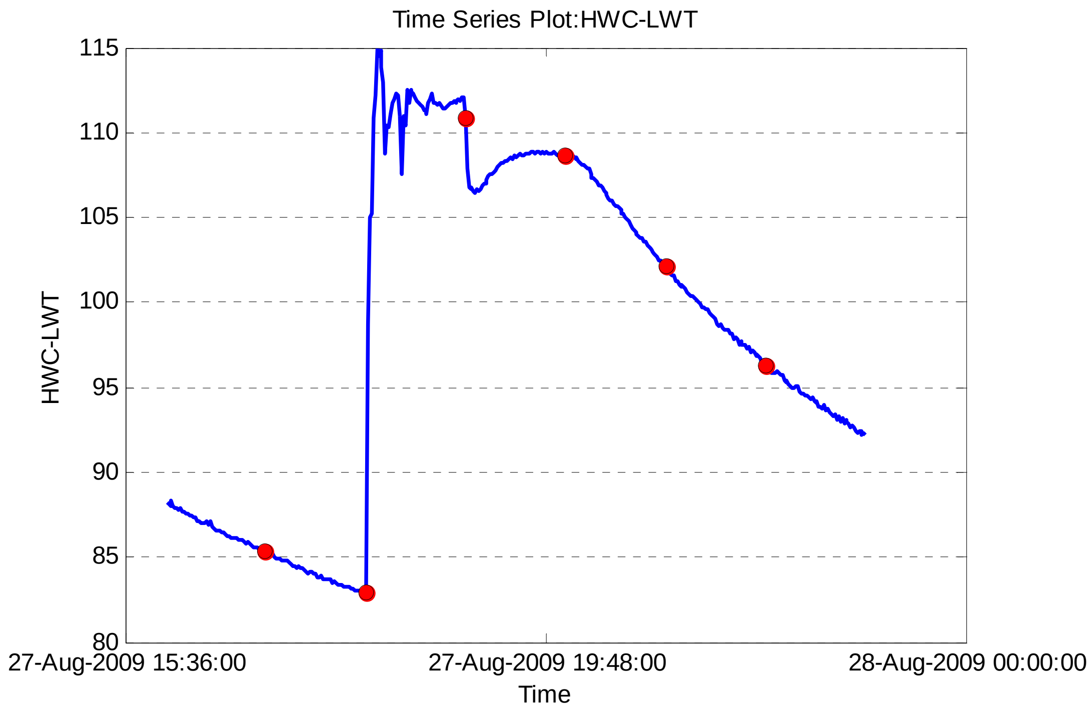



Figure 79. A typical temperature pattern for HWC-LWT, primary-secondary pumping


Figure 80. A typical temperature pattern for HWC-LWT, single pumping

Table 53. Template table for HWC-LWT

| Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 111 | 999 | 0 | 999 | 0 | 999 | 131 | 999 | 131 |
| | 112 | | 112 | | 223 | | 111 | | 132 | | 132 |
| | 113 | | 113 | | 312 | | 112 | | 231 | | |
| | 131 | | 131 | | 313 | | 113 | | 232 | | |
| | 132 | | 132 | | 411 | | 121 | | 233 | | |
| | 133 | | 133 | | 412 | | 122 | | | | |
| | | | | | 413 | | 123 | | | | |
| | | | | | 421 | | 241 | | | | |
| | | | | | 422 | | 242 | | | | |
| | | | | | 423 | | 243 | | | | |
| | | | | | | | 321 | | | | |
| | | | | | | | 322 | | | | |
| | | | | | | | 323 | | | | |

## 7.12 Heating Water Coil Mixing Water Temperature

The heating water coil mixing water temperature differ from the other two heating water temperatures in that in the initial several minutes of period 4 the mixing temperature will jump significantly because of the switch over of the heating water control valve. The statistics table for heating water coil entering temperature is shown in Table 53.

