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ThermoSense: Thermal Crowd Detection and Temperature-Controlled Ventilation System

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ABSTRACT

Energy Demand has always been increasing globally. Thus, environmental issues have highlighted the energy inefficient. The Primary building energy inefficiency is due to HVAC and lighting systems that are statically operated without reacting to real-time occupancy. There have been different occupancy detection technologies provided with their fundamental tradeoff between sensing accuracy and occupant privacy. Passive Infrared (PIR) sensors might be one of the simple charge-free sensors to give privacy preservation, but they are not so efficient in distinguishing humans. This paper proposes ThermoSense: an integrated system that could be used to reconcile the previous approaches. The core principle of the ThermoSense methodology requires anonymous but accurate crowd detection and counting through lowspatial-resolution thermal array sensors. The resulting occupancy information is further used as input to a new context awareness-based control algorithm that manages the environmental systems of the building intelligently. The algorithm covers the various aspects of energy management, such as putting the comfort of indoor occupancy and the external environment into consideration while making decisions regarding natural ventilation before mechanical HVAC whenever outdoor conditions favor such. This paper looks at the multi-layered architecture of the system, its machine-learning-based occupancy estimation module, and intelligent control logic. Some of the acclaims of ThermoSense include energy savings, good dependability of operations in all conditions of light, and inbuilt commitment to data privacy from the outset. These characteristics qualify ThermoSense as a feasible, scalable, and sustainable solution for intelligent building management in future generations.

1. Introduction

1.1. The Case of Energy Efficiency in the Built Context

The built environment as one of the largest single sectors in the consumption of energy globally. Buildings account for a considerable proportion of world energy consumption, thus being the significant contributors to carbon dioxide emissions.1 A large share of this energy consumption is served by its building services, designed to suit occupant comfort and safety, namely an energia these systems refer to heating, ventilation, and air conditioning (HVAC).3 The energy even wasted by these systems operating in an inefficient manner is one major challenge. For instance, HVAC and lighting systems in most commercial and public buildings are programmed to work under fixed schedules believing the places are full at most times when they operate.5 They fail to see that the usage of buildings is really dynamic and variable so that the conditioning and illuminating conditions are set at empty or sparsely populated spaces. Therefore, this misallocation of energy expenditure vs. actual need leads to extensive energy waste, higher operational costs, and greater environmental footprint.6 Hence, developing intelligent, responsive building automation systems will align energy with real-time occupancy, and these systems are justified not only as economic optimizations but also as environmental mandates.

1.2. The Occupancy Detection Dilemma: Accuracy versus Privacy

At the very heart of any responsive building automation system is the accurate perception of its internal state, primarily of the presence and number of occupants. But this relationship is additively sustained by a continuing and bitter difficulty of trade-off in the accuracy of data collected versus occupant privacy in buildings. On one hand, advanced computer vision techniquesthrough the latest camera-based systems available-can provide occupancy information that is precise and has a finegrained measurement including precise counts and location tracking or even movement analysis.8 On the other, however, such detailed surveillance includes deep implications of privacy, abuse of personal data, which can also arouse concerns in legal and ethical liabilities, making such systems untenable for deployment in many private or sensitive spaces, such as offices, schools, or restrooms. On the other end of the spectrum are technologies like Passive Infrared (PIR) sensors. These devices are widely adopted due to their low cost and inherent privacy-preserving nature, as they only detect the motion of heat sources.11 However, their utility is severely limited; they provide only binary presence-orabsence information and are notoriously unreliable for detecting stationary occupants, leading to scenarios where lights or HVAC systems are erroneously turned off.5 This technological dichotomy creates a significant "Privacy-Performance Gap," where building managers are forced to choose between effective but intrusive systems and private but functionally limited ones.

1.3 The following solution is proposed: ThermoSense System:

The purpose of this paper is to present ThermoSense, a completely new and holistic solution designed to close the accuracy-privacy gap in occupancy sensing and building automation, as indicated in the conceptual framework. ThermoSense integrates two innovations: first, low-resolution thermal array sensors for crowd detection and counting. These heat sensors are capable of detecting the heat signatures of human bodies and thus are able to accurately count occupants, regardless of lighting conditions and regardless of whether they are moving or stationary. Given the inherently low resolution, personal identification is impossible. Hence, privacy is preservedby-design. Second, it includes intelligent context aware control logic that goes beyond mere occupancy-based triggers. The control logic makes occupancy-based decisions, whereby some external environmental conditions are also thrown into the decision-making algorithm. Such pertinent conditions include outdoor temperature and humidity, aside from the real-time occupant count, by which ThermoSense could potentially make advanced, energy-efficient decisions, when external climate conditions are good, like switching off mechanical HVAC for natural ventilation via the automated windows.[12]

1.4. Contribution and Paper Structure

The main contributions of the work are threefold, these being: (1) an integrated multi-layered systems architecture for realtime building automation consisting of privacy-preserving sensing, edge-based processing, and centralized control; (2) a new, context-aware decision algorithm for energy savings developed through the synergistic management of active (HVAC) and passive (natural ventilation) environmental control strategies; and (3) a comprehensive characterization of the influence of such a system on various performance indicators, including energy efficiency, operational robustness, and data privacy.

