A FRAMEWORK FOR BUILDING INFORMATION FUSION

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ABSTRACT

Data reported by supervisory control and data acquisition (SCADA) systems is critical for evaluating the as-operated performance of a facility. Typically these systems are designed to support specific control domains, but facility performance analysis requires the fusion of data across these domains. Since a facility may have several disparate, closed-loop SCADA systems, resolution of data interoperability issues (heterogeneities) is a prerequisite to cross-domain data fusion. There are no general methods for resolving these heterogeneities in the context of a nonproprietary core building information model (BIM) format. This article describes how these standard data models are applied to a general framework for the integration of building information models and building sensor telemetry. Given the number of very large corporations, each with its own research agendas and proprietary products, and the large number of installed buildings, each with its own control systems, yet another control scheme or technology will not make an impact on improving this market. The authors propose solutions to these underlying data heterogeneities by adopting existing data standards and introducing new data schemas (only when necessary) based on consensus between industry, government, and academic stakeholders. The Industry Foundation Class (IFC) 2X4 controls domain is the foundation of the authors' decomposition of SCADA systems as components, assemblies, and connections that relate to other objects in the facility. The Open Building Information eXchange (oBIX) provides the basis for the authors' representation of raw telemetry streams that map to the underlying IFC model. The system concept described in this article is part of an effort that is expected to produce an Industry Foundation Class Model View Definition (MVD) for building SCADA systems, product type templates for building SCADA products, the architectural design of an integration platform, and the specification of common predictive and analytical functions for deriving usable intelligence from the integration framework.

Keywords: Smart Buildings, Data Fusion, Building Controls and Automation, Building Information Modeling (BIM), Industry Foundation Classes IFC

1. BACKGROUND

Approximately $15.8 billion of annual U.S. capital facility industry efficiency losses are due to inadequate interoperability in design, engineering, facilities management, and business process software systems, as well as redundant paper records management (Gallaher et al. 2004). The Department of Defense, the majority stakeholder in the U.S. federal capital facility industry, is responsible for approximately 560,000 facilities worldwide and 247,000 facilities in the United States. The majority of building life-cycle cost occurs in the operations and maintenance (O&M) phase, and these O&M costs increase annually as the building ages. Handover data and building information models (BIM) from the design and construction phases may be provided to O&M stakeholders in standard formats. However, this information is underutilized because it is typically not considered during the design of facility management information systems for auditing, scheduling, and reporting. Some buildings collect valuable data through various Supervisory Control and Data Acquisition (SCADA) systems, but today's specifications for multiple, individual, customized building SCADA systems focus only on individual disciplines such as HVAC, electrical, security, etc.. Thus there is no interoperability even among the most sophisticated systems. Furthermore, monitoring systems often collect data from numerous raw data streams that can quickly overwhelm a domain analyst (information overload). As a result, evaluating building equipment and occupant behaviors against as-designed and as-built building information models is a labor-intensive, cost-prohibitive activity that requires domain experts and is not practical for use in a facility management building control cycle.

2. INTRODUCTION

Multisensor data fusion is a process that combines parts into wholes to generate estimations and predictions with a higher degree of certainty, accuracy, completeness, and representation (i.e., level of abstraction) (Mitchell 2007). Ideally, multisensor data fusion for buildings will provide new, valuable knowledge that facility engineers may immediately incorporate into their control cycle or decision-making process. Delivering those results requires data fusion at the individual sensor level (realizing system information), fusion of information between systems, and fusion of system dependencies and operational knowledge. While there are computational approaches for inferring multilevel dependencies (e.g.. Bayesian networks), the state of the art in capital facilities industry data model interoperability is only beginning to provide the pre-requisite schema mapping support necessary for large-scale, generic data fusion between heterogeneous data sources.