For the 70 test cases, the common main patterns for the entering heating water are: 131-131-0-131-131-131. An example pattern for primary-secondary chilled water system configuration is shown in Figure 81. The temperature patterns for this test case are: 131-131-413/000-242/131-131-131. An example of a single pumping chilled water system configuration pattern is shown in Figure 82. The temperature patterns for this test case are: 131-131-422/000-131-131-131. The final template table for the heating water leaving temperature is listed in Table 54.

Table 54. Statistics on HWC-MWT pattern occurrence

| Transition Pattern Occurrence | % | Main Pattern Occurrence | % | Period# | Temperature Pattern Code |
|---|---|---|---|---|---|
| | | 5 | **7.1%** | 1 | 111 |
| | | 64 | **91.4%** | | 131 |
| | | 1 | **1.4%** | | 221 |
| | | 5 | **7.1%** | 2 | 111 |
| | | 65 | **92.9%** | | 131 |
| 3 | **4.3%** | 66 | **94.3%** | 3 | 0 |
| 1 | **1.4%** | | | | 242 |
| 1 | **1.4%** | | | | 243 |
| | | 1 | **1.4%** | | 313 |
| 4 | **5.7%** | 3 | **4.3%** | | 412 |
| 34 | **48.6%** | | | | 413 |
| 23 | **32.9%** | | | | 422 |
| 3 | **4.3%** | | | | 423 |
| 4 | | 12 | **17.1%** | 4 | 0 |
| | | 47 | **67.1%** | | 131 |
| | | 8 | **11.4%** | | 132 |
| | | 1 | **1.4%** | | 221 |
| 22 | **31.4%** | | | | 241 |
| 11 | **15.7%** | | | | 242 |
| 3 | **4.3%** | | | | 243 |
| 27 | **38.6%** | 1 | **1.4%** | | 413 |
| 2 | **2.9%** | | | | 423 |
| | | 1 | **1.4%** | | 521 |
| | | 68 | **97.1%** | 5 | 131 |
| | | 1 | **1.4%** | | 132 |
| | | 1 | **1.4%** | | 222 |
| | | 66 | **94.3%** | 6 | 131 |
| | | 1 | **1.4%** | | 132 |
| | | 3 | **4.3%** | | 221 |