The remaining structure of this paper consists of: Section 2, which encompasses state-of-the-art literature review on occupancy sensing technologies, machine learning algorithms for thermal data analysis, and building automation architectures; Section 3, which deals with the detailed description of ThermoSense system including its hardware and software architecture, crowd detection module, and context-aware control logic; Section 4, which analyses project performance and impact of system with respect to energy optimization, privacy advantages, and scalability; and finally Section 5, which concludes the paper summarizing the key findings and contributions of the ThermoSense project.

2. Foundations of OccupancyCentric Building Automation: A Review of the State-of-the-Art

2.1. An Appraisal of Different

Technologies for Sensing Occupancy

Any intelligent building system rests heavily on its input data. Indeed, the different occupancy sensing technologies can be scrutinized in terms of possible solutions based on their working principles, tradeoffs, and many more.

- Passive Infrared (PIR): Most occupancy sensors are passive infrared, detecting the continuous change of infrared radiation emitted by objects within their field of view to detect an occupant. Hence, they can be cost effective and anonymous; however, their downfall rests in the fact that they're purely motion-based. They deliver binary information and usually cannot detect fixed persons, leading to false negative readings.[8]
- Ultrasonic Sensors: Active ultrasonic information detection devices emit high notes and judge occupancy through change in reflection notes by movement. They are more expensive and are usually prone to false firing from non-human sounds or motions such as those caused by vibrations and airflow11, but they can cover larger and more complicated areas than PIRs.
- Waste Time-of-Flight (ToF) sensorbased system: By emitting a pulse of light (generally infrared) and measuring the time needed for the light to reflect from a surface and return to the sensor, ToF creates a very accurate 3D depth map of the environment, allowing for highly accurate counting of individuals while keeping them completely anonymous because no fine-grain visual information is collected.[11]
- Camera-Based or RGB Sensors: These systems use commercial optical cameras and very advanced algorithms in computer vision, capable of specifically counting, tracking movement patterns, and behavior analysis. Such detail, however, includes considerable loss of anonymity, since inevitably, identifiable video footage will be captured all the time, exposing the system to the highest level of data security risks, legal challenges such as those stated in the GDPR, and negative impacts on employee morale and productivity.[8]
- Low-Resolution Thermal Array Sensors: It emerges as a very promising alternative in an environment set up to balance performance and privacy. They reliably count the numbers of moving and even stationary people on base of how much heat their bodies reveal, and are not affected by visual obstructions.6 and critically because they have low pixel counts (32x24 or 80x64 pixels), it is impossible to capture personally identifiable information, which makes them by definition privacy-preserving, meeting stringent requirements of data protection legislation.

Table 1: Comparative Analysis of Occupancy Sensing Technologies

Technology	Principle of Operation	Typical Accuracy	Relative Cost	Privacy Implications	Robustness to Environment
Passive Infrared (PIR)	Detects changes in radiated heat (motion)	Low (Binary Presence)	Low	High (Anonymous)	Poor for stationary occupants
Ultrasonic	Emits sound waves and measures reflection	Medium	Medium	High (Anonymous)	Good in partitioned spaces
Time-of-Flight (ToF)	Measures time for a light pulse to reflect	High (Counting)	Medium-High	High (Anonymous)	Sensitive to sunlight/reflective surfaces
RGB Camera	Computer vision analysis of video stream	Very High (Counting, Tracking)	High	Low (High PII risk, GDPR concerns)	Poor in lowlight/darkness
Low-Res Thermal Array	Detects static heat signatures (bodies)	High (Counting)	Low-Medium	**Very High (Inherently Anonymous)**	**Excellent (Works in all light conditions)**

2.2. Machine Learning Paradigms for Occupant Estimation from Thermal Data

Extracting an accurate occupant count from raw thermal sensor data requires sophisticated processing algorithms. Most of the traditional approaches in this area depended on image-processing techniques. Cokbas and his co-authors combined Gaussian average-based background subtraction to isolate foreground heat signatures with k-Nearest Neighbors (k-NN) classifiers to classify detected events.14 The same applies to Qin et al. On the same premise, they also published a multi-step pipeline that combines both intensity-based and motion-based segmentation techniques, which K-means clustering was used for segmentation of frames, a "difference catcher" which identifies the motion between the subsequent frames, and connected components labeling to cluster pixels correspondent to distinct occupants.[19]

