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An information model for building automation systems

J. Schein

National Institute of Standards and Technology, 100 Bureau Drive, MS 8631, Building 226, Room B122, Gaithersburg, MD 20899–8631, United States

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Abstract

An information model of a building automation system (BAS) was created. It encapsulates several views of the system: the device list, network topology, points list, and sequences of operation. The model allows a single persistent representation of a BAS to be maintained from system specification through design to operation and maintenance. It will also allow other applications such as energy simulations, maintenance management systems, and building commissioning applications to extract information about the BAS. The model is not intended to represent control application programs; however, it would be possible to develop a software tool to parse the information model, then create the required configuration database and control application programs as output. The model was tested by creating an experimental implementation based on a BAS installed in a medium-sized office building.

Keywords: Building automation; Direct digital control; Energy management system; Information model

1. Introduction

The process of specifying, designing, and installing building automation systems (BAS) typically begins with the plans and specifications produced by the mechanical, electrical, and plumbing (MEP) design engineer. The MEP plans and specifications include equipment and process schematics that specify the location of sensors and control elements for the mechanical system. Also included is a narrative "Sequence of Operations" which describes how the mechanical system is to be controlled. Despite its name, the "Sequence of Operations" does not describe a sequential process; it is an overall specification of the control strategy for the heating, ventilation, and air conditioning (HVAC) system. This information is provided to the control system integrator, who then creates a configuration database for the control system, which establishes communication, network, and device parameters as well as input/output (I/O) configuration parameters. The control system integrator also develops control application programs for the controlled equipment based on the narrative "Sequence of Operations." There is a great deal of variability in the level of detail provided in the "Sequence of Operations." The system integrator must determine how much detail is provided, then apply judgment in determining precisely how the mechanical equipment will be controlled. Ultimately, the building owner will receive the control schematic drawings and "Sequence of Operations" from the MEP design engineer in addition to as-built control system drawings and a user manual from the control system integrator.

The building owner needs to extract information about the architecture and operation of the BAS for various participants: the building engineer, maintenance contractor, commissioning agent, and energy consultant have diverse information needs related to the network topology, I/O configuration, hardware part/inventory data, software version numbers, as well as the control strategies and sequencing. Very little of this information can be extracted directly from the documents delivered to the building owner; it must be read, interpreted, and manually re-entered into a spreadsheet, database, maintenance management system, commissioning tool, or energy simulation program.

A far more effective solution to the problem of passing information about the BAS to each of the parties would be a single, persistent, computer processible representation of the BAS from specification through design to operation and maintenance. An open, standard exchange format would allow a number of software tools to be developed which

E-mail address: jeffrey.schein@nist.gov.

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could enable the MEP engineer to communicate the necessary BAS specification to the control system integrator at a consistent level of detail; allow the system integrator to automatically extract the BAS specification information, “fill in the blanks,” and create the configuration database and control application programs; and allow the building engineer, maintenance contractor, commissioning agent, and energy consultant to automatically extract the information they need and enter it into their software applications. Development of the exchange format is the necessary first step, but to make this vision a reality, software tools must be developed which use the format to exchange information. For example, one software application might allow an MEP engineer to identify the components of the HVAC system and how they are to be controlled. The results would be saved in a file based on the exchange format, which could be opened by the system integrator using a different software application which allows him to view the information created by the MEP engineer, make additions or changes as necessary, create a system of control hardware and software for the system, and save in a file using the same exchange format. The system integrator’s software might also automatically generate the configuration database and/or control application programs. Software applications already used by the building engineer, maintenance contractor, commissioning agent, and energy consultant might be modified to be able to read the files created by the MEP engineer or system integrator and extract the information needed for their specific applications, for example, a maintenance management system might look for the model numbers of the control hardware, while an energy simulation program might look for whether the air-side economizer is temperature or enthalpy based.

2. Methodology

There are two elements of the exchange format: a model of the information to be exchanged, and a method of encoding the model in an electronic format. The second part is provided by an international standard, International Organization for Standardization (ISO) 10303–21:2002 [1], which specifies the encoding of an information model written in the

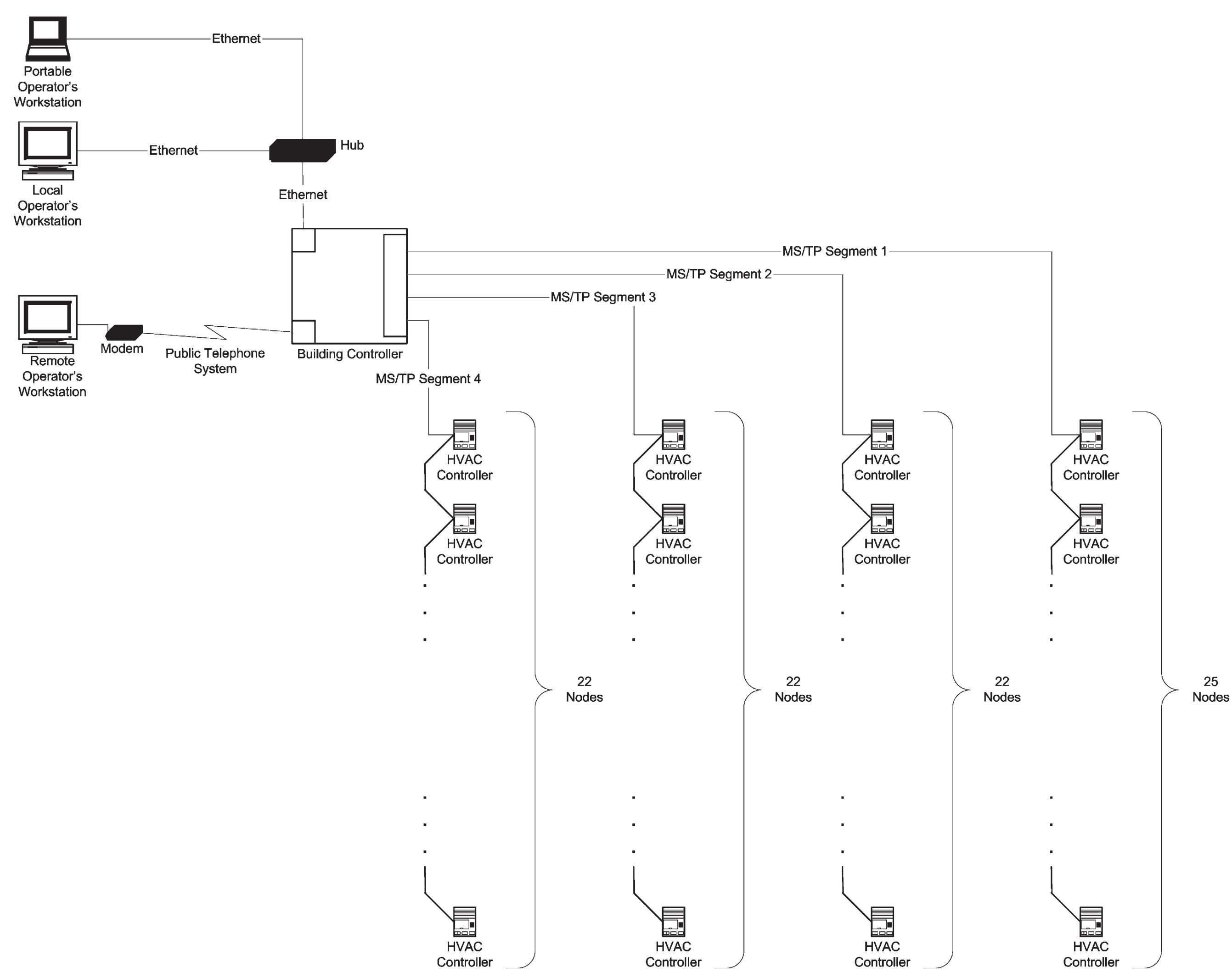

Fig. 1. Building automation system information model data point entity diagram.

EXPRESS modeling language [2] (EXPRESS is also an ISO standard). This study focused on developing an EXPRESS model of a BAS suitable for encoding according to ISO 10303–21:2002.

Schenck and Wilson [3] give a detailed description of EXPRESS. A brief summary is presented here. An EXPRESS model consists of related entities. An entity is an element of the model that represents some item of interest in the real world. For example, a controller, a temperature sensor, and a Proportional-Integral-Derivative (PID) loop are all entities in the BAS model. For the purposes of this study, there are two relationships between entities: *attribution* and *inheritance*. Attribution is a "has-a" relationship, in that each entity may "have" attributes, which could be other entities or simple data types, for example, strings, integers, or real numbers. Inheritance is an "is-a" relationship, where one entity may be a subtype of one or more other entities (its supertypes). The subtype "inherits" the attributes of the supertypes. There are both lexical (text) and graphical representations of EXPRESS. The graphical representation, EXPRESS-G, was used in this study. Each entity is represented by a rectangle. The attribution relationship is shown as a lightweight line connecting the entity with its attribute; a circle at one end of the line indicates the attribute. A dotted line indicates an optional attribute. A set of attributes is shown by "[0:#]" following the name of the set of attributes, where # indicates the number of elements in the set; a "?" for "#" indicates a variable set size. The inheritance relationship is shown as a heavier weight line connecting the supertype and subtype; a circle at one end of the line indicates the subtype. If an entity has attributes which are simple data types such as real numbers, integers, or strings, these are indicated by a rectangle with a vertical bar. An entity may be classified as abstract, which may not be instantiated directly, but only exists so other entities may use it as a supertype. It is represented by the symbol "(ABS)" preceding the name of the abstract entity. In most cases, EXPRESS models require more than a single page, but the rectangular entity symbol only appears once, on the page where the entity's attributes are defined. An oval proxy symbol is used if the entity appears elsewhere in the model, typically as an attribute or supertype of another entity.