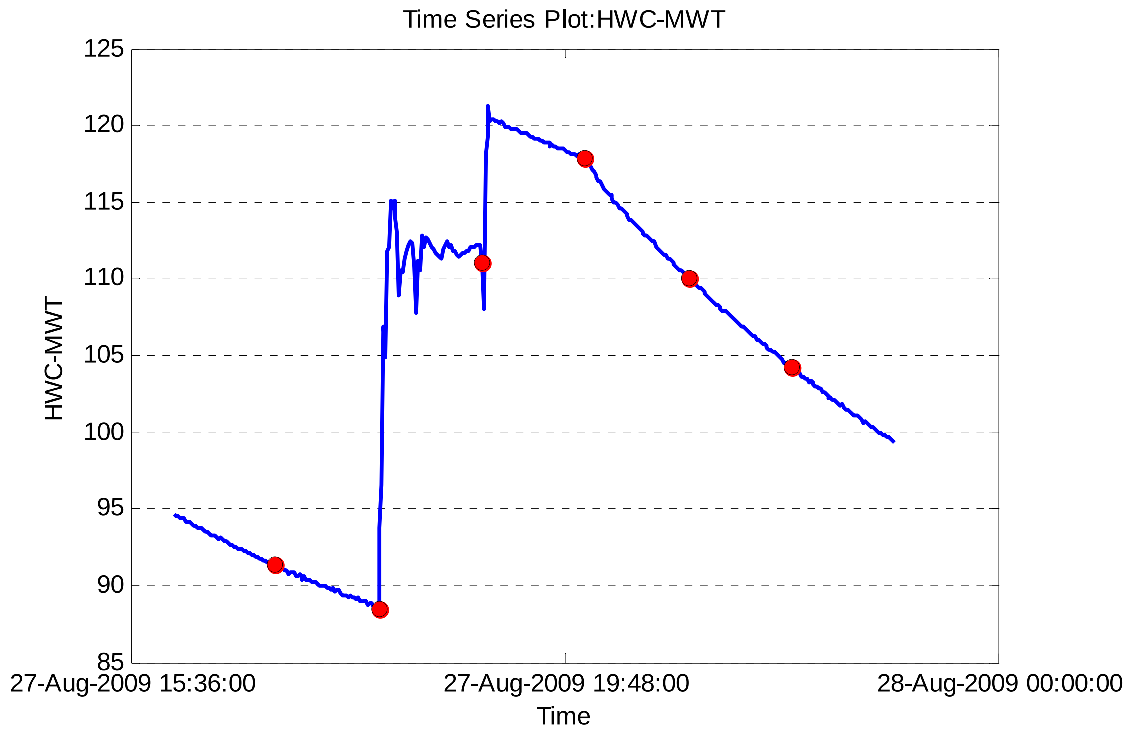



Figure 81. A typical temperature pattern for HWC-MWT, primary-secondary pumping

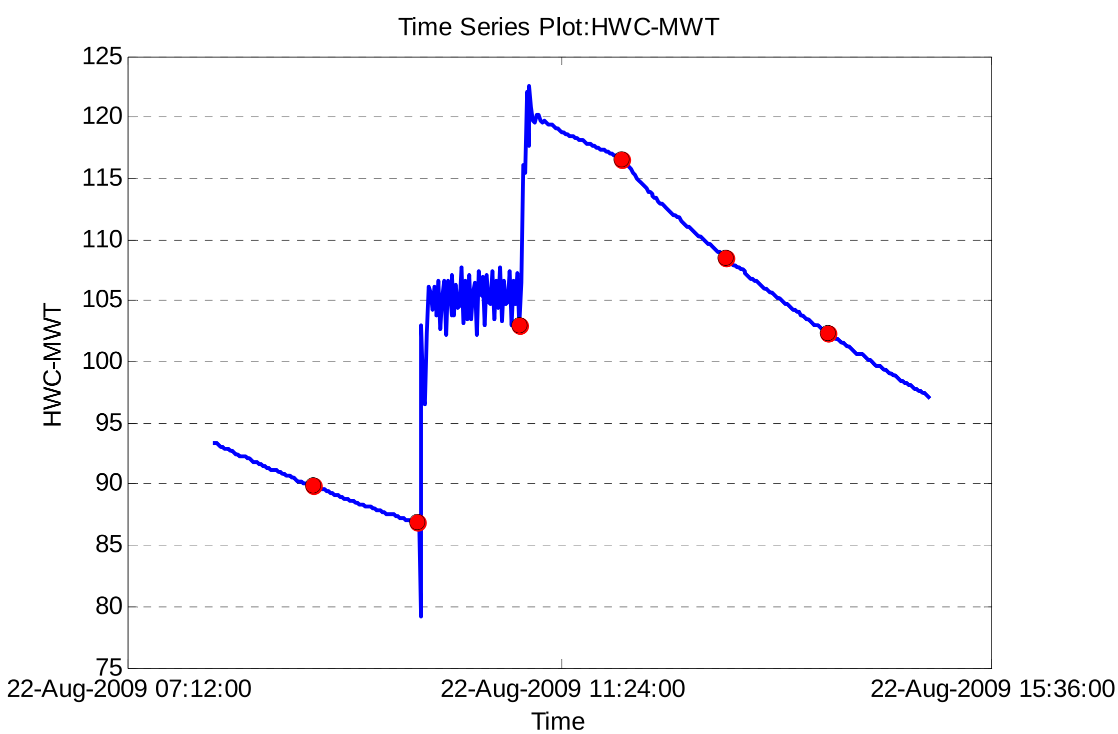



Figure 82. A typical temperature pattern for HWC-MWT, single pumping

Table 55. Template table for HWC-MWT

| Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* | *T* | *M* |
| 999 | 111 | 999 | 111 | 999 | 0 | 999 | 0 | 999 | 131 | 999 | 131 |
| | 112 | | 112 | | 312 | | 131 | | 132 | | 132 |
| | 113 | | 113 | | 313 | | 132 | | | | |
| | 131 | | 131 | | 411 | | 133 | | | | |
| | 132 | | 132 | | 412 | | 221 | | | | |
| | 133 | | 133 | | 413 | | 222 | | | | |
| | | | | | 421 | | 223 | | | | |
| | | | | | 422 | | 412 | | | | |
| | | | | | 423 | | 413 | | | | |

## 7.13 AHU Temperature Location Recognition Results and Analysis

After using the temperature templates described in section 7.2 to 7.12 and the temperature pattern recognition algorithm described in Chapter 5, the pattern recognition algorithm is used on the training data sets (Category A, 129 cases where the original ERSTEST system sensors and Johnson Controls METASYS building automation system is used). The recognition results are listed in Table 55.

