3) BUILDING ENERGY OPTIMIZATION (BEO)

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**Current Status:**
Building operations account for approximately 40% of US energy usage and carbon emissions [1, 2], and 75% of peak electrical demand [3]. The successful completion of this project thrust will result in the next generation of building energy management systems critical to achieving Net Zero Energy Buildings (NZEB). The crux of this thrust is identifying inefficiencies due to poorly controlled or coordinated energy systems and developing modular distributed predictive control strategies to optimize building energy usage while meeting occupant requirements. Methods and techniques developed under this thrust will be implemented on selected Texas A&M University (TAMU) campus buildings in coordination with TAMU Utilities. This effort will coordinate and leverage research results with the Campus Energy Optimization (CEO) thrust and industrial partners.

Over the past eight years, Texas A&M University has embarked on an aggressive energy conservation campaign, resulting in the following notable results:
- Reduced overall energy use per gross square foot (GSF) on campus by 33%
- Reduced total campus energy consumption by 23% while GSF served increased by 16%
- Achieved $90 million cost avoidance as a result of energy efficiency improvements
- Improved building operating efficiency by 6% per GSF

These achievements were the result of the following building operation improvements:
- Upgraded building automation system (BAS) monitoring and control capabilities
- Installed 1200 utility meters with automated consumption measurement and monitoring
- Implemented new utility rate model, with automated reporting capabilities
- Implemented campus-wide space temperature standard for occupied and unoccupied times
- Completed building energy audits and initiated ongoing a building retro-commissioning program

This project proposes to build upon these successes with a particular emphasis on developing and implementing advanced control strategies for campus buildings. Several recent Dept. of Energy (DOE) and industry reports [4-7] discuss the potential savings of advanced building controls technology, noting that these estimates “have very large uncertainties because of wide ranges in expected market penetration” but that the current market share has exceeded energy economics predictions. A reasonable estimate presented to DOE in [5] reports that these advances in building controls have the potential to reduce energy consumption by **one quad (quadrillion BTUs) annually**. This represents a reduction in carbon emissions of over 16 billion kg annually. The projected campus energy savings resulting from the proposed efforts is uncertain, and quantifying these benefits will be the primary objective of the initial auditing tasks. However, these efforts represent the next major advance in energy saving technologies and are critical to ensuring a continued reduction in campus energy usage.
**Expected Outcomes:**
The expected outcomes of this effort are four-fold:

- The development of automated energy audit systems that enable high-performance buildings by identifying 1) necessary equipment retrofits, 2) faulty systems or deficient system integration, and 3) opportunities for advanced sensing and energy-conscious control logic.
- The formulation of optimal management strategies for robust Proportional-Integral-Derivative (PID) Controllers for the hundreds of individual components that comprise a typical building energy system.
- The creation of coordinated decentralized predictive control strategies will help building systems achieve the efficiencies possible with centralized control, but preserve the flexibility and modularity critical to practical building systems operation.
- The integration of occupant feedback strategies will serve to enable two-way performance improvements. First, occupant comfort will serve to guide the energy optimization efforts, while feedback to the occupants regarding predicted energy usage will assist in shaping occupant behavior.

**Technical Solution:**
With increasing frequency building energy systems are being implemented as a complex network of components designed to meet many distributed heating and cooling demands. Simultaneously, the rising cost of energy and growing environmental concerns are driving the industry towards Net-Zero Energy buildings and Building-as-a Power-Plant ideals. Central to the success of these approaches is the ability to coordinate the many interacting systems to optimize building performance and minimize energy usage. While a single centralized control approach is a potential solution, inherent characteristics of a building energy system (spatially distributed, limited communication, frequent changes in system configuration) demand a more flexible and scalable approach.

This project proposes a decentralized approach to modeling, control, and optimization of building energy systems. The successful completion of this thrust will result in enabling control algorithms that: 1) coordinate a large number of components to optimize and manage system efficiency; 2) guarantee stability despite uncertain, nonlinear, and interacting subsystem dynamics; and 3) are scalable to large commercial buildings and flexible for integration of energy generation, thermal storage, and other auxiliary systems. These efforts will be pursued at both the component and system level.

**Energy Audits**
A necessary companion effort to the proposed control development efforts is identifying the components and systems that are key candidates for energy saving initiatives. These efforts will extend beyond typical equipment-focused energy audits with a particular focus on controls-enabled energy savings.