A number of ongoing efforts could enable data fusion applications by resolving interoperability issues relevant to the schema mapping stage of integration. Existing works have promoted BIM interoperability through data representations (East 2007; East 2009; East 2010; IAI 2010; Lee et al. 2007; Lin and Soibelman 2006; Lipman and Reed 2000; OASIS 2006 Organization for the Advancement of Structured Information Standards), schema transformations (Beetz et al. 2009; Bogen and East 2011; Nisbet and East 2009; Wang et al. 2009), and domain-specific applications (Ko 2009; Lydon et al. 2005; Zhang et al. 2009). There are also conceptual representations of BIM system frameworks that facilitate total building life-cycle integration by defining standard BIM schemas and encapsulating and logically organizing BIM representations, transformations, and domain-specific applications (East 2007; East et al. 2010; East et al. 2009; Succar 2009).

In the sensors, automation, and control domain, interoperability standards have been introduced to address interoperability at various levels of abstraction: LonWorks (LonMark 2005), BACnet (Bushby 1997), oBIX (OASIS 2006), and SensorML (Open Geospatial Consortium Inc. 2007) LONWORKS and BACNET are data communication protocols designed specifically for building automation and control networks on local area networks (LAN). oBIX is designed to be the vehicle by which BACNET and LONWORKS systems are exposed to the Internet – i.e. the TCP/IP layer. SensorML originated from the OpenGIS community and provides an XML schema for representing the geometric and observational characteristics of sensor systems in their geospatial context. Finally, the recent IFC2X4 release candidate (RC) 2 provides the *Building Controls Domain* (buildingSMART International 2011) with elements and property sets for products such as sensors, actuators, controllers, alarms, and unitary control elements (e.g., thermostats).

There are numerous applications of sensor network technologies to address building monitoring and control problems such as campuswide sensor networks (Rowe et al. 2009), alert reporting for first responders (Vinh 2008), fall hazard detection (Navon and Kolton 2007), and virtual building testbeds (Bushby et al. 2010). Such applications of building automation and control technology illustrate the utility of building telemetry while recognizing the potential for more substantial integration with BIM.

3. PROBLEM STATEMENT

Current facility monitoring applications capitalize on the advances in control system hardware interoperability and availability of affordable sensors. Integrating this telemetry with BIM can enrich complex data fusion and data mining algorithms by considering relations and facets across multiple perspectives – e.g. architectural, mechanical, electrical, energy analysis, and facility operations and maintenance (O&M). Typically this integration requires custom data mapping structures (e.g. a database) to relate building monitoring/control system schematics, spatial aspects of the building, attributes of the building equipment/resources, the intended use of building spaces, and sensor telemetry. The recent introduction of the IFC *Building Controls Domain* provides a new alternative approach that allows for multi-faceted modeling of SCADA systems in an open BIM model. Because these schemata are new, there is a minimal amount of guidance documentation for its practical applications – and there are no SCADA tools for exporting these models. Furthermore, there are no information exchange requirements and application scenarios for IFC *Building Controls Domain* models in a facility life cycle. Finally, there are no experimental methods for relating IFC *Building Controls Domain* models to telemetry data models. The authors' goal is to fill some of these gaps by addressing the following problems:

- Capturing building automation and control product data in the context of building life-cycle data exchanges and the nuances of the product manufacturing industry
- Defining the necessary level of detail to represent building control and automation or SCADA systems in the IFC 2X4
- Relating raw telemetry streams to their corresponding BIM-integrated metadata structures
- Evaluating general pre-processing approaches for first-order analysis (level 0 data fusion) on building telemetry - to provide reliable approaches for reporting high-level performance history results in a corresponding IFC model

4. APPROACH: BUILDING INFORMATION FUSION FRAMEWORK

The authors present a building information fusion framework (BIFF) by considering data exchanges between IFC2X4 BIM model views and oBIX representations of data collected from building automation and domain-specific telemetry systems (BACNET, LONWORKS, etc.). A typical design coordination view Industry Foundation Class (IFC) model does not usually contain detailed information about building automation and controls systems. To provide spatially referenced descriptions of SCADA components, assemblies, and connections, the BIFF includes two existing IFC2X4 model view definitions (MVDs), design coordination and facility management handover, while proposing a new MVD, SCADA View. The roles of each model view are as follows:

- Design Coordination View represents spatial boundaries, structural elements, and geometries.
- Facility Management (FM) Handover View provides descriptions of specific product components that are related to spaces (or elements) in the Design Coordination View.
- SCADA View describes the components, assemblies, and connections between building automation and control products related to spatial elements in the Design Coordination View. The automation and control products in the SCADA View may also reference less detailed descriptions of components and assemblies in the FM Handover View.

oBIX was selected as the common representation of data generated by the materialized elements of the SCADA View model because of its equal consideration of building telemetry modelling and the TCP/IP (Internet) delivery of the data–through a generic Representational State Transfer (REST) software service architecture. The BIFF provides schema mapping by assuming traceability (through globally unique identifiers, GUIDs) between the oBIX and IFC artifacts the BIFF. As a final consideration, the BIFF prepares for the data fusion stage by providing generic telemetry stream processing methods for pattern matching and anomaly detection. Figure 1 represents a conceptual model of the BIFF by illustrating the flow of information from stakeholders, to design tools, referentially consistent IFC/oBIX models, and, finally, to data fusion products.

The authors are beginning to realize the BIFF concept by developing SCADA product data exchanges (Section 4.1), specifying an initial IFC SCADA MVD (Section 4.2), designing IFC-friendly oBIX contracts (Section 4.3), and evaluating generic approaches to telemetry data generation, pattern matching, and anomaly detection (Section 4.4).

4.1 SCADA Product Data Exchanges

The FM Handover model view provides a generic way to represent product components and assemblies, and, to some extent, connections. Since the IFC has recently expanded to provide substantial coverage for *Building Control Domain* elements (i.e., SCADA products), work was conducted to develop a way to populate IFC models from Construction Operations Building Information Exchange (COBie) 2.3 (Nisbet and East 2011) product templates. An initial set of COBie SCADA product type templates was developed based on element types and property sets in the existing IFC2X4 Building Control Domain. Nisbet and East (2009) provide *bimServices* transformations to transform between COBie and IFC files.

To develop practical SCADA product type templates the authors formed a building automation and control group within the context of the larger Specifiers' Properties Information Exchange (SPie) initiative (East 2010). The SPie provides a framework for manufacturers to work with the buildingSMART alliance to create practical open product type schemas because manufacturers are the ones who ultimately own and control product information. The authors introduced the group to examples of specific product components and assemblies represented using COBie with transformation support from bimServices (Nisbet and East 2009). Manufacturers were invited to participate in the SPie process to refine product type templates and ultimately realize a transformation of their mostly unstructured product data publications (e.g., .PDF specification sheets) into ifcXML.