Table 56. Temperature location auto recognition results for Category A cases

| | RA-TEMP | MA-TEMP | HWC-DAT | CHWC-DAT | SA-TEMP | CHWC-EWT | CHWC-LWT | CHWC-MWT | HWC-EWT | HWC-LWT | HWC-MWT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total | 129 | 129 | 129 | 129 | 129 | 129 | 129 | 129 | 70 | 70 | 70 |
| Correct | 120 | 128 | 126 | 125 | 126 | 121 | 125 | 126 | 66 | 63 | 62 |
| Incorrect | 15 | 1 | 3 | 2 | 3 | 4 | 1 | 3 | 5 | 2 | 2 |
| | | | | | | | | | | | |
| Correct % | **93.0%** | **99.2%** | **97.7%** | **96.9%** | **97.7%** | **93.8%** | **96.9%** | **97.7%** | **94.3%** | **90.0%** | **88.6%** |
| Incorrect % | **11.6%** | **0.8%** | **2.3%** | **1.6%** | **2.3%** | **3.1%** | **0.8%** | **2.3%** | **7.1%** | **2.9%** | **2.9%** |

The “total” in Table 55 is the total number of cases used for statistics. The “correct” is the number of cases where the specific temperature location is correctly identified (or at least is in one of the detected locations). The "Incorrect" is the total number of cases where the specific temperature location is not recognized at all or at least identified as one of other temperature sensor(s). Assuming the true temperature sensor is in the return air temperature (RA-TEMP) location, an illustration of how to count "correct" and "incorrect" cases for different scenarios is shown in Table 56. As can be seen from the table, the count depends on the occurrence frequency of each scenario, the "correct" cases and "incorrect" cases may not add up to the "total" number of cases.

Table 57. Illustration of counting "correct" and "incorrect" cases

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|
| Detected Locations by the Algorithm | RA-TEMP | RA-TEMP or MA-TEMP | | MA-TEMP | MA-TEMP or SA-TEMP |
| Correct | +1 | +1 | | | |
| Incorrect | | +1 | +1 | +1 | +1 |

Overall in more 90% of the cases, the temperature sensor locations are correctly identified, and there is less than 10% of a chance that a temperature sensor is not identified or identified incorrectly.

For the plug and play prototype cases (Category B, 40 cases where the smart temperature sensors are used and the sequence of operation is automatically controlled by the prototype National Instruments data acquisition system), the results are listed in Table 57. Some of the temperature sensor locations (e.g. SA-TEMP, RA-TEMP) are not exactly the same locations as those in the category A cases. As long as the temperature sensors are installed in the correct AHU sections, the pattern recognition algorithm should be able to correctly identify them in practice.

Table 58. Temperature location auto recognition results for Category B cases

| | RA-TEMP | MA-TEMP | HWC-DAT | CHWC-DAT | SA-TEMP | CHWC-EWT | CHWC-LWT | CHWC-MWT | HWC-EWT | HWC-LWT | HWC-MWT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total | 40 | 40 | 40 | 40 | 40 | 19 | 15 | 19 | 21 | 25 | 21 |
| Correct | 40 | 39 | 38 | 37 | 37 | 17 | 15 | 16 | 21 | 25 | 20 |
| Incorrect | 2 | 1 | 2 | 3 | 3 | 2 | 0 | 3 | 0 | 1 | 1 |
| | | | | | | | | | | | |
| Correct % | **100%** | **98%** | **95%** | **93%** | **93%** | **89%** | **100%** | **84%** | **100%** | **100%** | **95%** |
| Incorrect % | **5%** | **3%** | **5%** | **8%** | **8%** | **11%** | **0.0%** | **16%** | **0%** | **4%** | **5%** |