The Energy Systems Lab, directed by Dr. Claridge, conducts ongoing energy audits on campus buildings, recommending equipment retrofits to improve energy efficiency. This project will expand these efforts by identifying and quantifying inefficiencies due to poor control or faulty operation. The team will conduct a detailed energy analysis of typical building systems comparing actual vs. manufacturer specifications for energy usage, revealing systems that are not being operated and controlled as designed, or subject to equipment or software faults. This task will also examine system interactions, identifying possible methods of exploiting system integration to minimize energy consumption.
The final auditing task is to identify alternative energy-saving control logic. Recently Texas A&M Utilities implemented a campus-wide standard for temperature setpoints in occupied/unoccupied spaces. This project will identify and quantify energy savings possible through additional changes to control logic, such as: dehumidification control, elimination of excess air flow, integration of occupancy sensors and lighting/HVAC control, etc.

Long term research efforts will extend these results to create “best-practice” recommendations, and resources for energy auditors to augment their efforts to include building control systems. Where possible, the team will also develop automated energy audit systems that utilize data mining and pattern recognition to identify inefficient systems and opportunities for retrofits and controller tuning.

**Component-Level Control**

A typical building energy system utilizes comprises thousands of sensors and hundreds of control loops. The vast majority of these controllers are Proportional-Integral-Derivative (PID) Controllers (e.g. the Zachry building on the A&M campus has 347 control loops each equipped with a PID controller). However, a variety of studies agree that most of these control loops are improperly tuned, if at all, resulting in inefficient operation and poor performance. If tuned, most such control loops are tuned using the Ziegler-Nichols formulas, a technology developed in 1943 for simple first and second order single loop control systems. It is easy to show that these tuning rules are inadequate for such large scale multivariable systems, yet these techniques are in use for a lack of better procedures, that is for a lack of adequate theory and efficient algorithms.

With the above as motivation we propose the problem of energy optimization using optimum settings for banks of PID controllers. This challenging problem has an obvious and potentially immediate payoff, simply due to the scale involved. An effective control solution will be adopted in thousands of office and industrial buildings so that even a modest improvement in performance (energy saving) will be multiplied. The challenge is due to the fact that even though each controller has only 3 parameters there are hundreds in each building and coordinating their design intelligently is a monumental task.

We should mention that the co-PIs have original, recent and breakthrough contributions to both Model Based [8-10] and Data Based [11] PID controller design. Based on our prior experience, we believe that the problem of energy optimization through control is a solvable one. This optimism stems from a number of reasons: first, the $L_2$-norm of a time-domain signal is a measure of its energy. In the frequency domain, the same time-domain norm corresponds to the $H_2$ norm, whose minimization is well studied in the control literature [8]. However, the main difference will be that now the $H_2$ norm minimization will have to be carried out while imposing the PID structural constraint on the controllers. The second reason why we are so optimistic is that very recently we have obtained some as-yet-unpublished preliminary results on model-free design based only on measurements. The results obtained to date readily generalize the well-known Thevenin’s Theorem of circuit theory. Specifically, we have shown that given a complicated resistive network, the current flowing through any known resistor that is inserted between any two nodes in this circuit can be determined by just making pairs of

**Demonstration Project: Energy Audit Thrust**

During the first two years of the project, the BEO team will select a campus building to serve as the testbed for developing the energy controls audit procedures. This task will also serve to quantify the expected energy savings from the proposed control tasks. These activities will leverage the expertise and and ongoing efforts of the Energy Systems Laboratory at Texas A&M University.
current-voltage measurements involving the same two nodes, with two or at most three different known resistors connected, one at a time, across them. Currently, we are working on generalizing this static measurement-based approach to dynamical systems. We believe that this approach will be relevant to the control-based energy optimization problem in the following way: now in a given network of PID loops, one could iteratively minimize the energy usage by adjusting the PID parameters in the direction of the negative gradient of the energy function with respect to these parameters. In a large network with many PID controllers, these gradients will be some complex functions which will be extremely difficult to analytically determine from a model of the network. If, however, we can make a few simple measurements to arrive at the gradient functions, energy minimization may be possible even without having detailed knowledge of the network connections. This approach is reminiscent of the sensitivity approach to adaptive control which was first used in the 1960’s [12, 13].

