Comparative Analysis of Low-Cost Thermostats and Advanced HVAC Control Systems for Residential Energy Efficiency in State-of-the-art HIBO Laboratory

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Introduction: Residential buildings account for a significant portion of global energy consumption at around 27% and also 17% of CO_2 emissions [1]. Despite the ubiquitous application of various heating, ventilation, and air conditioning (HVAC) systems, many buildings still suffer from inadequate energy efficiency while facing difficulties in finding cost-effective renovation and retrofitting solutions [2]. To address this lackluster development, smart thermostats and advanced HVAC control systems offer promising solutions by optimizing energy use based on real-time environmental and occupancy data [3].

The research question explores the differences between low-cost, easily accessible residential thermostats and state-of-the-art HVAC control systems. The analysis of the provided papers reveals significant distinctions in terms of technology, energy efficiency, user interaction, and cost-effectiveness [4]. These differences highlight the evolution from basic programmable thermostats to advanced systems that incorporate intelligent control strategies and predictive algorithms [5]. Utilizing the Human-centered Integrated Building Operation (HIBO) laboratory (shown below), which offers advanced capabilities in human perception and human-building interaction experiments, this project will provide valuable insights into the trade-offs between low-cost solutions and high-end commercial-grade systems. HIBO's facilities, including fully customizable HVAC control, tunable white lighting, and dynamic envelope operation, enable an unparalleled test environment for this study.

The primary objective of this project is to assess the performance of low-cost residential thermostats in comparison to advanced systems. We will analyze key parameters such as response time, accuracy, and energy efficiency. Furthermore, we aim to identify opportunities for optimizing the low-cost thermostats to bring their performance closer to that of their high-end counterparts.

Figure 1: HIBO Lab – Outside View

Figure 2: HIBO Laboratory – Commercial-grade RTU

Figure 3: HIBO Laboratory – Test Room

Background: The building automation industry has seen a steady growth in the integration of smart technologies aimed at improving energy efficiency. However, the adoption of such technologies in residential settings remains limited, primarily due to the high cost and complexity of commercial-grade systems. On the other hand, there has been a proliferation of affordable, off-the-shelf smart thermostats in the consumer market. These devices, though inexpensive, may lack the precision and performance required for significant energy savings.

Previous research has demonstrated the effectiveness of advanced control systems in optimizing building energy use through features like predictive maintenance, adaptive learning, and multi-zone management [6], [7]. Yet, the scalability and cost-effectiveness of these systems in the residential market remain questionable. This study will directly address this gap by comparing the performance of low-cost residential thermostats with the advanced, commercial-grade systems available at the HIBO lab.

Methodology: This project will be conducted in two main phases: experimental setup and performance analysis. The methodology involves several key steps:

1. **Device Selection and Categorization**: We will select best possible low-cost thermostats from popular consumer brands and compare them with high-end, commercial-grade systems such as those available in the HIBO lab. The devices will be prioritized based on cost, functionality, and features such as programmable schedules, remote control capabilities, and learning algorithms.

2. **Experimental Setup**: The experiments will be carried out in the HIBO lab, where both sets of devices will be installed in controlled environments. The lab's advanced infrastructure will allow for precise control, monitoring and data logging over many variables such as indoor temperature, humidity, and occupancy. This setup will enable us to simulate typical residential conditions for a more realistic comparison.
3. **Performance Metrics**: The following metrics will be measured:
   - **Response Time**: The time taken by the thermostat to detect changes in temperature and adjust the HVAC system accordingly.
   - **Accuracy**: The precision with which the thermostat maintains the desired temperature.
   - **Energy Consumption**: The amount of energy used by the HVAC system when controlled by each type of thermostat.
   - **Delay Analysis**: Any potential delays in communication between the thermostat and the HVAC system, especially in wireless models.
   - **Comfort Analysis**: We will gather feedback on ease of use and perceived comfort levels from individuals interacting with both systems.
4. **Data Analysis**: Collected data will be analyzed using statistical tools to identify patterns, strengths, and weaknesses of both types of systems. A detailed comparison of energy savings, user comfort, and overall system performance will be conducted.

Expected Results: We expect to demonstrate that while low-cost residential thermostats may not match the performance of high-end systems in all aspects, they still offer considerable benefits in terms of cost savings and energy efficiency for the average homeowner. Our findings will likely reveal that, with some optimization, these low-cost systems can provide sufficient control over residential HVAC systems, making them a viable option for improving energy efficiency in homes. The study will also provide valuable insights into how advanced systems can be adapted or scaled down for residential use.