The results of percentage of correct and incorrect identifications for all temperature sensor locations are similar to those of the category A cases. This shows the effectiveness of this temperature sensor auto recognition algorithm in a plug and play framework system. From all these test cases and their results, it is shown that the plug and play framework for HVAC AHU control system and the temperature sensor location auto recognition algorithm can work in the real world. The reason why these temperature sensors are not being 100% correctly recognized may due to the following reasons:

1. The following initial assumption/observation may be true, but it is very hard to find a short sequence of operations to generate unique recognizable patterns to fit various initial temperature conditions, environmental temperature conditions, internal load conditions, and different HVAC system configurations.

   *Any distinct input/output point in an AHU serves a unique purpose (except redundant points used for reliability). Therefore, given a specified sequence of operation on the outputs, the inputs from different logical locations should display identifiable, unique, time-series patterns. The logical locations of these* *inputs/outputs can be recognized by studying the sequence of operations and the output patterns generated.*

From all the test cases using the given control sequences and the basic patterns defined in Chapter 5, some different temperature sensor locations may generate similar pattern combinations, therefore special heuristic rules or more control sequences may be needed to fine tune the template matching classification method in the recognition algorithm.

2. Water temperature sensors seem more difficult to identify than air temperature sensors due to their fast response to temperature changes and the transition period patterns that need to be carefully examined. The sampling rate of 1 minute per sample may not be quick enough to generate distinguishable transition period patterns for two different water temperatures.
3. In prototype testing cases, several cases occurred in very low outside air temperatures (e.g. Case 30 ~ 33) that did not happen in the training cases. The sequence of operations for the final step 6 need to add an operation that changes AHU from 100% outside air mode to 100% recirculation mode to minimize the low outside air temperature's effect on AHU air temperatures.

Overall, though not perfect yet, the plug and play framework for HVAC AHU control system and the temperature sensor location auto recognition algorithm is a good start for a mature plug and play HVAC control system and self configuring HVAC control system.

# CHAPTER 8. CONCLUSIONS

## 8.1 Conclusions

This research starts with an overview of the current plug and play technologies and their applicability to HVAC control systems, and then a plug and play framework for an AHU control system and a temperature sensor auto recognition algorithm using a structural pattern recognition technique were developed. A prototype plug and play AHU control system was built utilizing IEEE 1451 smart temperature sensors as components, and more than one hundred sixty test cases were implemented to test the feasibility of the framework and the recognition algorithm. The test results show the proposed framework and recognition algorithm works in a real world situation with very good results. All these steps are a good start toward the goal of developing a practical plug and play and self configuring HVAC control system.

## 8.2 Contributions

This research achieved the original research objectives of developing a break-through concept and pattern recognition algorithms to automatically identify temperature logical locations in the AHU. The major contributions are:

- Review and technology gap analysis of current plug and play technologies and applicability to HVAC control systems;
- Development of a plug and play framework for an AHU control system;
- Development of an AHU temperature sensor pattern recognition algorithm using structural pattern recognition technique;

- Design, build, program and test a prototype of the plug and play framework for an AHU and temperature sensor location auto recognition algorithm with good results.

## 8.3 Future Studies

The development of a plug and play framework for an AHU control system and the temperature sensor pattern recognition algorithm serves a solid foundation and provides a direction for future research on plug and play and self configuring HVAC control systems with the ultimate goal of reducing the complexity and errors, and time consumed for setting up HVAC control systems. There are many improvements that can be made on both the framework and the technologies in resolving system ambiguity.

- Find better AHU control sequences and basic temperature patterns and coding techniques so the auto recognition algorithm will have higher percentage recognition rate.
- Currently each control sequence lasts 1 hour so the total execution time is 6 hours. Reducing each period time (and thus total execution time) may be desirable and achievable without performance degradation.
- Other classification schemes could be tried.
- Increasing the sampling rate from the current standard 1 minute per sample to higher frequency (e.g. 10 seconds per sample) may improve the resolution of temperature data patterns and therefore identification percentage.

- The temperature sensor auto recognition algorithm needs to be implemented in other AHUs with similar configurations but different capacities to exam the performance.
- The temperature sensor location auto recognition algorithm can be expanded to recognize other types of AHU inputs: air flow rate, water flow rate, relative humidity, pressure, etc.
- The temperature sensor location auto recognition algorithm can be expanded to recognize AHU outputs: dampers, control valves, and fan and pump start/stop, etc.
- AHU control system mapping algorithm can be developed once AHU inputs/outputs are automatically identified. The mapping algorithm will be based on the control design intent – all AHU control strategies need to be standardized first – then mechanisms to analyze and convert the design intent to controller input/output and control loops configuration also need to be researched.
- A major obstacle of incompatible communication protocols between IEEE 1451 smart transducers with current prevalent open protocol in the HVAC control industry (mainly BACNet and LonWorks) needs to be resolved. Close cooperation among IEEE, NIST, ASHRAE, Echelon and related organizations is needed.

# REFEFRENCES

[1]. ASHRAE. 2008. ASHRAE Vision 2020, http://www.ashrae.org/docLib/20080226_ASHRAEvision2020.pdf, Date retrieved: May 2010

[2]. ASHRAE. 2004. *BACnet - A Data Communication Protocol For Building Automation and Control Networks*, ansi/ashrae standard 135-2004

[3]. ASHRAE. 2008. *ASHRAE Handbook – HVAC Systems and Equipments*

[4]. Armson, M., 2002. Before You Plug and Play: Things to Consider, *Honeywell Sensotec-Plug & Play Considerations (White Paper)*, http://content.honeywell.com/sensing/sensotec/pdf/beforeplugplay.pdf, Date retrieved: May 2010

[5]. Department of Energy. 2005. Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways

[6]. Echelon. 2005. ISI Protocol Specification, *Echelon doc.# 078-0300-01C,* https://www.echelon.com/support//documentation/Manuals/devtools/078-0300-01F_ISI_Protocol_Spec_V3.pdf, Date retrieved: May 2010

[7]. Echelon. 2005. ISI Programmer's Guide, *Echelon doc.# 078-0300-01F,* https://www.echelon.com/support/documentation/Manuals/devtools/078-0299-01F_ISI_Programmer's_GuideV3.pdf, Date retrieved: May 2010

[8]. Echelon. 2009. Introduction to the LonWorks® Platform, revision 2, *Echelon doc.# 078-0183-01B,*

http://www.echelon.com/support/documentation/Manuals/general/078-0183-01B_Intro_to_LonWorks_Rev_2.pdf, Date retrieved: May 2010

[9]. Fu, K. S., 1977. *Syntactic Pattern Recognition, Applications*. Springer Verlag, Berlin

[10]. Gonzalez, R. C., M. G. Thomason. 1978. Syntactic *Pattern Recognition: An Introduction*, Addison-Wesley Publishing Company, Inc., Reading, MA

[11]. Honeywell Sensing and Control, Reference and Application Data – Temperature Sensors, http://content.honeywell.com/sensing/prodinfo/temperature/technical/c15_136.pdf, Date retrieved: May 2010

[12]. Hordeski, M., 2001. *HVAC Control in the New Millennium*, Fairmont Press, Inc., Lilburn, GA

[13]. Horowitz, S. L., 1975. A Syntactic Algorithm for Peak Detection in Waveforms with Applications to Cardiography, *Communications of the ACM*, pp. 281-285

[14]. Iowa Energy Center. 2009. ERS Reference Documents -2009

[15]. Jain, A. K., R. P.W. Duin, and J. Mao. 2000. Statistical Pattern Recognition: A Review, *IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 22, No. 1*