2.1. Building blocks

Fig. 1 is the first page of the EXPRESS-G representation of the BAS model. The abstract entity, Point, represents an

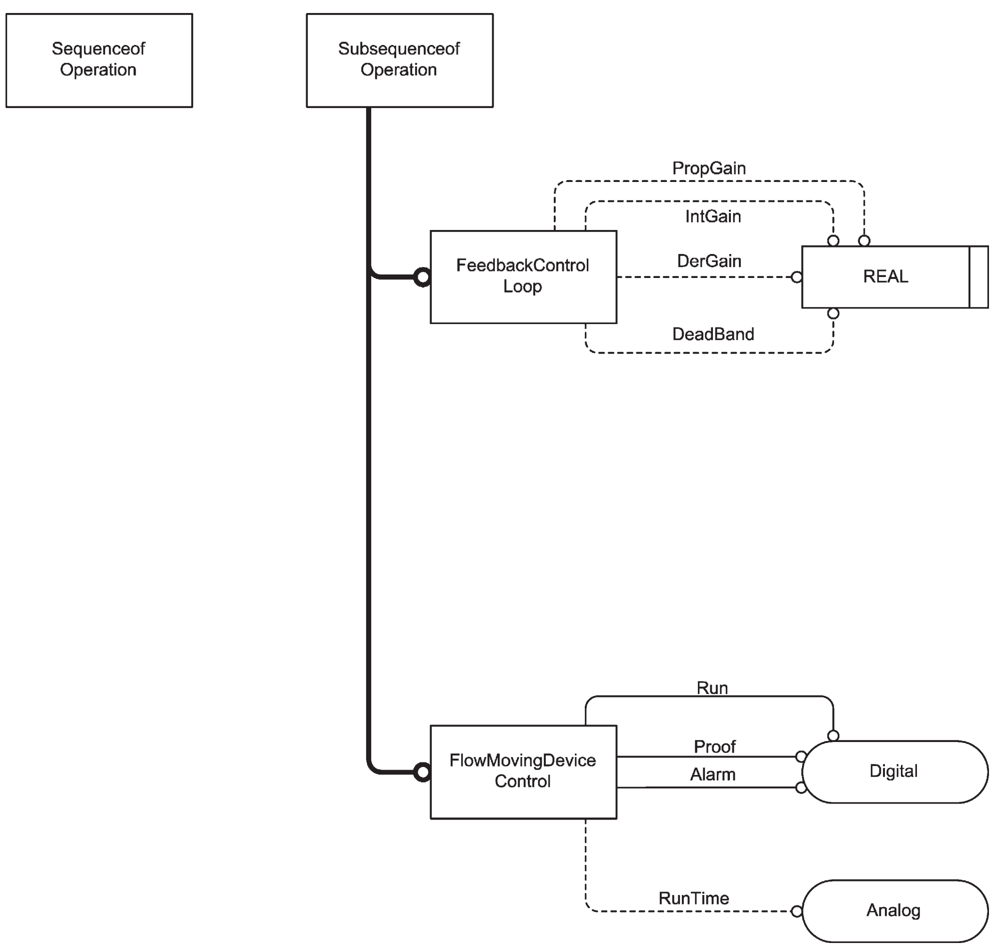

Fig. 2. Building automation system information model sequence/subsequence of operation entity diagram.

I/O point in the BAS. Point has a string attribute for the name of the point, an integer representing its instance number in the local device, and two real numbers for the high and low limits, which are optional. Point has two subclasses which are also abstract: Analog, meaning that the point varies continuously (subject to analog-to-digital or digital-to-analog converter resolution) within a specified range, or Digital, meaning that it can assume one of two possible states. Analog has three subtypes: AnalogInput, representing a sensor; AnalogValue, representing an internal analog value such as a setpoint; and AnalogOutput, representing an analog control element, such as a control valve or damper. Digital also has three subtypes: BinaryInput, representing a two-position input such as a differential pressure switch; BinaryValue, representing an internal status; and BinaryOutput, representing a two-position output such as a motor start/stop relay.

Another element of the BAS model is the entity SubsequenceOfOperation, as shown in Fig. 2. The entity SequenceOfOperation is reserved to represent the operation of a single, complete piece of equipment, for example, an air handling unit, terminal unit, etc., while SubsequenceOfOperation is always contained within a single controller. Sometimes, there is a one-to-one relationship between a controller and a piece of equipment, in which case, there will be a one-to-one correspondence between the SequenceOfOperation and the SubsequenceOfOperation. However, in some cases, a single device controls several pieces of equipment. There are also applications in which several controllers each store and execute parts of the sequence of operation for a single piece of equipment. In order to accurately represent this real-world "messiness," the SequenceOfOperation is not directly linked to the BAS hardware; instead, it has one or more SubsequenceOfOperation attributes which are assigned to controllers.

Some generic subtypes of SubsequenceOfOperation are also shown in Fig. 2. These represent common features of control systems and are provided so that other entities can inherit from them as subtypes. One is FeedbackControlLoop, which represents a PID, floating, or on–off feedback control loop. It has four real number attributes, all optional: PropGain, IntGain, DerGain, and Deadband. The input, setpoint, and output are not included because they will vary depending on the application and are therefore assigned by the subtype. Another generic subtype of SubsequenceOfOperation is FlowMovingDeviceControl, which represents a control

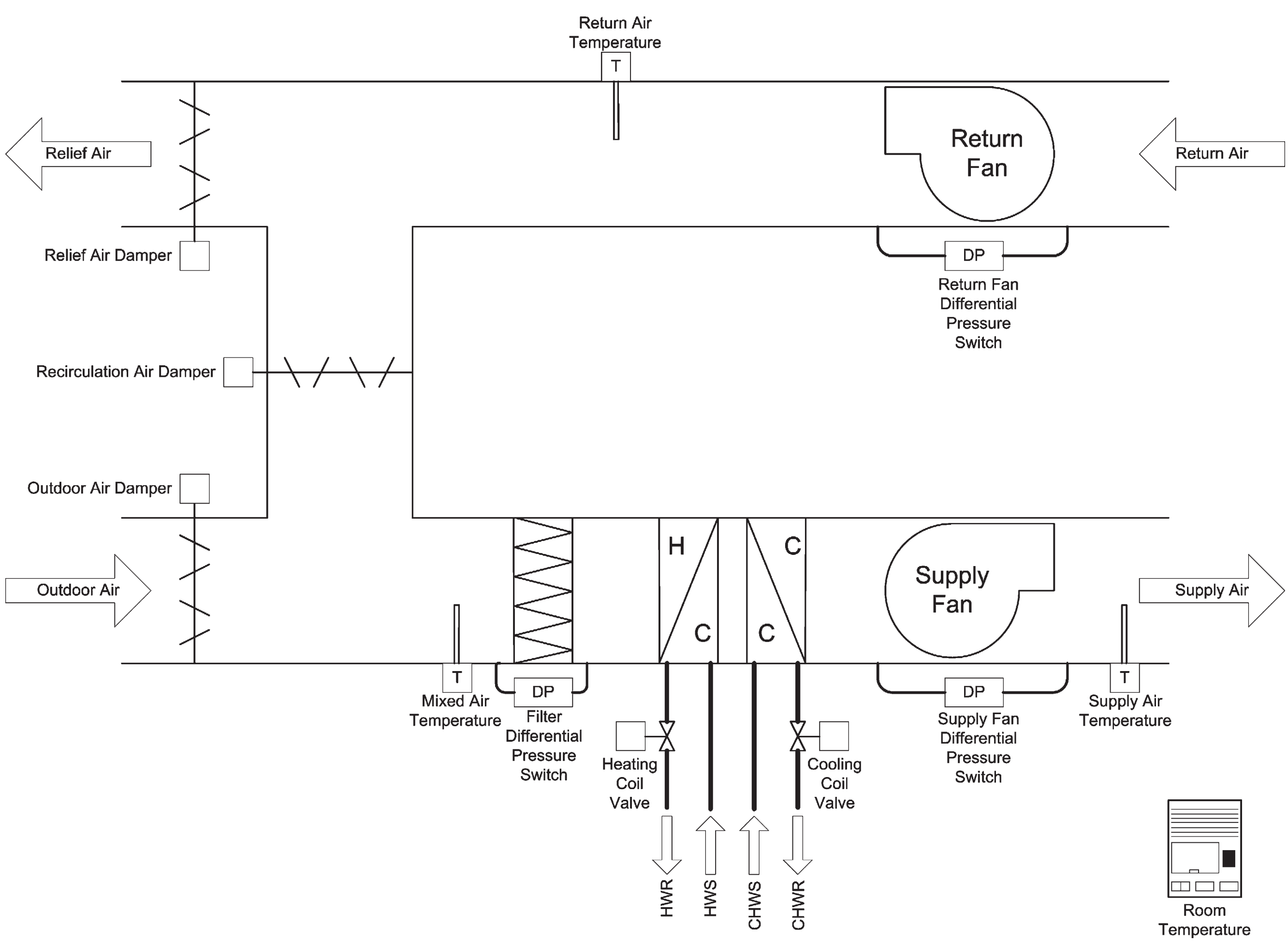

Fig. 3. Building automation system information model network topology entity diagram.

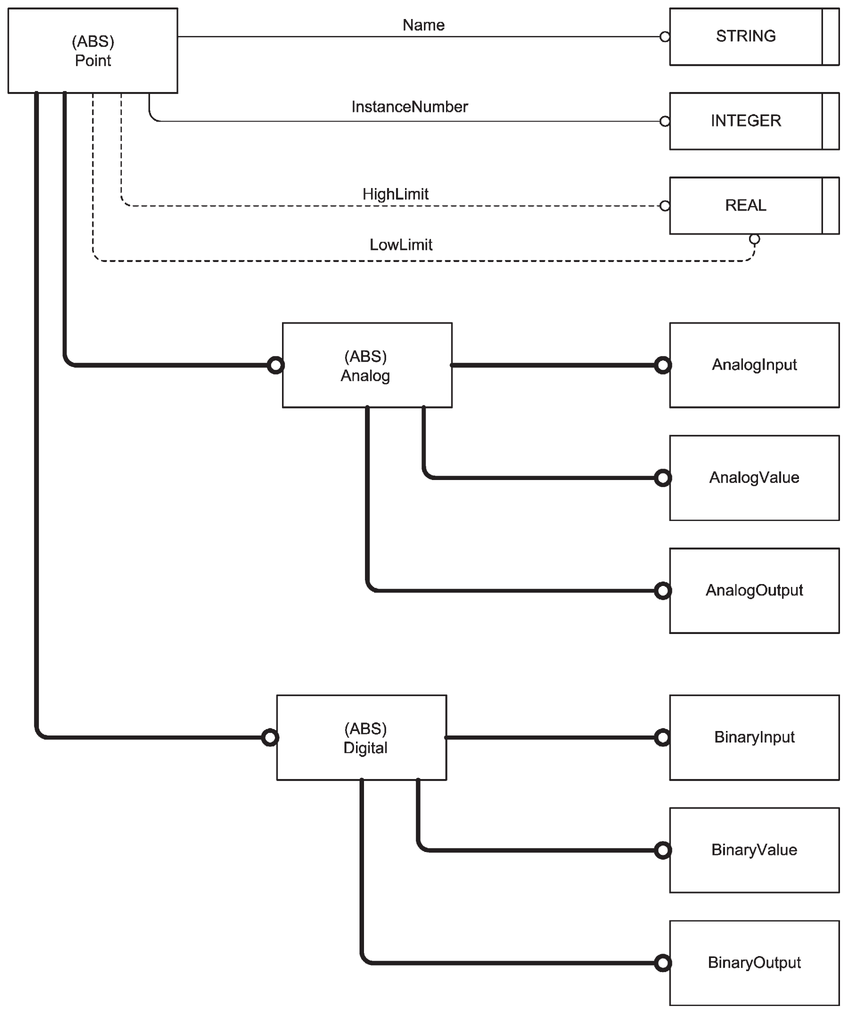

Fig. 4. Building automation system information model terminal unit control entity diagram.

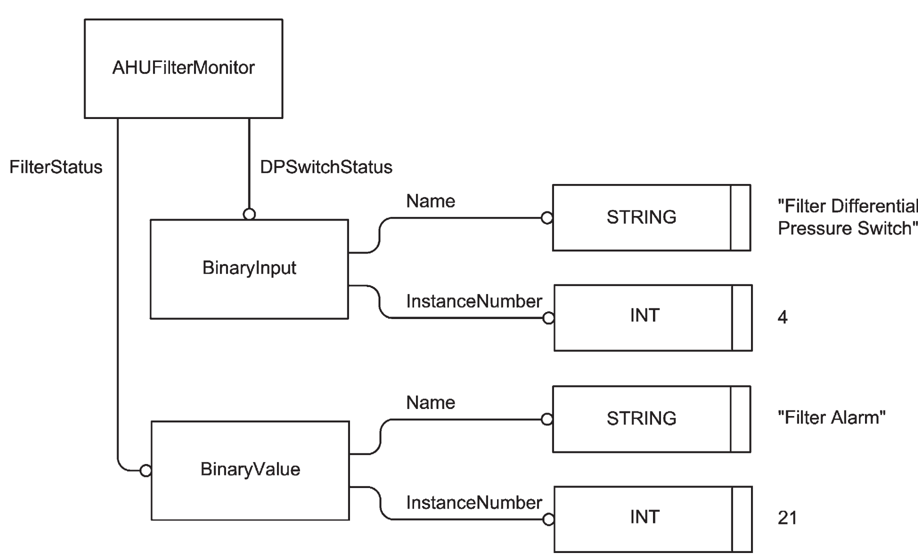

Fig. 5. Building automation system information model air handling unit control entity diagram.

sequence for a fan or pump. FlowMovingDeviceControl has three attributes that are Digital entities: Run, representing the control signal commanding the equipment to start; Proof, representing a current transformer or a flow or differential pressure switch for proof of flow; and Alarm, often representing the condition that the equipment is commanded to run but there is no proof of flow. There is also one optional Analog attribute: RunTime, representing the accumulated hours of operation for the equipment.

2.2. Network topology

Fig. 3 shows the model representation of the BAS network topology. Each network is characterized by a network number which must be unique within the building control system, by the data communication protocol, and by a set of connected devices. All types of devices share certain attributes: address, device name, manufacturer, model, serial number, location (optional), and description (optional). In addition, a device is classified as either a router, a workstation, or a controller. A router consists of a set of connected networks. A workstation consists of a set of software applications, each of which has a name, a manufacturer, a serial number, a version number, and a patch number. A controller consists of a set of points and a set of control subsequences. The ovals used to represent the Point and SubsequenceOfOperation attribute is used to indicate that these entities are defined elsewhere in the model. Some controllers are used only for data acquisition; in this case, the set of

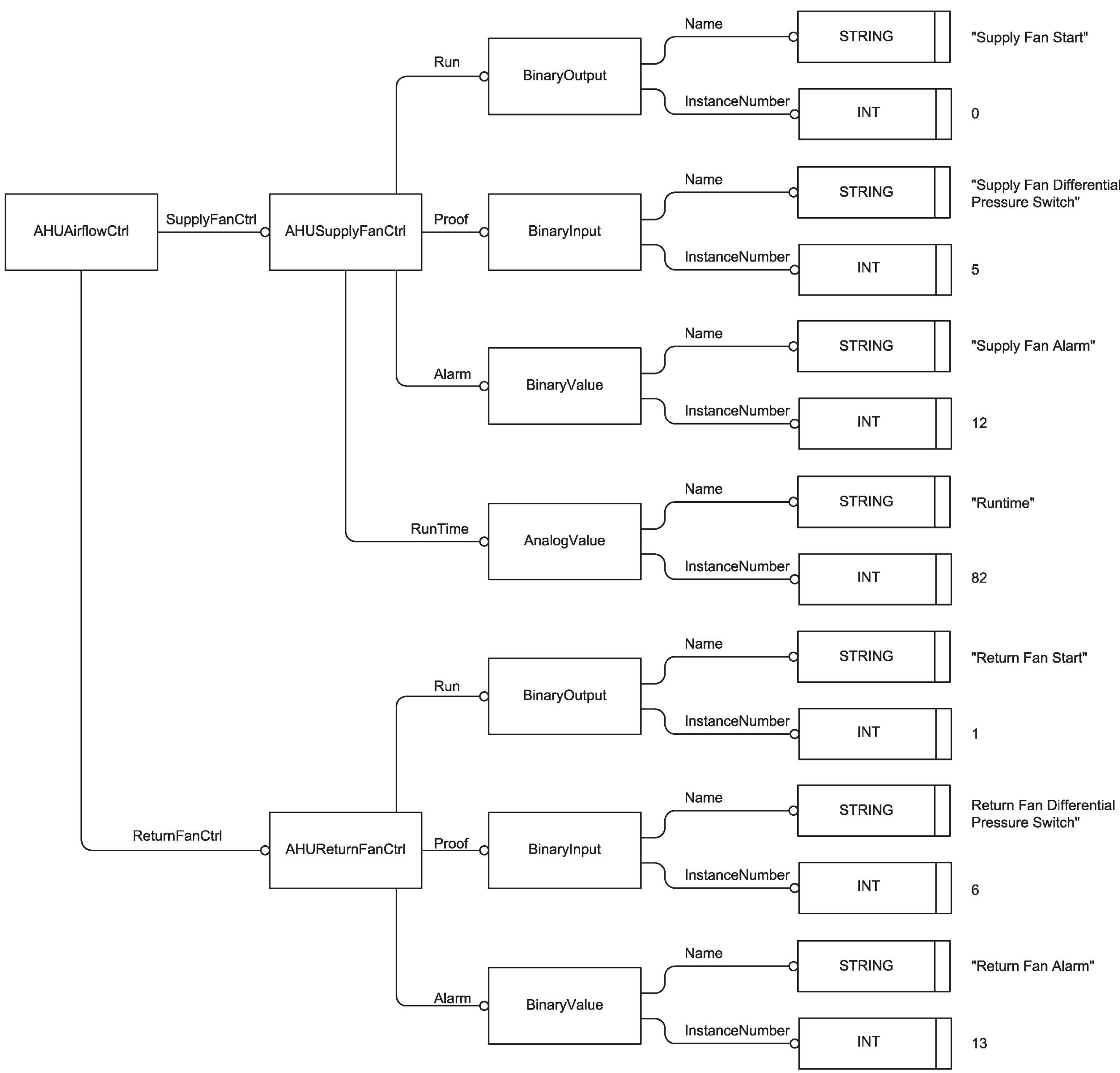

Fig. 6. Building automation system information model air handling unit airflow control entity diagram.

subsequences would be empty, and the controller would consist of a set of points only.

2.3. Terminal unit sequence of operations

The model representation of a terminal unit sequence of operation (a subtype of SequenceOfOperation) for a pressure-independent variable air volume (VAV) box is shown in Fig. 4. This subsequence is a subtype of the generic terminal unit control entity. Other terminal unit subsequences, for example, for fan coil units, unit ventilators, etc., could be developed which would also be subtypes of the terminal unit control entity. The pressure-independent VAV box control entity consists solely of a zone temperature control subsequence, which is also a subtype of a feedback control subsequence and, therefore, also a subtype of SubsequenceOfOperation. This architecture implies that the terminal unit sequence of operation is always contained within a single controller, although that controller may contain other subsequences as well.

The zone temperature control subsequence has nine Analog attributes: zone temperature, occupied and unoccupied heating setpoints and cooling setpoints, minimum and maximum airflow rate, and cooling and heating requests (optional). There are two subtypes of the zone temperature control loop: single and dual duct. The single duct subtype has one additional Analog attribute, the zone airflow setpoint, while the dual duct subtype has additional hot and cold airflow setpoints. The single duct temperature control loop has one airflow control loop as an attribute, while the dual duct temperature control loop has two airflow control loops as attributes, one for the cold deck and one for the hot deck. Like the zone temperature control loop, the airflow control loop is a subtype of a feedback control subsequence. In addition to the attributes inherited from the feedback control subsequence, each airflow control subsequence has several Analog attributes: airflow rate, zone airflow setpoint (derived from the appropriate zone airflow setpoint of the single or dual duct zone temperature control object), and supply air static pressure reset request (optional). The airflow control is classified as tristate or analog. If it is tristate, it has Digital "damper open" and "damper close" attributes. If the airflow control is analog, then it has one Analog damper control signal attribute.

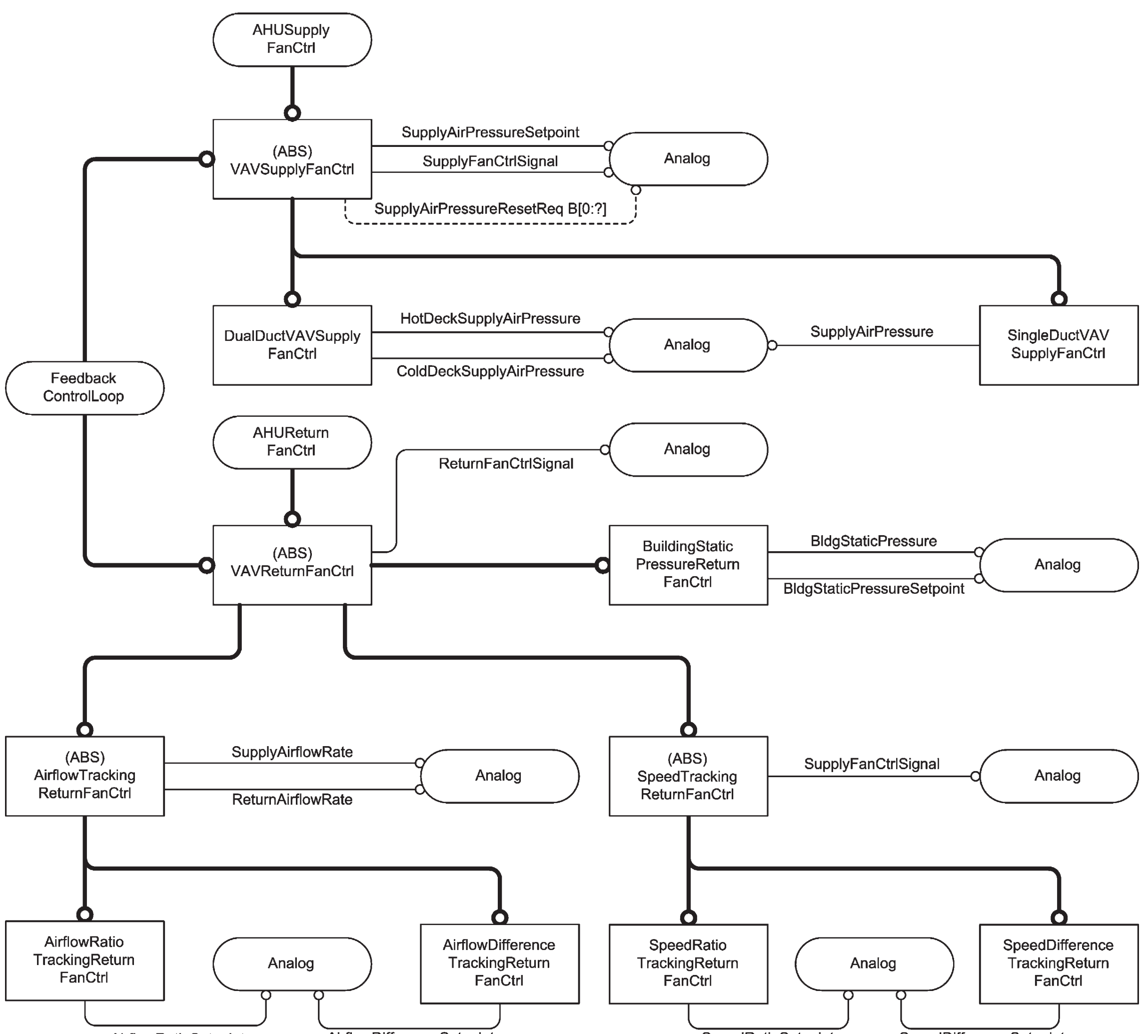

Fig. 7. Building automation system information model air handling unit temperature control entity diagram.

The single duct zone temperature control loop also has two subtypes. The fan powered subtype adds a fan run command attribute and a fan control type attribute (the dotted rectangle for fan type indicates that the value is selected from a list, in this case either series or parallel fan control). The second subtype is for terminal units with reheat and is further characterized by two subtypes: hydronic, with one Analog attribute representing the reheat coil valve control signal and one optional Digital attribute for a boiler run request; and electric, with a set of Digital attributes representing multiple stages of reheat.

2.4. Air handling unit sequence of operations

Unlike the terminal sequence of operations, the air handling unit (AHU) sequence of operations consists of several subsequences, so the AHU sequence of operations could be split over several controllers. Fig. 5 shows that the AHU sequence of operations has as attributes an airflow control subsequence and a temperature control subsequence. In addition, there is an optional filter monitoring subsequence which has Digital attributes representing differential pressure switch status and filter condition status as well as optional attributes representing filter alarm delay time and filter run time.

The airflow control subsequence has supply fan control, return fan control (optional) and minimum outdoor airflow control (optional) attributes. The minimum outdoor airflow control entity has attributes representing the minimum outdoor airflow rate, the minimum outdoor airflow setpoint, and the minimum outdoor damper control signal. Fig. 6 shows that the supply fan control entity, a subtype of the flow moving control subsequence, may be further classified as variable air volume (VAV). The VAV supply fan control subtype, which is also a subtype of the feedback control loop, adds the Analog attributes of supply air static pressure setpoint, supply fan control signal, and a set of supply air static pressure reset requests (optional). The VAV supply fan subtype is further classified as either single or dual duct. If it is single duct, then an Analog attribute representing the supply air static pressure sensor is added. If it is dual duct, two Analog attributes representing hot and cold deck supply air static pressure sensors are added. The set of supply air static pressure reset requests is provided so that they may each be linked to the supply air static pressure reset request attribute of a terminal unit sequence of operations.

Fig. 6 also illustrates the return fan control, which is also a subtype of the flow moving device control sequence. The return fan control sequence may also be further classified as VAV. The VAV return fan subtype, which is also a subtype of the feedback control loop, is further classified into five subtypes as the return

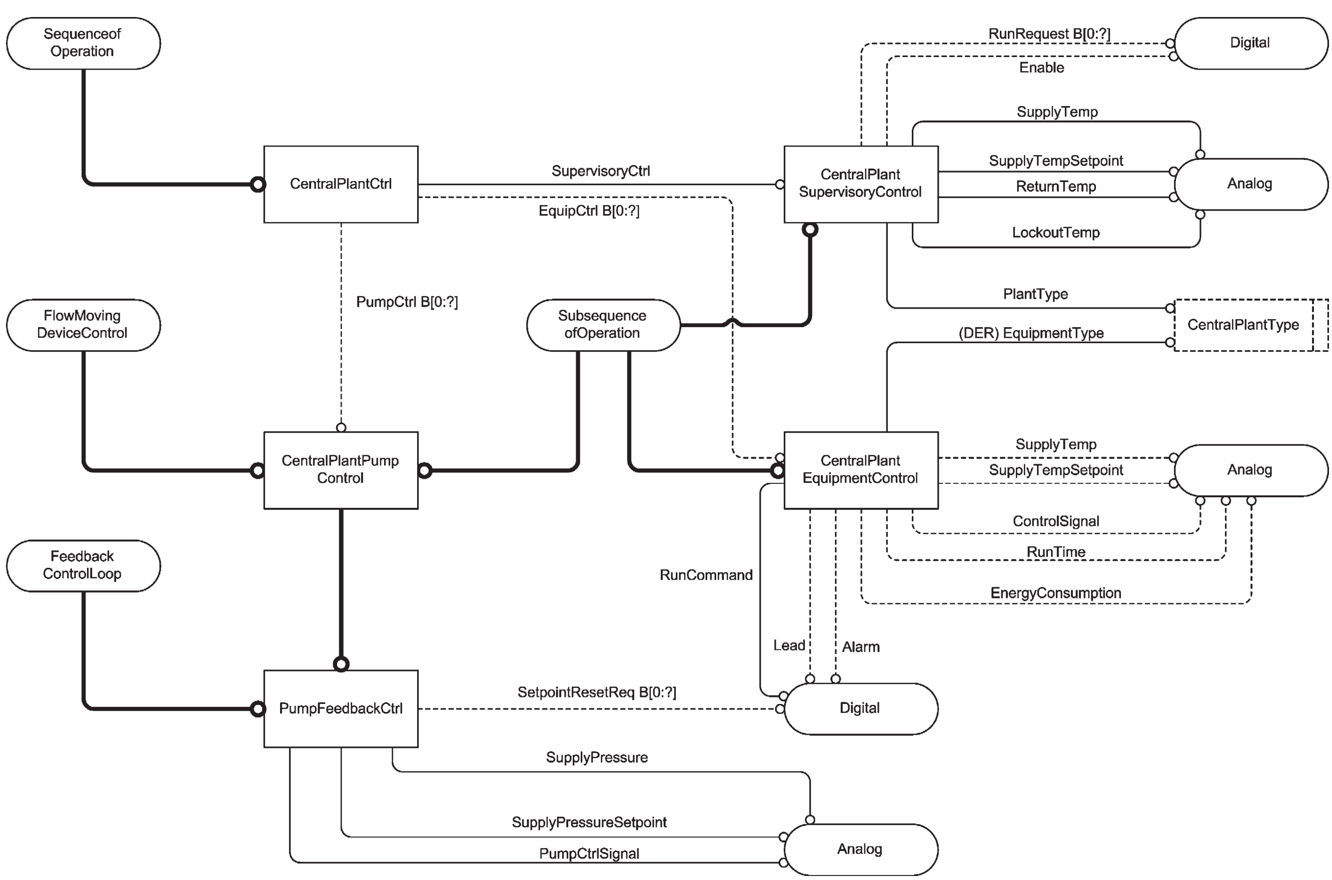

Fig. 8. Building automation system information model central plant control entity diagram.

fan control signal is modulated to maintain the process variable listed below at a setpoint value:

- Building static pressure
- The difference between supply fan speed and return fan speed
- The ratio of return fan speed to supply fan speed
- The difference between supply air flow rate and return air flow rate
- The ratio of return air flow rate to supply air flow rate.

Fig. 5 shows that the temperature control subsequence consists of setpoint logic, cooling control (optional), heating control (optional), and economizer control (optional). Fig. 7 shows that the setpoint logic has two subtypes: single-zone setpoint control for single-zone AHUs and supply air temperature (SAT) setpoint control for AHUs that serve multiple zones. The single-zone setpoint control entity has two Analog attributes: zone temperature and zone temperature setpoint, as well as an optional setpoint reset schedule based on return air temperature (RAT). The reset sequence has a RAT attribute along with minimum and maximum zone temperature setpoints. The SAT setpoint control is classified as being either single duct, with SAT and SAT setpoint attributes, or dual duct, with cold deck SAT, cold deck SAT setpoint, hot deck SAT, and hot deck SAT setpoint attributes. The SAT setpoint control entity also has an optional SAT setpoint reset attribute. The SAT setpoint reset is abstract but there are two subtypes, one based on RAT and the other on heating and cooling requests. The RAT reset entity (the same type as the single-zone temperature setpoint reset schedule) has a RAT attribute along with minimum and maximum SAT setpoints. The heating and cooling request reset entity has sets of heating and/or cooling requests along with minimum and maximum SAT setpoints. The set(s) of heating and/or cooling requests are provided so that the elements of the set(s) may each be linked to a heating or cooling request attribute of a terminal unit sequence of operations. The dual duct SAT setpoint control type has two optional SAT setpoint reset attributes, one for the cold deck and one for the hot deck.

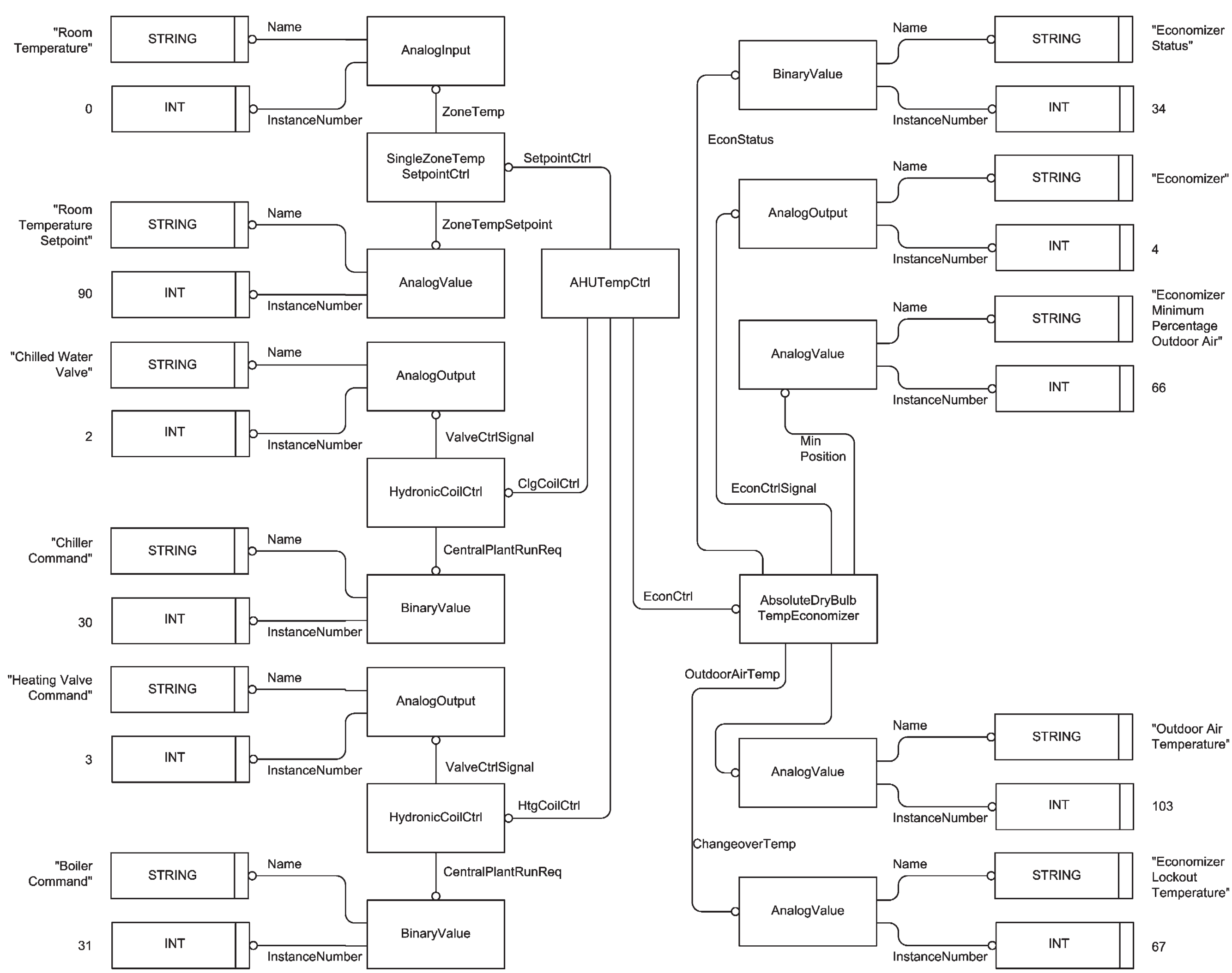

Fig. 9. Building automation system network diagram used for experimental implementation.

The abstract economizer control subsequence shown in Fig. 5 has attributes representing the economizer status, economizer control signal, minimum position, and low temperature limit (optional). The economizer is classified into four subtypes in Fig. 7, with the following additional attributes:

- Absolute temperature-based: outdoor air temperature and changeover temperature
- Relative temperature-based: outdoor air temperature and return air temperature
- Absolute enthalpy-based: outdoor air temperature, outdoor air humidity, and changeover enthalpy
- Relative enthalpy-based: outdoor air temperature, outdoor air humidity, return air temperature, and return air humidity.

The cooling and heating control subsequences are classified as either hydronic (chilled water for a cooling coil or hot water for a heating coil) or staged (one or more stages of refrigeration for a cooling coil and one or more stages of either electric heat or combustion furnace for a heating coil). The hydronic coil entity has a valve control signal attribute and an optional "central plant run request" attribute. The staged coil entity has a set of on/off stage command attributes.