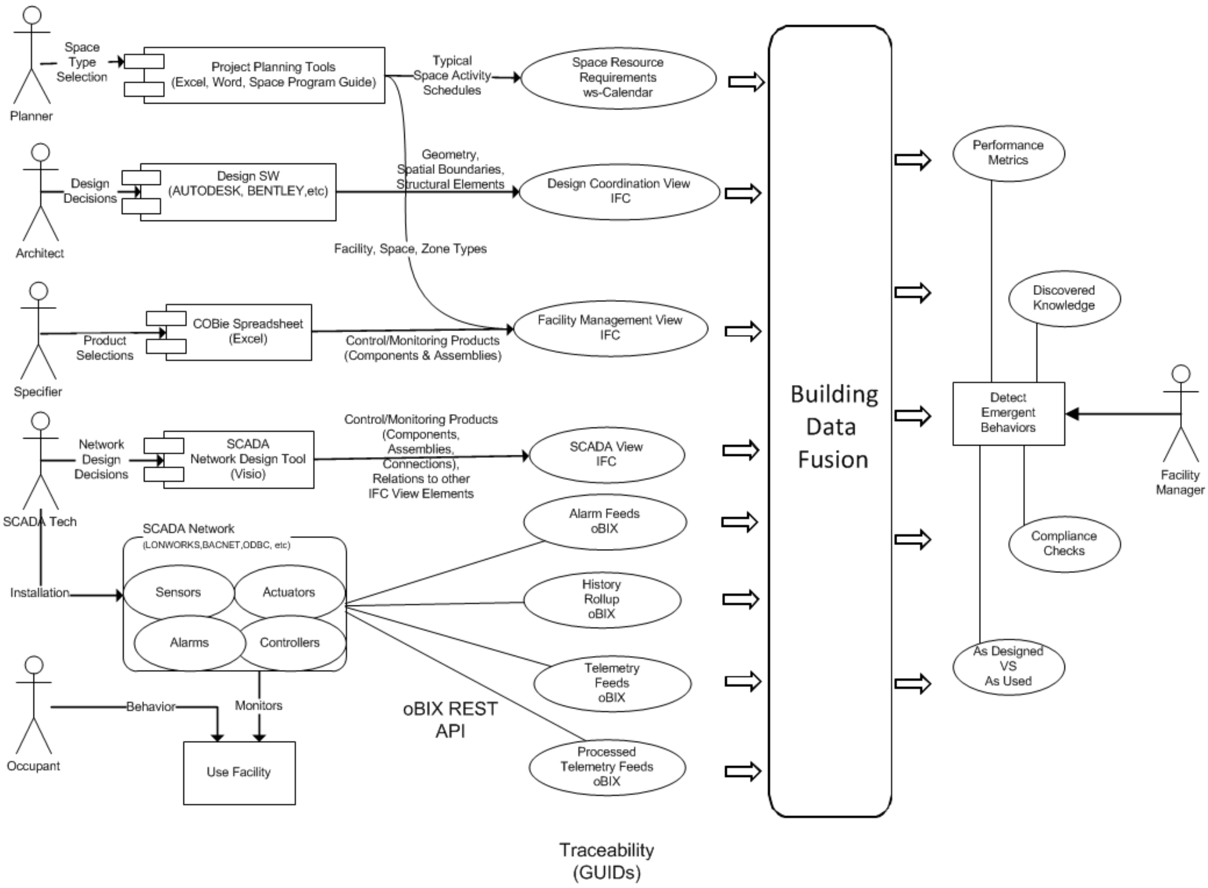

Figure 1: Building data fusion conceptual diagram

While realizing the initial product templates, the authors made some decisions about the scope of the SCADA product type attributes, identified necessary changes to the COBie 2.3 specification, and refined *bimServices* transformation:

- The *ElectricalDeviceCommon* property set from the IFC Electrical Domain was included in all SCADA product type templates. This electrical property set provided properties for such common product characteristic as current, voltage, and insulation class. While the existing IFC2X4 guidance for Building Control Domain elements does not directly prescribe the use of the *ElectricalDeviceCommon* property set, it is allowed by the IFC inheritance graph, and seems consistent with properties listed on manufacturer specification sheets.
- An "SPie Toolkit" was developed around *bimServices* to generate COBie 2.3 product type templates automatically based on reconfigurable property set mappings
- COBie 2.3 worksheet specifications were modified to

- Describe attributes about product ports (*IfcDistributionPort*) that represent the input and output terminals available on a device
- Connect entities through specific types of *IfcDistributionPort* entities
- Represent *IfcPropertyTableValue* data types that are used in some Building Controls Domain property sets (e.g., *Pset_ControllerTypeFloating*).

4.2 SCADA Model View Definition (MVD)

The IFC SCADA MVD will define how data about supervisory control and data acquisition (SCADA) systems may be exchanged between the design and operations stages of a building cycle. The product types covered in this model view are defined in the IFC 2X4 Building Controls Domain as unitary control elements, sensors, actuators, flow instruments, and alarms. The authors are producing sample models that will conform to the MVD such that they may be used in various project demonstrations and experiments. The scope of this view provides details about building SCADA systems at multiple levels:

1. Components & Assemblies: information provided by manufacturers that specify the operational specifications of a product. This information is provided at a sufficient level of detail suitable for product specifiers and manufacturers.
2. Connections (logical & physical): The logical and physical connections between SCADA system elements are modeled such that a system schematic may be derived and spatial relationships to architectural elements and spaces are specified.
3. Addresses: There are references to SCADA data structures that may occur in access protocols such as BACNet, LONworks, and oBIX. This information should be sufficient to allow programmatic access to live data streams, alarms, queries, histories, etc.
4. Configuration: Control system configurations may be captured including parameters for digital and analog inputs, programs for control loops, alarm/event handling, and time schedules.
5. Performance: Real-time or simulated data from sensors and alarm events may be captured and used as feedback into design or operations for evaluating efficiency of buildings and equipment.

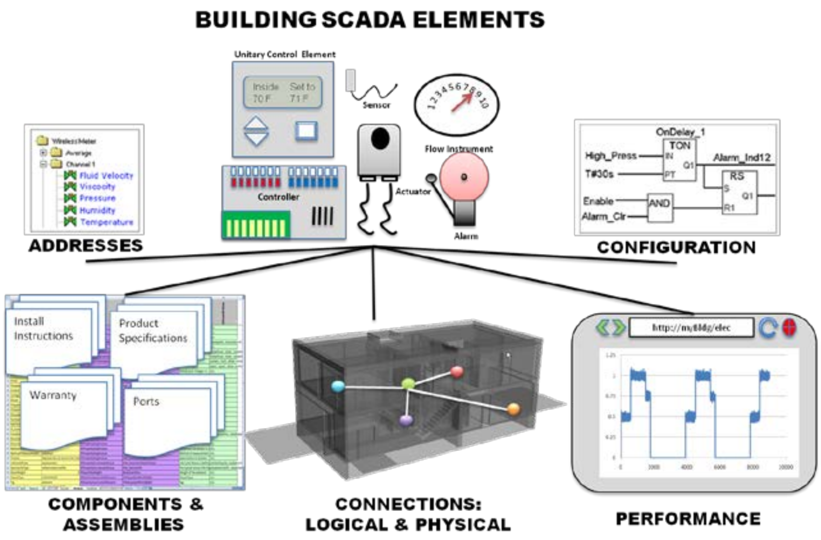

Figure 2: IFC SCADA MVD Scope

4.3 oBIX Contracts

The oBIX specification (OASIS OASIS 2006) includes a collection of foundational data types and a library of simple data structures known as *contracts*. The oBIX xsd schema includes fundamental elements such as Boolean (bool), enumeration (enum), error (err), and event feeds (feed). The oBIX specification is also accompanied by a library of standard contracts to represent concepts such as data points (Point), historical data (History), alerts/alarms (Alarm), and data subscriptions (Watch). Two key capabilities are not provided in the core set of oBIX that will be addressed by the BIFF:

- Contracts that relate telemetry data to elements in corresponding IFC BIM
- Contracts that represent normal state conditions for a corresponding space/zone and its usage schedule to enable a collection of reusable, generic alarm evaluation Web services.

Figure 3 illustrates a partial oBIX class (or contract) diagram where bold-face objects represent custom oBIX contracts that may be implemented to relate the telemetry to the IFC model. Item 1 will be fulfilled by implementing the IFC's *ifcRelAssociates* objectified relationship in oBIX and referencing it in a specialized *ifcPoint oBIX* contract. Item 2 will be fulfilled by first defining a format to represent space/zone requirements for lighting, electricity, water, equipment, and spatial footprint–*SpaceRequirement*. The representation of normal state conditions must allow for various combinations of sensory and temporal constraints. For example: *during the months of June and July, a temperature of 70 degrees Fahrenheit should be maintained in the building's executive office during the hours of 8:00 am-5:00 pm Monday-Sunday, but can reach as high as 75 degrees Fahrenheit otherwise*. The *SpaceRequiremnt* contract may represent a normal state of a space, and this provides a way to evaluate programmatically the planned usage requirements against actual performance. To illustrate this concept, the *SpaceUseAlarm* contract is modeled and would include a generic evaluation function to compare the current time and sensor data to the space use constraints. The open-source oX framework application programmer interface (API) and server software will be used to test these concepts when the design of the contracts is further refined and complete (Michalek 2010).

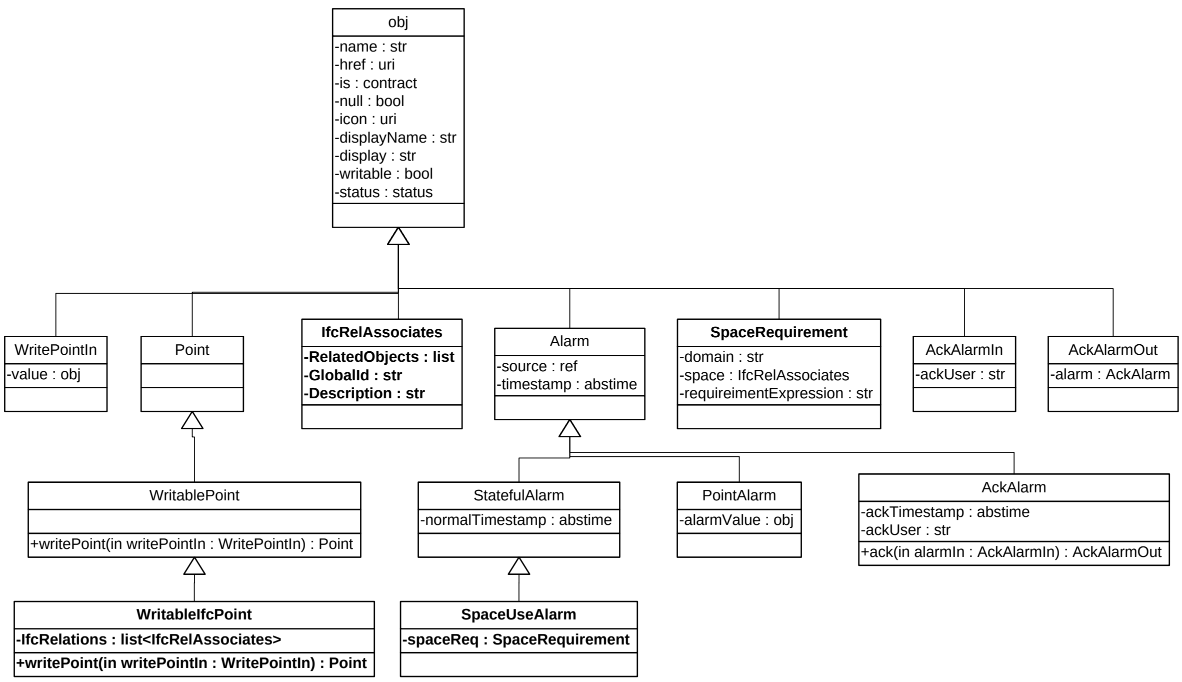

Figure 3: Partial IFC relevant oBIX class (contract) diagram

4.4 Level 0 Data Fusion for Building Telemetry

The primary motivation for the BIFF's pre-fusion analysis services is to provide a generic set of tools for filtering telemetry streams, removing noise, and extracting dominant patterns. Such analysis capabilities are required to efficiently filter volumes of data obtained from systems that provide building power management, heating ventilation and cooling (HVAC), water distribution, and other mission-critical domains. The authors are evaluating the application of Fast Fourier Transforms (FFT)

(Cooley and Tukey 1965) and clustering algorithms for extraction of periodic device usage patterns (daily, weekly, monthly, etc); . This processing approach, illustrated in Figure 4 may be considered as level 0 data fusion approaches (Hall and Steinberg 2001) that normalize and filter data before the later stages of multisensory data fusion.

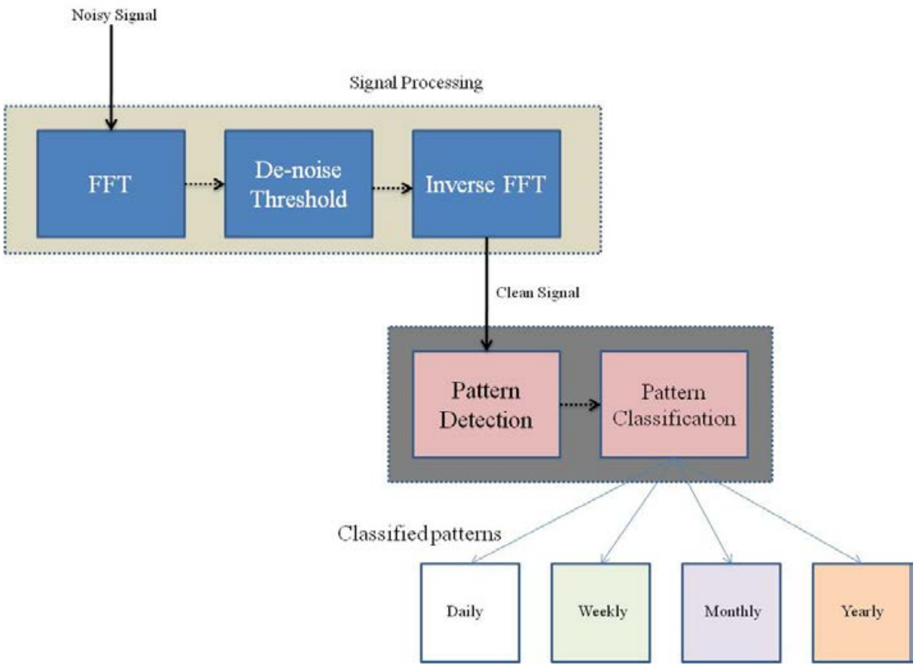

Figure 4: Level 0 Multisensor Data Fusion Approach (Pre-Processing)

Experiments will be performed to observe how the processing algorithm behaves under with variations in configuration conditions (i.e. parameters) and signal to noise variations on the frequency, amplitude, and duration of device usage patterns. The goal of these experiments is to determine effective processing approaches that will enable first-order, sensor-level analysis to compare actual behavior with expected resource usage as defined by planning and design artifacts. Initially these experiments will be run on a synthetic data generator with random introduction of noise. Later these experiments will be repeated on actual telemetry data. After these low-level fusion approaches are fully evaluated, the most useful techniques will be implemented and deployed as extensions to the open-source oBIX server, oX Server, and extracted patterns may be published to IFC SCADA View models as rolled-up performance history tables. These performance history tables could be visualized in their spatial context (e.g. color coding zones by energy usage) through IFC model viewer plug-ins.

5. CONCLUSIONS

The authors' building information fusion framework illustrates how building data models may be aligned across multiple domains–architecture, facility engineering, and SCADA. Such schema mapping approaches are necessary to enable large-scale, multisensor data fusion for intelligent buildings. The authors are overcoming some of the inherent challenges by

- Building consensus between government, industry, and academia on automation and control product type templates through the SPie
- Specifying an appropriate level of building automation/monitoring/control system metadata in a BIM by documenting a SCADA IFC MVD
- Designing oBIX data types that reference telemetry data streams to specific components, assemblies, and connections in the IFC model

- Representing space/zone usage requirements in oBIX so that they may be compared to telemetry streams in generic oBIX alarm evaluation functions
- Experimenting with first-order telemetry analysis for extracting behavioural patterns that may be compared against planned space resource consumption schedules

Product modeling efforts such as SPie produce relatively straightforward results, but they involve a substantial amount of collaborative, detail-oriented efforts between industry, academia, and government. Such consensus building activities are required to realize practical models or standards that will have the most impact on intelligent, multisensor data fusion approaches; otherwise, it is likely that domain-specific application developers will introduce work-around solutions for relating BIM data views.

6. RECOMMENDATIONS

A data fusion framework prototype should be implemented using existing IFC and oBIX tools to evaluate the feasibility of the approach. Experiments must be conducted to evaluate the performance of the data fusion framework on a variety of building models and integration cases; the authors are planning experiments on building models for a duplex apartment, an office building, and a hospital. Existing telemetry data should be collected, when possible, from existing sources to indicate typical energy consumption cycles of building systems–e.g., HVAC systems. When it is not possible to use real data, synthetic data must be generated based on device characteristics and sound mathematic/statistical algorithms. While the SPie efforts have successfully provided initial results, additional participation from automation, monitoring, and controls manufacturers is required to provide a more definitive definition of product type templates; and possibly influence the IFC building control domain entities and property sets.

ACKNOWLEDGMENTS

The authors would like to acknowledge Toby Considine of TC9, Inc., for informing us about current oBIX events, Nicholas Nesbit of AEC3 for his IFC and COBie expertise, and Tim Chipman of Constructivity.com (LLC) for answering questions about the new IFC2X4 controls domain elements/properties.

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