[16]. http://jini.org, Data retrieved: May 2010

[17]. Johnson Controls. 1994. *Valve and Actuator Manual – Valve Basics and Sizing Information Section, Engineering Data Book Vb1*, http://cgproducts.johnsoncontrols.com/MET_PDF/347VB.PDF#xml=http://cgproducts.johnsoncontrols.com/search_lit.aspx?cmd=pdfhits&DocId=1129&Index=C%3a%5cinetpub%5cwwwroot%5c72%2e3%2e145%2e66%5cquicklit%5cexcaliburCD&HitCo

unt=33&hits=f+75+78+7c+14f+204+33e+47c+54c+5d1+6f4+7fc+8dc+9a2+ae0+cd6+d63+e51+f4b+105f+10cb+11b1+128b+12f9+13bb+1463+15ab+15af+15b5+15b9+15ee+1714+181a+&hc=35&req=vb1+, Date retrieved: May 2010

[18]. Kastner, W., G. Neugschwandtner, S. Soucek, and H. M. Newman. 2005. Communication Systems for Building Automation and Control, *Proceedings of the IEEE, Vol. 93, No. 6*

[19]. Katipamula, S., and S. Gaines. 2003. Characterization of Building Controls and Energy Efficiency Options Using Commercial Building Energy Consumption Survey, National Building Control Information Program (NBCIP) Report, http://www.energy.iastate.edu/Efficiency/Commercial/download_nbcip/NBCIP_PNWD_3247%20F.pdf, Date retrieved: May 2010

[20]. Kintner-Meyer, M., K. Gowri, and C. Young, Conceptual Design of a Self-Configuring HVAC Control System, ASHRAE Technical Committee Smart Building Systems draft work statement, version 4

[21]. Ko, W. H., and C. D. Fung. 1982. VLSI and Intelligent Transducers, *Sensors and Actuators*, *(2)*, pp. 239–250.

[22]. Konstantinov, K. B., and T. Yoshida. 1992. RealTime Qualitative Analysis of the Temporal Shapes of (Bio) process Variables, *AIChE Journal, 38(11)*. pp.1703–1715

[23]. Koski, A., M. Juhola, and M. Meriste. 1995. Syntactic Recognition of ECG Signals by Attributed Finite Automata, *Pattern Recognition, 28(12)*. pp. 1927–1940

[24]. Lee, K., 2004. Introduction to IEEE 1451 Family of Standards, Presentation at Wireless Sensor Standard Workshop/Meeting Sensors Expo/Conference,

http://grouper.ieee.org/groups/1451/5/Wireless%20Sensing%20Wksp%20VI%20Files/Introduction_1451%20Family%20Standards_060704.pdf, Date retrieved: May 2010

[25]. Lee, K., 2000. IEEE 1451: A Standard in Support of Smart Transducer Networking, *Proc. 17th IEEE Instrumentation and Measurement Technology Conference*, vol. 2, pp. 525 - 528

[26]. Levenhagen., J. I., 1998. *HVAC Control System Design Diagrams*, McGraw-Hill, New York, NY

[27]. Love, P. L. and M. Simaan, 1988. Automatic Recognition of Primitive Changes in Manufacturing Process Signals, *Pattern Recognition, 21(4)*. pp. 333–342

[28]. Mathworks, *MATLAB Help Document for Curve Fitting Toolbox*, MATLAB version R2007b

[29]. Mindshare Inc., T. Shanley, 1995. *Plug and Play System Architecture*, Addison-Wesley Publishing Company, Reading, MA

[30]. Nadler, M., and E. P. Smith. 1993. *Pattern Recognition Engineering*. John Wiley & Sons INC., New York, NY

[31]. National Instruments, NI CompactDAQ Overview, http://www.ni.com/dataacquisition/compactdaq/, Date retrieved: May 2010

[32]. Neugschwandtner, G., 2006. Towards Plug and Play in Home and Building Automation Networks, *Proc. 11th IEEE International Conference on Emerging Technologies and Factory Automation*, pp. 461-464

[33]. Neugschwandtner, G., 2007. Plug and Play in Distributed Home and Building Automation Systems: An Introduction, *Presentation at KNX Scientific Conference*, Duisburg, Germany

[34]. Olszewski, R. T., 2001. Generalized Feature Extraction for Structural Pattern Recognition in Time-Series Data, PH.D. Thesis, Carnegie Mellon University, Pittsburgh, PA