Contribution to the Field: This project contributes to the ongoing efforts to make residential buildings more energy-efficient and cost-effective. By providing a comprehensive comparison between consumer-grade and commercial-grade HVAC control systems, this research will help bridge the gap between high-performance technologies and affordable solutions. The results could inform future developments in low-cost smart thermostats and encourage wider adoption of energy-saving technologies in residential settings.

Project Timeline:

Timeline	Activity
May 2025	- Literature Review - Selection and acquisition of thermostats; initial experimental setup in HIBO lab.
June-July 2025	- Running experimental trials; collecting and analyzing preliminary data. Adjust the range of variables based on the preliminary tests. - Starting to write the manuscript.
August 2025	- Final data analysis and comparison. - Writing and submitting the final report.

Student/Faculty Mentor Roles: The student will be responsible for conducting the experiments, collecting data, and performing the analysis. They will also take the lead in writing the final report and preparing any related publications. The faculty mentor will guide the experimental design, assist with data interpretation, and provide feedback throughout the project. Regular meetings will be held to ensure that the project stays on track.

Previous Internal Funding: None

Budget and Budget Justification:

Given my preliminary research into residential energy efficiency and the availability of advanced testing environments in the Human-centered Integrated Building Operation (HIBO) laboratory, I am confident that the lab's infrastructure will provide all the necessary equipment and facilities for conducting the experiments. The HIBO lab is fully equipped with customizable HVAC systems, and dynamic envelope operation, eliminating the need for significant additional material purchases.

For my involvement in this project, a budget of $5,000 is required. This amount will be allocated primarily as a stipend to compensate for the time and effort I will dedicate to conducting experiments, analyzing data, and optimizing the systems under study. The breakdown is as follows:

Tasks	Time (hours)	Budget
Literature review	20	$400
Working in the lab and data collection	140	$2800
Data analysis and writing report	90	$1800
Total	250	$5000

References

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October 11th, 2024

Dear members of the GRACA Grant Selection Committee:

With this letter, I'm excited to express my enthusiastic support for my PhD student, Mohammad Amin Erfani Moghaddam as a candidate for the GRACA award in 2025.

Amin has recently started an ambitious research direction about developing a methodology and technical infrastructure to bring intelligent and autonomous automation systems to residential buildings. Although such concepts have been in the frontpage of building science for a few years now, the infrastructure deficiencies in residential environments have hindered their widespread application. The approach that Amin is working on is based on low-cost solutions, such as smart thermostats, and if implemented in housing can change the landscape in climate resilience and health equity; for the first, with significantly reducing the energy footprint of the housing sector, and for the latter with giving the opportunity to lower socioeconomic status households to enjoy healthy building operation. These directions reflect the hot areas of current high-performance building challenges and are highlighted in the most impactful journals (e.g., Building and Environment), professional associations (e.g., ASHRAE, IES), and are in the focus of federal entities that can provide funding (e.g. NSF and DOE). Through promoting climate resilience and health equity, these are also very well aligned with the N2025 strategic plan. In that sense, I expect Amin's contributions to attract interest as well as funding from various sources, and UNL to be very well benefitted by his presence.

The support of the GRACA grant is essential towards Amin's objectives, as it will in part cover his support for summer 2025. During that period, from May to August, he will complete all phase of his work on smart thermostats, including literature review, experimental development and data collection, and data analysis and results dissemination. Amin has been funded by me through research grants until last year, and currently is under a GTA appointment for 2024-2025. With his previous projects, he has developed a commendable attitude towards deadlines and responsibilities when it comes to projects. For next year, I'm planning to resume funding him through several proposal that at this moment are still pending.

As his mentor, I will be advising him on his work during our weekly meetings. In this setting, he will be presenting his developments in a structured way, going through not only the technical details but also emphasizing how these advancements can benefit the field and promote research. Amin will have access to the Human-centered Integrated Building Operation (HIBO) laboratory, which I have founded in 2023 and provides a unique infrastructure to serve the objectives of this research. In addition, I will further train Amin in other aspects of a researcher's duties, such as proposal development, papers authoring, and interacting with interdisciplinary group, while I will also encourage him to participate more in professional organizations where I'm holding leadership positions (e.g. ASHRAE) and are related to his work and the project's objectives.

Amin is a very bright and motivated graduate student. He came to our lab with an already impressive track record in research and publications, his background in Mechanical Engineering has equipped him well to tackle current challenges in smart building technologies, and his plans for the future are fully aligned with making an impact in the field of smart buildings. He has already presented his work in one of the most prominent building science conferences internationally (CISBAT 2023), is currently wrapping up his first major journal paper with us, and I'm excited to see his next steps. Receiving the GRACA grant will enable his research vision and will be a significant asset in his quiver towards a promising career.

Sincerely,

Iason Konstantzos, PhD.
Assistant Professor
Durham School of Architectural Engineering and Construction - University of Nebraska - Lincoln