**Demonstration Project: Component-Control Thrust**

During the first two years of the project, the BEO team will demonstrate the robust PID control design process for large scale systems on a selected campus building. Over 80 buildings on the Texas A&M Campus are equipped with complete Direct Digital Control (DDC), with more than 200,000 sensing and control points. As such it is one of the largest such facilities in the United States. Using state-of-the-art monitoring and control hardware and software (Siemens/Apogee) the project team has access to historical and real-time data for the full range of building system components, including chillers, Air Handling Units, cooling towers, hot water heaters, refrigerant-based terminal units, etc.

**System-Level Control**

Although the vast majority of modeling and control research for building energy systems is concentrated at the component level, significant efficiency benefits are possible by coordinated control of components and subsystems [14-18]. For example, in [15] the authors illustrate this principle using a vapor compression refrigeration system; by over-driving the compressor and under-driving the fans, the system provides the same level of cooling capacity, while utilizing significantly less energy (Figure 1).

Building energy systems are complex, spatially distributed, and subject to changes in equipment, configuration, and building aging. Thus designing a single centralized control strategy is largely impractical. The disparate time and spatial scales involved, and the need for modularity have led to decentralized strategies that ignore component interactions and opportunities for coordination. Thus the majority of the literature on building systems control either focuses on particular components or system level optimization efforts that ignore dynamics, and focus on generating optimal set-points for
lower level control [19-22]. Moreover, the push towards Net-Zero Energy [23, 24] and “Building as a Power Plant” (BAPP) paradigms [25, 26] is leading towards additional energy systems and deeper integration, such as integrated air conditioning and hot water heating, and cascaded combinations of solar thermal, fuel cells, micro-turbines, etc. for on-site power generation and environmental conditioning. Thus, the typical building is a “system-of-systems” with dynamics that evolve on multiple time scales with many varied performance objectives.

Advances in building systems sensors, actuators, and communication serve as enabling technologies for the control strategies proposed here. In the near-to-mid future, we anticipate wide spread use of small, low-cost, wireless, multi-sensors that simultaneously measure temperature, humidity, indoor air quality (IAQ), and air flow. General room occupancy sensors will be augmented with occupant tracking technologies (e.g. RFID tag, smart-phone tracking, etc.) that provide specific information regarding occupant location. Combination of these technologies results in an information rich environment, where the building energy management system has knowledge of occupant location, comfort, and preferences. We anticipate similar advances in actuators, such that variable speed fans, variable flow pumps, active window dampers, etc. become the norm. However, these devices will only result in increased performance and efficiency if the control systems can properly interpret conflicting occupant demands, and coordinate systems to balance occupant needs with energy usage.

The primary purpose of buildings is to serve the needs of the occupants. The lengthy list of occupant requirements includes proper regulation of ambient temperature, humidity, pressure, lighting, $\text{CO}_2$ levels, air circulation, etc. However, attempting to provide more precise occupant comfort is generally more energy intensive (e.g. simultaneously heating and cooling neighboring cubicles). There is considerable research regarding human thermal comfort [27], with various comfort metrics proposed (e.g. PMV-Predicted Mean Vote). ASHRAE standards establish acceptable ranges for temperature, humidity, air flow, etc. [28]. Recent research confirms basic intuition that occupants are reasonably comfortable and productive for a range of conditions, with some variations due to gender, age, etc. [29, 30].

Beyond effectively interpreting occupant demands, next generation building energy management systems should provide users with feedback regarding current energy usage behaviors, and ways to alter those behaviors to reduce energy consumption. Recent initiatives such as “The Smallest User” competition in Memphis, TN [31] and detailed energy consumption metering technology (e.g. Google Power Meter [32], GE’s Home Energy Manager [33]) indicate a growing energy consciousness, and that users will adjust behavior with proper incentives. The next generation of building energy management systems can meet this need by assisting users in making informed decisions about energy usage behaviors.
At the system-level, the Building Energy Optimization thrust seeks to meet occupant demands, while simultaneously minimizing energy usage. The research plan is pragmatic, focusing on the challenges of actual buildings with aging equipment, communication limitations, and existing sensors and actuators. We propose to develop distributed model predictive control (DMPC) algorithms that preserve system modularity, but coordinate among subsystems to optimize efficiency. This approach will share information between local controllers to simultaneously optimize local and global criteria, and is naturally amenable to advanced energy management strategies, such as demand limiting, identifying potential energy savings, and integrating thermal storage and power generation systems. Initial efforts will demonstrate the approach using a selected campus building air handling system, and then expand the DMPC strategies to create a plug-and-play framework for control of building energy subsystems.