[35]. Microsoft. 2007. PnP-X: Plug and Play Extensions for Windows Specification, http://download.microsoft.com/download/a/f/7/af7777e5-7dcd-4800-8a0a-b18336565f5b/PnPX-spec.doc, Date retrieved: May 2010

[36]. Price, B. A. and T. F. Smith. 2000. Description of the Iowa Energy Center Energy Resource Station: Facility Update III, Technical Report: ME-TFS-00-001, The University of Iowa, Iowa City, IA

[37]. PsiNaptic Inc., 2004. Jini and Universal Plug and Play (UPnP) Notes, http://www.psinaptic.com/link_files/jini_and_plugandplay.pdf, Date retrieved: May 2010

[38]. Rengaswamy, R. and V. Venkatasubramanian. 1995. A Syntactic Pattern Recognition Approach for Process Monitoring and Fault Diagnosis, *Engineering Applications of Artificial Intelligence*, 8(1). Pp. 35–51

[39]. Schalkoff, R.J., 1992. *Pattern Recognition: Statistical, Structural and Neural Approaches*, John Wiley & Sons, Inc., New York, NY

[40]. Song, E. and K. Lee. 2008. Understanding IEEE 1451—Networked Smart Transducer Interface Standard, *IEEE Instrumentation & Measurement Magazine*, pp 11-17

[41]. IEEE. 2007. *for a Smart Transducer Interface for Sensors and Actuators — Common Functions, Communication Protocols, and Transducer Electronic Data Sheet (TEDS) Formats, IEEE STD 1451.0-2007*, IEEE Instrumentation and Measurement Society,

TC-9, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, September 21, 2007.

[42]. IEEE. 1999. *Standard for a Smart Transducer Interface for Sensors and Actuators—Network Capable Application Processor (NCAP) Information Model, IEEE STD 1451.1-1999*, IEEE Instrumentation and Measurement Society, TC-9, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, June 26, 1999.

[43]. IEEE. 1997. *Standard for a Smart Transducer Interface for Sensors and Actuators–Transducer to Microprocessor Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats, IEEE STD 1451.2-1997*, IEEE Instrumentation, SH99685, and Measurement Society, TC-9, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, September 25, 1998.

[44]. IEEE. 2003. *Standard for a Smart Transducer Interface for Sensors and Actuators—Digital Communication and Transducer Electronic Data Sheet (TEDS) Formats for Distributed Multidrop Systems, IEEE STD 1451.3-2003*, IEEE Instrumentation and Measurement Society, TC-9, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, March 31, 2004.

[45]. IEEE. 2004. *Standard for a Smart Transducer Interface for Sensors and Actuators—Mixed-Mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats, IEEE STD 1451.4-2004*, IEEE Instrumentation and Measurement Society, TC-9, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, December 15, 2004.

[46]. IEEE. 2007. *Standard for a Smart Transducer Interface for Sensors and Actuators—Wireless Communication and Transducer Electronic Data Sheet (TEDS) Formats,*

*IEEE STD 1451.5-2007*, IEEE Instrumentation and Measurement Society, TC-9, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, October 5, 2007

[47]. The Object Management Group (OMG). 2003. Smart Transducer Interface Specification, http://www.omg.org/cgi-bin/doc?formal/03-01-01.pdf, Date retrieved: May 2010

[48]. Travis, J. and J. Kring. 2006. *LabVIEW for Everyone*: *Graphical Programming Made Easy and Fun (3rd Edition)*, Prentice Hall, NJ.

[49]. Trahanias, P. and E. Skordalakis. 1990. Syntactic Pattern Recognition of the ECG, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12(7). pp. 648–657

[50]. Stockman, G. C. and L. N. Kanal. 1983. Problem Reduction Representation for the Linguistic Analysis of Waveforms, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-5(3). pp. 287-298

[51]. Yu, X. and T. F. Smith. 2002. A Model for the Dynamic Response of a Cooling Coil, *Technical Report: ME-TFS-02-003*, The University of Iowa, Iowa City, IA