2.5. Central plant sequence of operations

Chiller and boiler manufacturers often package the controls with their products, but the BAS may perform plant-level control, for example, equipment sequencing/scheduling, alarming, and possibly setpoint reset. The central plant control sequence shown in Fig. 8 consists of a subsequence representing the supervisory control strategy, an optional set of pump control subsequences, and an optional set of energy conversion equipment control subsequences. The supervisory control subsequence has attributes of plant type (boiler or chiller), supply temperature, supply temperature setpoint, return temperature, lockout temperature, run enable (optional), and a set of run requests (optional). The run requests are provided so that they may be linked to a boiler or chiller run request attribute of an air handling unit or terminal unit sequence of operations.

The pump control subsequence is a subtype of the flow moving device control subsequence. It may be further classified as a pump feedback control subsequence, which is a subtype of both the pump control and the feedback control subsequences. In addition, the pump feedback control entity has supply pressure, supply pressure setpoint, and pump control signal attributes along with an optional set of supply pressure setpoint reset requests.

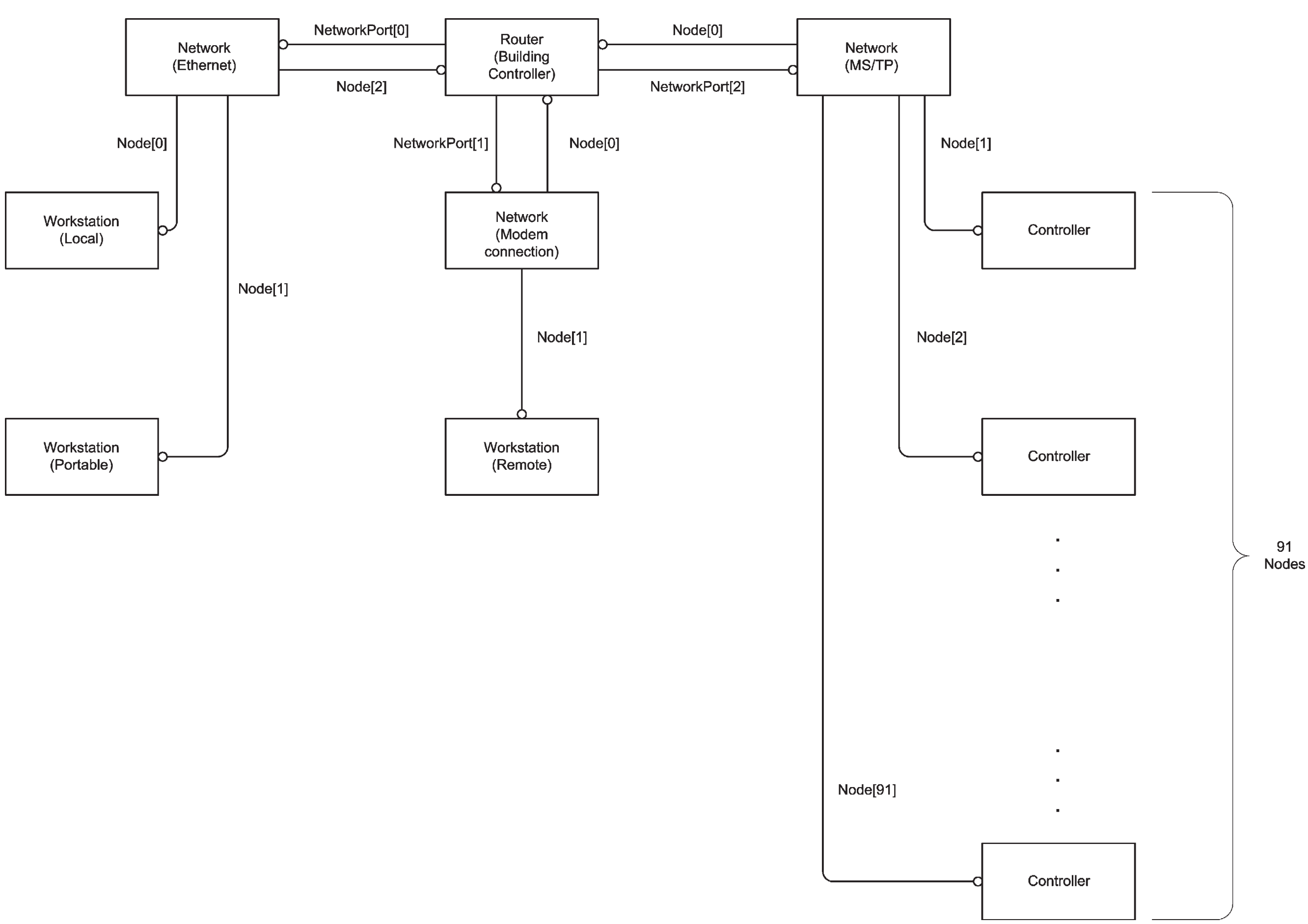

Fig. 10. Experimental model representation of network topology.

The energy conversion control subsequence is for supervisory control over a boiler or chiller with packaged local controls. It consists of the device type (derived from the central plant type), run command, lead/lag status (optional), alarm (optional), supply temperature (optional), supply temperature setpoint (optional), control signal (optional), run time (optional), and energy consumption (optional).

3. Experimental implementation

The narrative "Sequence of Operations," as-built control system drawings, and control application programs were obtained from a recently installed BAS in a medium-sized office building. These sources of information were used to develop an experimental implementation of the BAS information model. Fig. 9 illustrates the BAS network topology, which is representative for a building of this size and type. There is a single "building controller" that acts as a router between each of the networks as well as serving as a real-time host for scheduling, alarm/event handling, and trend logging. The building controller supports four Master–Slave/Token Passing (MS/TP) segments which form a single network connecting all the HVAC equipment controllers for AHUs, terminal units, and the central plant. One segment has 25 nodes and the other three each have 22 nodes, for a total of 91 nodes, not including the building controller. An Ethernet hub connects the building controller with fixed and portable operators' workstations. The building controller also has an internal modem for dial-in access by a remote workstation. Each of the workstations is provided with a software package for viewing current and historical states of the system, reporting alarms/events, changing the configuration of the BAS, and archiving data.

The model representation of the BAS network topology is shown in Fig. 10. The building controller is represented by a Router entity, with a set of three NetworkPort attributes, one each for the modem, Ethernet, and MS/TP connections. The modem connection is represented by a Network entity with two Nodes: the building controller and the remote workstation, which appears as a Workstation entity. The Ethernet network is also represented by a Network entity with three Nodes: the building controller and the local and portable workstations. The MS/TP network is represented by a Network entity with a set of 92 Nodes: one for the building controller and one for each

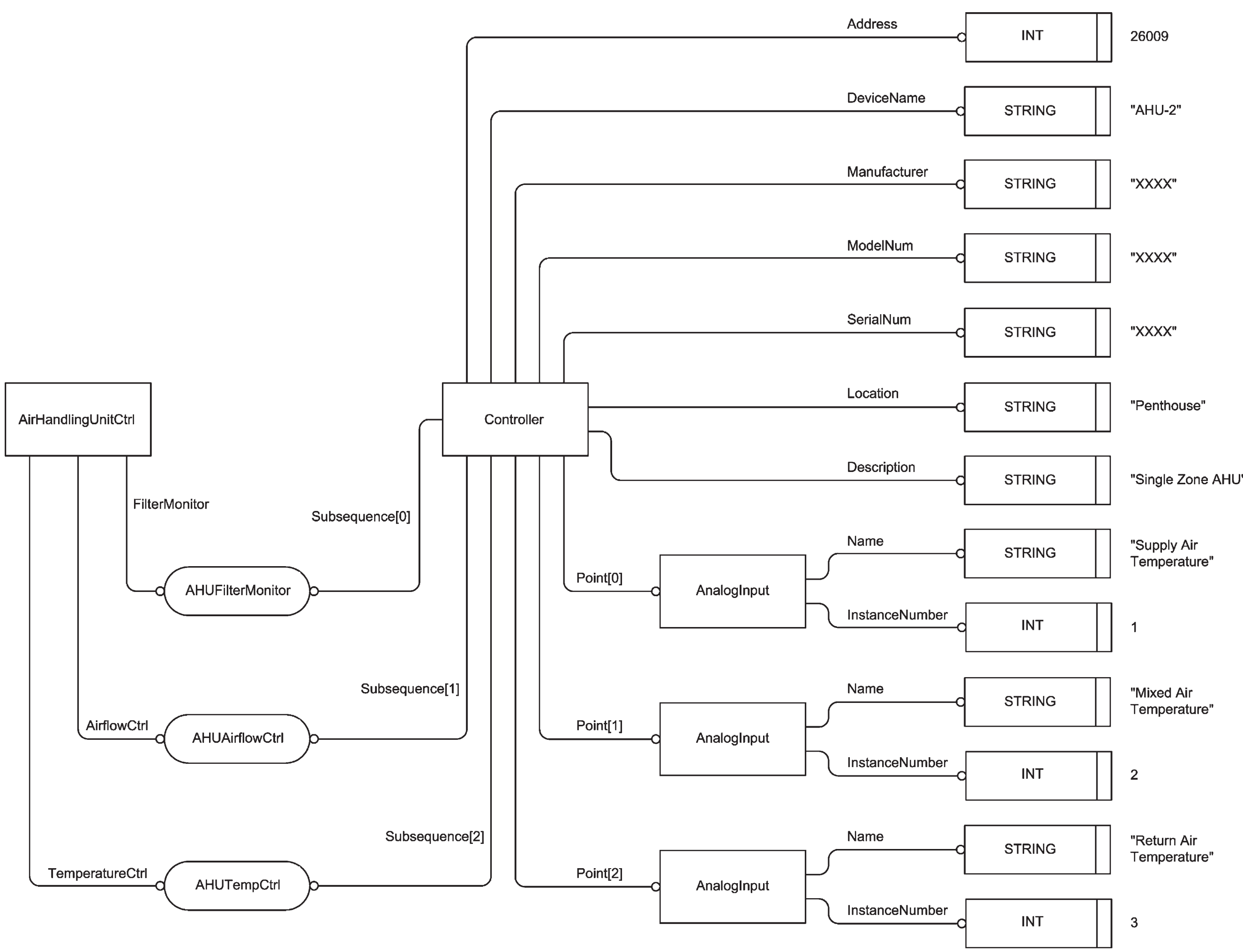

Fig. 11. Air handling unit schematic diagram used for experimental implementation.

equipment controller, each of which is represented by a Controller entity. The network and device entities have additional attributes which are not shown in Fig. 10.

The model representation of one of the controllers in the system, controlling a single-zone AHU, is explored in more detail. Fig. 11 is a schematic diagram of the AHU. The constant-speed supply and return fans are each monitored by differential pressure switches, as is the filter bank. The heating coil valve, cooling coil valve, and economizer are modulated in sequence to maintain the room temperature at the setpoint. The outdoor air temperature (obtained from another controller via the MS/TP network) is compared to a fixed changeover temperature to determine whether to enable economizer operation. Supply, return, and mixed air temperature sensors are used for diagnostics and troubleshooting, but not for control.

The model representation of this controller and its operation is shown in Figs. 12–15. Fig. 12 starts with the Controller entity (one of the 91 Controllers from Fig. 10) and the SequenceOfOperation entity for the AHU. The filter, airflow control, and temperature control subsequences are each attributes of both the Controller and SequenceOfOperation entities, since in this case, there is a one-to-one correspondence between them. The Controller entity also has attributes inherited from the Device entity and a set of three Point attributes, representing the supply, return, and mixed air temperature sensors. The optional attributes appear as normal attributes if they are present; if they are not present, then they do not appear at all. The details of the filter monitoring, airflow control, and temperature control subsequences are shown in Figs. 13–15, respectively. Beside each simple data type attribute (integer or string) is its value.

4. Conclusion

An information model of a BAS was created, encompassing the device list, network topology, points list, and sequences of operation. This model allows a persistent representation of the BAS from system specification through design to operation and maintenance. It provides an open, standard exchange format

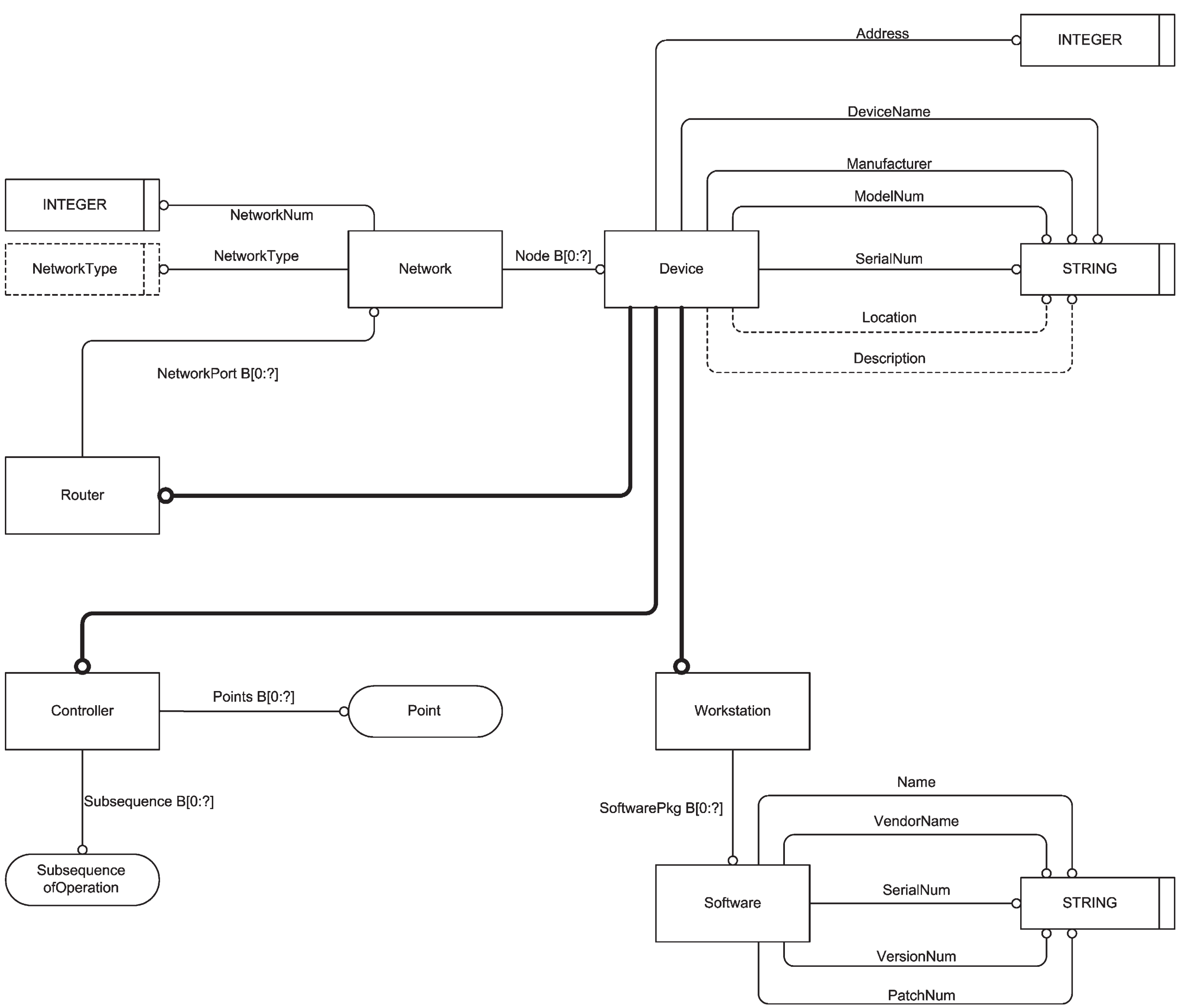

Fig. 12. Experimental model representation of air handling unit controller and sequence of operations.

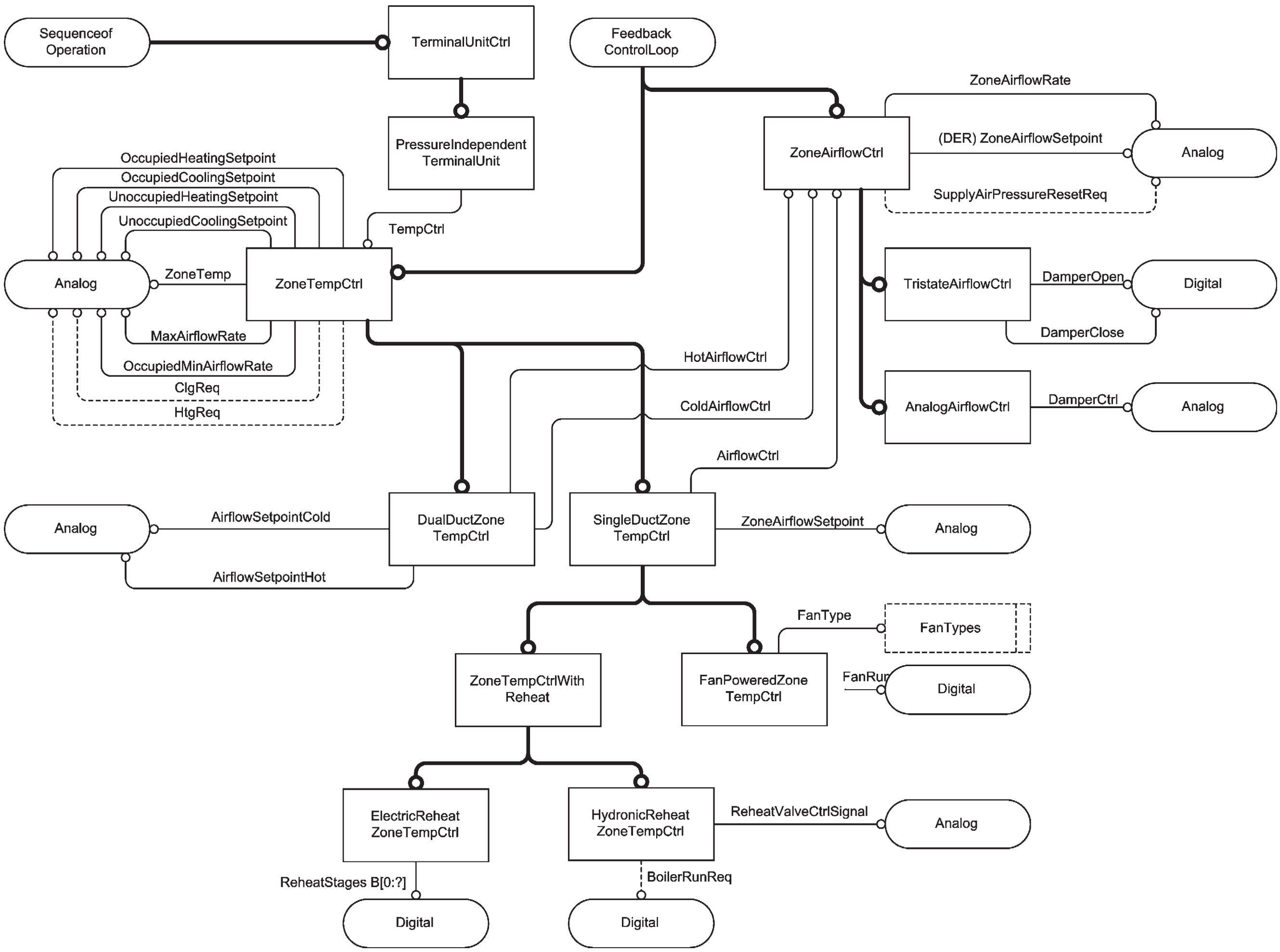

Fig. 13. Experimental model representation of air handling unit filter monitoring subsequence.

allowing software tools to be developed to enable the exchange of information between the MEP engineer, control system integrator, building engineer, maintenance contractor, commissioning agent, and energy consultant. The model was tested by creating an experimental implementation based on a BAS installed in a medium-sized office building.