These tools also provide an effective means for both interpreting occupant comfort demands and providing essential feedback that can shape occupant behaviors for greater energy efficiency. This will not simply include identifying occupant comfort limitations, but methods of actively including occupants in the optimization effort via feedback and behavior modification. This human-in-the-loop aspect of the thrust is critical for practical success.

**Demonstration Project: System-Control Thrust**

During the first two years of the project, the BEO team will demonstrate the technical feasibility of the decentralized model predictive control approach by implementation on two systems:

1) A small-scale multi-evaporator chiller system (right). This benchmark system reflects the complexities of interconnected building HVAC systems, and is equipped with electronic actuation of the electronic expansion valves (EEVs), discharge valves (SDR), variable speed compressor, and water flow valves (WFVs). Temperature, pressure, and mass flow sensors are placed throughout the system permitting a complete characterization of dynamic responses. These are interfaced to a real-time data acquisition and control system for implemented custom control strategies.

2) The air handling system in the Texas A&M Utilities Business Office building. This building was identified as a safe location for experimental control strategies and is equipped with variable speed pumps & fans, actively controlled dampers, variable hot water heating, etc., as well as a full array of sensors. As part of this project the existing set of power metering will be expanded to include sub-metering of power at individual components, and occupancy sensors.

**Assessment of Benefits:**

The proposed energy analysis will not only identify key focus areas for energy savings, but also establish a baseline for assessment of benefits. Using a series of small scale case studies, the energy savings of
individual initiatives will be evaluated. These efforts will be facilitated by the Texas A&M University Utilities office, which has pledged its support. After successful demonstration in selected building systems, the PIs will work with industry partners to implement the proven strategies on several buildings on campus for large scale evaluation.

Deployment Strategy:

Short-term (1-2 years): The short-term objectives of this thrust include:

- **Building Energy Performance Limits**: quantify discrepancies between actual and predicted building energy usage given existing equipment, and identify energy losses due to poor control or integration of subsystems
- **Building Energy Savings Identification**: quantify benefits of potential energy savings measures of both improved control/coordination and equipment retrofits where appropriate (e.g. integration of occupancy, lighting, HVAC, and computing controls, use of virtual computing to reduce plug loads, etc.)
- **Building Control Optimization**: demonstrate energy optimal PID control tuning on a subset of building system controllers with quantifiable energy benefits
- **Building Energy Optimization**: create a proof-of-concept demonstration of distributed predictive optimization of building air handling system with modular component based controls that coordinate to achieve system level optimality

Long Term (3-5 years): The long-term objectives of this thrust include:

- **Automated Building Energy Audits**: develop automated energy audit approaches for isolating and identifying energy waste and savings measures, utilizing the latest in data mining and pattern recognition techniques
- **Building Occupant Feedback**: identify effective means of integrating occupant and building energy controls technology, including occupant comfort limits, information transfer strategies for occupant feedback and behavior shaping
- **Building Control Optimization**: demonstrate automated tuning of robustly optimal PID control tuning for large scale building control systems
- **Building Energy Optimization**: create a comprehensive strategy that enables plug-and-play component controls that enable building level efficiency optimization using Distributed Model Predictive Control techniques

Management & University commitment:
Bryan Rasmussen (MEEN) will serve as the lead in this effort, and as a primary researcher in developing the optimization and coordinated control strategies, leveraging his extensive experience in energy systems dynamic modeling and control. David Claridge (ESL) has decades of demonstrated success reducing building energy usage and will oversee the energy auditing activities. Jorge Alvarado (ETID) will lend his analytical expertise to help identify energy savings potential and assist in the integration of occupant feedback strategies. Shankar Bhattacharyya and Aniruddha Datta will work to redefine how local component level controllers (PID) are tuned, by automating the tuning process and ensuring robust
performance. As head of Texas A&M Utilities, James Riley will ensure access to actual building control systems and facilitate in-situ evaluation of control and optimization techniques.

Budget:

Short-term (1-2 years) projection: TBD

Long Term (3-5 years) projection: TBD

References:


