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EFRI-SEED Preliminary Proposal Summary

Building-Integrated Information Technology: A Unified Engineering and Architectural Framework for Sustainable Design

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Building-integrated information technology (BIIT) distributes IT hardware such as user workstations, display devices, and commercial or scientific high performance computing servers throughout an institution (e.g., a campus of buildings or municipality) instead of consolidating the hardware in a single, centralized facility. The BIIT nodes operate in synergy with the energy requirements and capabilities of each building to deliver recoverable waste heat to offset a building's energy requirements and to utilize free cooling from the building. However, to be ***truly integrated***, the deployment of BIIT nodes in a building must consider the optimal engineering solution and potential impact on architectural form (function, usability, scale) in parallel. **The goal of this research program is to establish the method for optimizing BIIT implementation by developing a unified architectural and engineering modeling framework that quantitatively assesses IT integration in sustainable building design.** This will be accomplished through four objectives:

(1) Establish a unifying modeling framework that simultaneously addresses engineering and architectural concerns.

(2) Validate the model against a BIIT prototype from a current collaboration between the University of Notre Dame and the City of South Bend, Indiana.

(3) Conduct case study optimizations of BIIT-enhanced building retrofits and new designs using the model to optimize energy performance and architectural function.

(4) Conduct a case study on the design of a large-scale BIIT-enhanced institution (university campus) to demonstrate practical implementation and control on a large scale.

Intellectual Merit

The intellectual merit of this proposal is that it will establish a new approach to the operation and deployment of IT hardware where buildings and information technology (IT) infrastructure interact in a sustainable, energy efficient way. It will also establish a method to unify architectural and engineering design approaches, extending cross-disciplinary interaction between architecture and engineering to achieve truly integrated, sustainable building design.

Broader Impact

Nearly $5 billion dollars is spent annually in the United States to operate and cool HPC hardware. Not only will BIIT will have a direct impact on energy conservation and fossil fuel consumption by both buildings and IT hardware, but solutions such as BIIT will provide a new paradigm for sustainable building in which the distribution framework for IT serves as a catalyst for identifying other sources of heat recovery. Direct integration of this research into courses and applied research will also establish collaboration in architectural and engineering education.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

EFRI-SEED Preliminary Proposal Description
Building-Integrated Information Technology: A Unified Engineering and Architectural Framework for Sustainable Design

1. Vision and Goals

In order for the United States to address the grand challenges of energy security, global climate change, and energy availability, new sustainable design practices and technologies must be developed and integrated with existing passive design principles. Passive heating technologies, such as solar and geothermal sources, can be a critical element in sustainable design practice because of the potential to capitalize on unutilized, existing energy sources. One practice of passive heating is heat recovery, which recovers and reutilizes excess heat from a resident system. In collaboration between the University of Notre Dame and the City of South Bend, Indiana, the excess heat from high performance computing (HPC) hardware (e.g., servers) is being utilized to heat a building. By integrating the HPC hardware from the computing grid with the building, this new, passive heating source helps offset the centralized heating requirements of the building – an example of **building-integrated information technology (BIIT)**.

BIIT is a new concept for autonomy and interdependence where building and information technology (IT) infrastructure interact in a sustainable, energy efficient way. Further, BIIT is a radical approach to the sustainable implementation of IT, where hardware resources are distributed across a collection of buildings or an institution rather than being consolidated into large, centralized facilities. These BIIT nodes can be used as elements of a distributed computing *and* heating grid to help offset the energy needs of the buildings, and cooling resources from the buildings can be used to help maintain the IT hardware. To that end, BIIT essentially solves two major problems – it reduces the fossil fuel energy needs of BIIT-enhanced buildings and also more efficiently operates IT hardware. However, for IT to be ***truly integrated*** with a building or buildings, three essential implementation questions must be addressed by the engineering and architecture team:

(1) How can BIIT be integrated into existing durable building stock in ways that limit the impact on architectural form and the function of a building, limiting adverse affect, direct or perceived, on the building occupants?

(2) What is the potential for a technology such as BIIT to contribute to optimized form-generation (of new buildings) in concert with other existing passive design strategies (*e.g.*, building location, orientation, massing, materiality, and other bioclimatic responses)?

(3) How should BIIT be controlled within a building or across a collection of buildings such that it meets the requirements of ***both*** the IT (*e.g.*, computing) users and building occupants?

We propose that for any real success in practical implementation, architectural concerns (function, usability, scale, character, habitability, etc.) must be assessed and weighed *in-line* with the optimized engineering solution. **The goal of this research program is to establish the method for optimizing BIIT implementation by developing a unified architectural and engineering modeling framework that quantitatively assesses IT integration in sustainable building design.** The over-arching principle of this model is to determine a measureable building 'signature' that is based on both energy performance and architectural form. This unified framework will then be applied to BIIT to assess the overall impact of BIIT and establish guidelines for optimizing BIIT implementation. The objectives of this research program are:

(1) Establish a unifying modeling framework that simultaneously addresses engineering and architectural concerns.
(2) Validate the model against a BIIT prototype from a current collaboration between the University of Notre Dame and the City of South Bend, Indiana.
(3) Conduct case study optimizations of BIIT-enhanced building retrofits and new designs using the model to optimize energy performance and architectural function.
(4) Conduct a case study on the design of a large-scale BIIT-enhanced institution (university campus) to demonstrate practical implementation and control on a large scale.

2. Approach and Methodology

From an engineering perspective, BIIT only considers the aggregated interactions between IT users, a building's heating requirements, and the IT hardware cooling requirements. Placing BIIT nodes within a building, however, raises important concerns regarding utilization of space , occupant perception, and existing infrastructure. For instance, the heat generated by the BIIT nodes is usually low-grade and must be consumed locally within the building. This means the placement of BIIT nodes must take into account the building's existing heating, ventilation, and air conditioning (HVAC) infrastructure (for a retrofit) or be designed in tandem with the HVAC system (for a new building). Additionally, to be *truly integrated*, the BIIT nodes should have minimal impact on occupants' space or perception of the space. For instance, if BIIT nodes break up usable and desirable public spaces in a building, the overall footprint of that building may need to be increased to compensate for lost usable space, or, in the case of a retrofit, the value of the building to its occupants may be degraded to the point where occupancy declines. The challenge, therefore, involves determining how to integrate the evaluation of architectural values into the framework of an engineering model in such a way that all concerns can be weighed equally and integrated into the design or retrofit of BIIT-enhanced buildings.

2.1 Overview of Unifying Modeling Framework

In most engineering systems, the performance of the system can be quantified by an efficiency η. For different engineering systems in a building, different efficiencies can be assigned (for example a thermal efficiency, electrical efficiency, etc.). The engineering signature of the building, therefore, is a vector quantity consisting of some function of all the sub-system efficiencies or

$$\eta_{engineering} = f\left(\eta_{thermal}, \eta_{eletrical}\right) \tag{1}$$

Often times this function takes the form of a weighted product, but that is not necessarily so. In the same way, we propose that the 'signature' of a building can be similarly described by a vector function of energy (thermal) performance *and* architectural performance. While thermal energy performance can be assessed through a validated thermal model, it is less clear how one quantifies architectural 'performance'. As a simple example, consider the impact of a BIIT node (*e.g.*, a container with multiple HPC server racks) on usable space. If a BIIT node reduces a building's useable area by a factor *x*%, then the space efficiency of the BIIT is

$$\eta_{space} = 1 - x\% \cdot 100 \tag{2}$$

If the building originally had a thermal efficiency of $\eta_{thermal}$ and BIIT reduces the heat required from the HVAC, this results in an improved efficiency of $\eta_{thermal*} > \eta_{thermal}$. The signature of the building, therefore might become

$$\eta_{building*} = \eta_{space}\eta_{thermal*} \tag{3}$$

While this simple model illustrates the unified model approach, it does not fully take into account architectural concerns.

2.2 Model Development

The unified modeling framework we propose is a dual-module approach where the output from each module contributes to determining the signature of the building. The architectural module will assess and develop quantification rules for the architectural 'performance' of a building and the thermal-control module develop a control model to assess and optimize the thermal performance.

***Architectural Module* (Buccellato/Go/Lemmon)**

In addition to prevailing parametric building information modeling (BIM) used to analyze and anticipate building performance (*e.g.*, Ref. [1]), this research will develop new analytical tools to ascertain the potential impact of BIIT emplacement and to formulate a methodology for the integration of BIIT in both existing and new buildings. These analytical tools will generate a new series of metrics to quantify certain characteristics about building space including function, occupant load, occupant need and occupant values (*e.g.*, sense of scale, sightlines to views, quality of lighting, and controllability of local environment) such that the impact of a BIIT emplacement can be mathematically quantified. Whereas some metrics such as physical space are straightforward to quantify, other metrics such as occupant comfort are less direct.

We propose to evaluate those building characteristics that may be most affected through a series of specific quantifiable metrics. Comfort, for instance, might be quantified by first assigning general efficiency values of $\eta = 1$ (good) or $\eta = 0.5$ (bad). This value could then be further refined if the contributing factors to comfort are evaluated more directly. Consider retrofitting a building with BIIT nodes, where the location of the nodes is initially constrained by both practical and energy performance limitations: it must be connected to the centralized HVAC system and duct work and it must be located near to the room(s) it will be helping to heat. If the building contains a large, open floor of cubicles, placing the BIIT somewhere along the existing HVAC ducts may not only impact the physical space, but also decrease the usable space, alter the temperature distribution in the room, affect sightlines, and impact the lighting in the room. For any location and orientation along the existing HVAC duct line, these impacts can be objectively quantified (for example, the percentage of the room with no view of a window) and assigned η factors. When analyzed together, we propose that these characteristics contribute to evaluating the qualitative comfort of a space or series of spaces.

This is the baseline approach in the development of the architectural module, and will require significant collaboration between the architecture (Buccellato) and engineering disciplines (Lemmon/Go), as the quantification of these variables is a transformative concept. Architectural input will be required to guide survey and spatial analysis, design data implementation, and best design practices, while cross-disciplinary simulations are required to assess temperature distributions, sightlines, and other factors.

***Thermal-Control Module* (Go/Lemmon/Brenner)**

Because of the time-variant nature of a building's heating and cooling requirements, defining the thermal efficiency of a building requires understanding the time-averaged performance of the building. In order to properly assess this, a clearer understanding of how BIIT nodes interact with a building, and how this interaction is temporally controlled, is needed. Further, a real implementation of BIIT must also include a control scheme that is coordinated with the building's HVAC system.

However, the introduction of BIIT as part of an HVAC system complicates an already exhausted control system. By itself, an HVAC system attempts to deliver a combination of outside air and conditioned air from air handling units (AHU) in order to maintain a comfortable temperature (68-72 °F [2]) and good air quality (15 ft^3/min per person) *during peak load conditions* based on expected occupancy patterns. Typically, in a large building, the floor plan is separated into zones. The AHU controls air flow rate and the ratio of outside air to return air. AHU controller set points are scheduled on an hour-by-hour basis under expected occupancy patterns. Actual heating loads and air quality, however can vary randomly from expected peak values and this variation is handled by zone controls which adjust damper positions and reheating elements in the HVAC systems' terminal box. Traditionally, these zonal controllers and AHU controllers work independently of each other, thereby resulting in poor energy efficiency and possibly poor health or comfort of building occupants.

The introduction of BIIT nodes as reheating elements in the HVAC systems' terminal boxes is complicated by the time-varying nature of the BIIT node's activity. BIIT nodes produce heat as a by-product of computational loads, but the computational load distribution can fluctuate over time. A major challenge faced in this project is the control of the building's existing HVAC system in order to make optimal use of the excess heat generated by the BIIT nodes while exceeding health and comfort standards [2]. Similarly, when the BIIT is obtaining free cooling, which may also be time-variant based on the HVAC's production; the computing loads must be accordingly distributed in order to preserve the hardware.

This research program will develop a distributed control model that controls AHU and zone controls while simultaneously dispatching computational loads to BIIT units in a way that optimizes energy usage and computational output. This requires a high degree of coordination between the AHU, zone, and computing dispatch controllers. The high throughput computing software Condor® [3] will be used as the backbone to distribute computing loads underneath the larger umbrella of the building control model, as prior studies by the PIs (Brenner), have shown that Condor® can successfully modulate computing loads to meet a desired thermal control point [4]. A networked system model will be developed to coordinate the activities of the AHU and zonal controllers. Ultimately, the BIIT thermal-control module will mesh three disciplines of engineering – thermal modeling (Go), control modeling (Lemmon), and distributed computing (Brenner).

2.2 Model Validation and Case Studies

Through a collaboration between the University of Notre Dame and the City of South Bend, IN, a prototype BIIT node has been implemented at the City of South Bend Botanical Garden and Greenhouse (BGG) under the direction of Dr. Brenner [4]. This prototype BIIT node contains HPC servers that generate as much as 50 kW of recoverable heat within an 8' wide x 20' long x 8' high container. In this configuration, the BIIT node is placed external to the building (Fig. 1) and is ducted to the BGG. The utility of this prototype is three-fold:

(1) The architectural module techniques will be applied to assess the impact of the prototype on BGG architectural values.

(2) Through detailed measurements, the exact thermal conditions and recovered energy by the BGG can be quantified to validate the building and BIIT thermal models.

(3) The control model will be implemented in the BGG to demonstrate that BIIT can be controlled in such a fashion to enhance building energy performance.

(4) An assessment of the BGG signature and guidelines for optimization will be made.

After validating the model, case studies will be conducted at different scales (single room, multiple BIIT nodes in one building, multiple buildings) to explore the design space of

BIIT-enhanced buildings and identify pathways and recommendations for optimization. These case studies will be conducted within the context of undergraduate and graduate education in the School of Architecture and will consider new and retrofit building projects planned for the University of Notre Dame campus as well as retrofit possibilities in the City of Chicago. Conducting these case studies will require close collaboration between the PIs, graduate students, and undergraduate students: the PIs and graduate students working on the thermal-control module will give guest lectures to architecture students to explain concepts of mathematical optimization and its application in building design, particularly buildings designed to integrate BIIT technology. The architecture and engineering students will work closely together as the thermal-control module is developed to evaluate optimal node placement and generate fully-integrated building designs. Graduate students will be co-advised by both the engineering PIs and architecture PI.

Figure 1 Prototype BIIT node at the BGG.

3. Impact

Unlike current approaches to managing IT hardware, BIIT integrates IT into buildings to create heat where it is already needed, to exploit cooling where it is already available, and to minimize the overall IT *and* building energy consumption of an organization. The wide spread implementation of BIIT will have a transformative effect on the United States energy budget. IT hardware consume more than 3 % of the U.S. electrical budget, and this consumption will only grow as the demand for increased computing capability continues. To that end, the national energy expenditure is proposed to increase by 50 % from 2007 to 2011 [5]. Therefore, there is both a strong economic and strong energy need to readdress how IT hardware are deployed and utilized as information technology continues to impact and shape modern life. This research program will establish that BIIT is not only a valid alternative, but also an essential direction to take for an information-based economy.

The American Physical Society suggests that up to 30 % of the energy used in commercial buildings is wasted [6,7], and it has been shown that HVAC accounts for 50 % of the energy consumed in commercial buildings [8]. Efforts to improve building energy efficiency through the LEED program have achieved limited success [9] with the "lack of innovative controls and monitoring" identified as one the chief obstacles to high energy efficiency. The development of a networked, distributed control model for BIIT deployment and optimization could also set the standard for improved approaches for traditional HVAC systems.

Finally, the *parallel* and *co-dependant* treatment of architectural and engineering requirements in a single quantitative model could prove to be a transformative step in the philosophy of sustainable design. Though both energy [10] and building [1] modeling tools already exist, as new sustainable methods and technologies are discovered, new approaches may be needed to optimize their integration. While not all principles of architectural design can be mathematically optimized, this research will develop quantitatively based guidelines for the sensitive integration of BIIT technology into the built world: guidelines that may also become applicable to other sustainable technologies. By incorporating the development and usage of the unified model into undergraduate and graduate curricula, this research program will establish a new approach the education of engineers and architects, removing the isolation that usually occurs between disciplines and propagating integrated design philosophy in both fields.

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