Additional work is needed to develop more sequences of operation for different types of terminal units, AHUs, and chiller and boiler plants. New sequences are also needed for other common building equipment including fan coil units, unit ventilators, heat pumps, cooling towers, and lighting. The model should be enhanced to include typical automation functions such as alarms, trend logs, and schedules. In addition, software applications should be developed to exchange information using the exchange format provided by the model. Development and use of such software could be encouraged by modifying an existing information exchange standard, such as the Industry Foundation Classes [4], to include the BAS information model.

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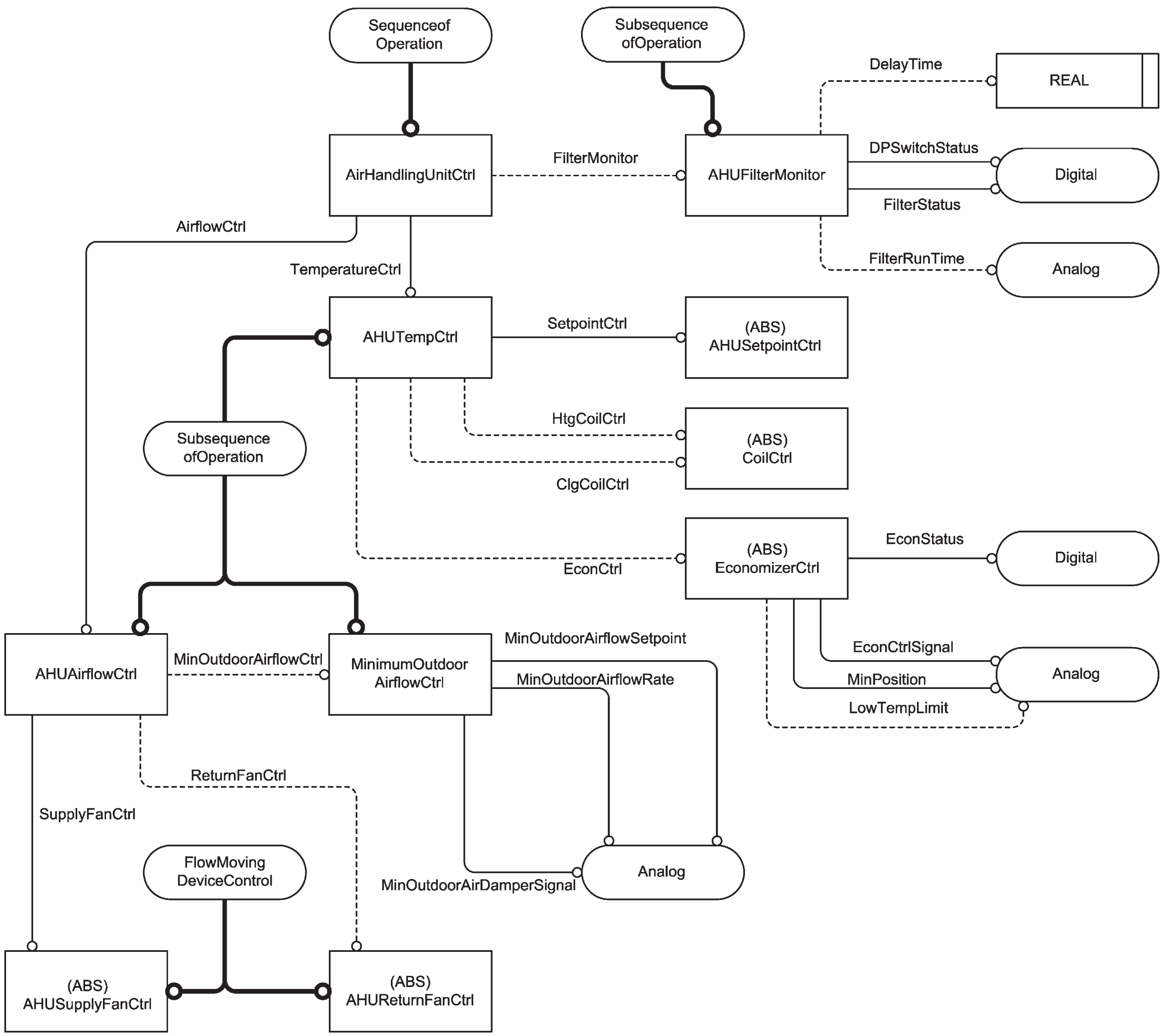

Fig. 14. Experimental model representation of air handling unit airflow control subsequence.

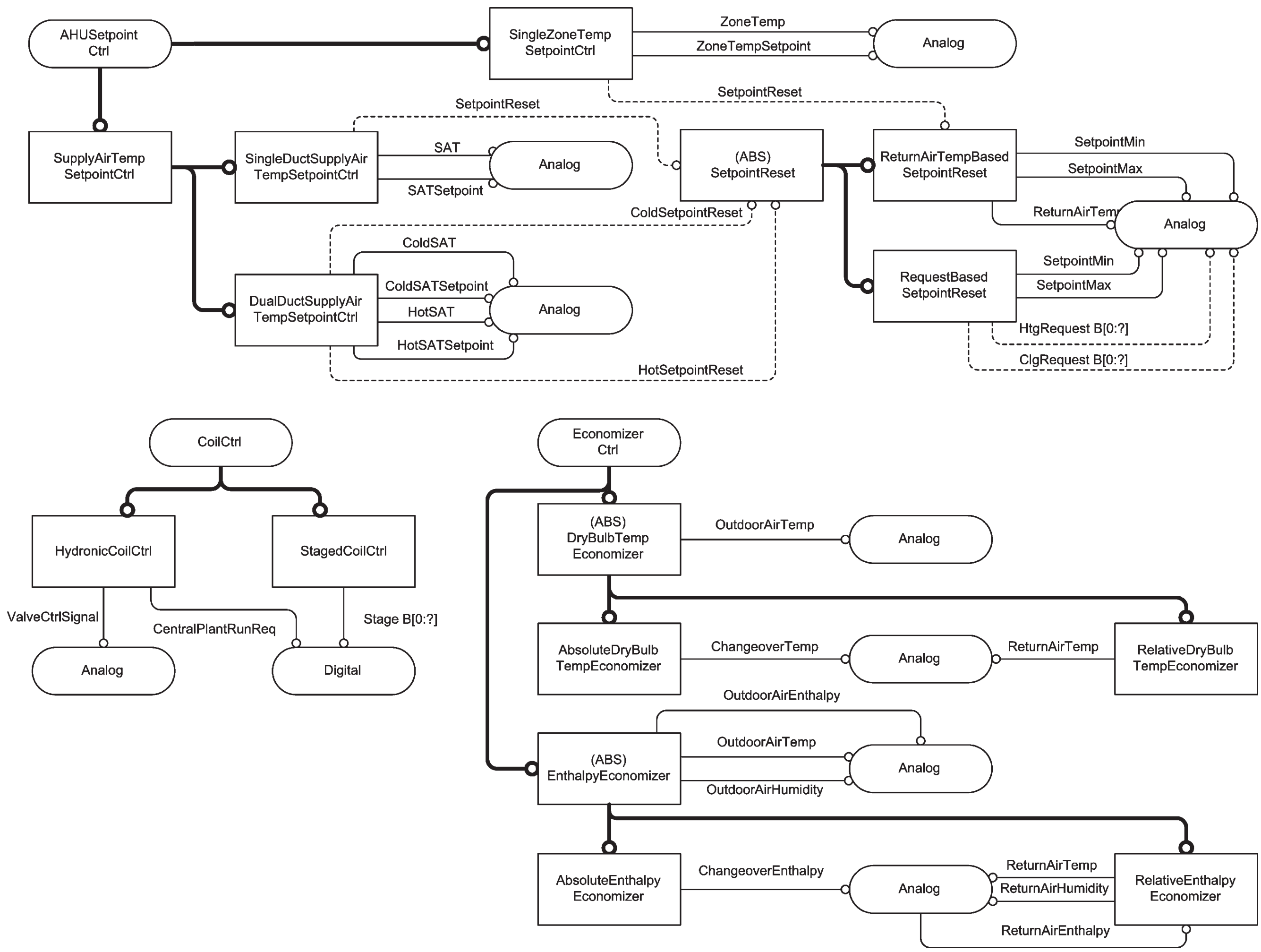

Fig. 15. Experimental model representation of air handling unit temperature control subsequence.