Though it works, this is a pretty brittle method that requires tuning for the different environment, as it is often parameter dependent. Most effective are today's advanced, powerful techniques, which take advantage of deep learning and most specifically the Convolutional Neural Networks (CNNs). U-Net-like encoderdecoder architecture has been particularly successful regarding this objective.1 In this specific architecture, the model describes that the network would first encode the input low-resolution thermal image into a compressed low-dimensional feature representation within the latent space. Then, this latent representation is decoded and produces an output referred to as the occupancy density map. With this occupancy density map output, one can describe a 2D grid, wherein the value of each pixel corresponds to the probability of the presence of an occupant at that location. Further summation over all the pixels would allow the system to make a continuous estimate of the total number of occupants it can derive from it.22 Compared to simple classification, this regression-based approach would allow more flexibility in dealing with diverse crowd sizes since classification is limited by the maximum number of classes (i.e., people) it can learn.21 These light-weighted CNN models can also be optimized and quantized for application in resourceconstrained edge devices for real-time processing at the location of the sensors.[21]

2.3. Architectures for Intelligent Building Control

That is, ThermoSense, which is embedded in a much wider technological ecosystem of Building Automation Systems (BAS), also called Building Management Systems (BMS). Such centralized control is applied for HVAC, lighting, access control, and security systems in buildings. Traditionally, those were closed, monolithic, proprietary systems. However, variety of access made by intelligent architectures has left the horizon from the Internet of Things paradigm change.[3]

There are different typified layers in such an information architecture in an automated modern control over IoT. The layers are : [25]

1. Physical/Sensing Layer: This is the most base layer, comprising distributed sensors collecting real-world events - environmental sensors (temperature, humidity), energy meters, and, most importantly for this application, occupancy sensors.[25]
2. Communication Layer: This layer automatically collects and communicates all data from sensors to processing units. A plethora of other wires and wireless methodologies are adopted by this layer such as Wi-Fi, Zigbee, LoRaWAN for lowpower wide-area networking, or even legacy building protocols like BACnet and LonWorks. [23.]
3. Data Management/Cybernetic Layer: All integrated processes occur in this "brain" of the system for accumulation, preservation, analysis, and control decisions. Such processing occurs on the centralized cloud server or, increasingly, at the edge of the network, directly at the local computing devices.[3.]

This significant architectural change goes on from a centralized, schedule-based control to distributed, data-driven intelligence. Initially, decentralized activity response to relatively simple inputs has been understood in the older BAS designs. From now on, however, the paradigm of IoT will allow more proactive, distributed intelligence. ThermoSense then sticks to this modern view because the peoplecounting model is located on an edge device directly attached to a thermal sensor. Important advantages offered by such decisions are huge reductions in the latency associated with a network since no raw video data have to be streamed for processing at a central server; purification in terms of data privacy and security since sensitive thermal data would be locally processed and never leave the room; and improved resilience because the sensing module can keep functioning even if central network connectivity is lost temporarily.17 Thus, ThermoSense is not simply an application but, indeed, an exemplar of a modern, distributed intelligence architecture for smart buildings.

3. The ThermoSense System: Architecture and Operational Logic

3.1. Multi-Layer System Architecture

The ThermoSense system, structured as a modular, multi-layer architecture, is seamless in integrating sensing, processing, and actuation to pursue its goals of energy optimization and intelligent environmental control. This construction comprises the three main layers, each of which performs distinct functional roles.

● Sensing Layer: This is the physical interface with the building environment. The primary component is a network of lowresolution thermopile array sensors, such as 32x24 or 80x64 pixel models, which are strategically mounted on the ceiling to provide an unobstructed overhead view of the monitored space.1 They are low-power sensors, cost-effective, and they can reliably sense the thermal footprints of occupants.6 This layer is further augmented by other sensors that detect Crucial contextual data is that of indoor sensors for ambient temperature and humidity, and a connection to an external weather data service (or dedicated outdoor sensors) in order to acquire real-time outdoor temperature and humidity readings.

Processing Layer: This layer consists of a distributed network of edge computing devices, like single board computers or powerful microcontrollers, each co-located with a thermal sensor. The key premise behind the architecture is that computation-intensive tasks shall be performed locally to enhance privacy and decrease latency. Each of the edge devices is responsible for running the optimized machine learning model, which processes the raw thermal image stream from its attached sensor and produces one anonymized integer: OccupancyCount.17 By processing data on the edge, the system ensures that only the final anonymized count, which is not personally identifiable, gets transmitted over the network, thus fundamentally protecting the privacy of the occupants.

Actuation & Control Layer: The central control unit at the heart of this layer may be either a dedicated server or a virtual machine, and it will be the central decisionmaking node for the entire system. It will receive anonymized Occupancy Count from all processing nodes together with data from the indoor and outdoor environmental sensors. It will then execute the core context-aware control algorithm (described in Section 3.3). Based on the output of this algorithm, the control unit sends commands to various systems automated by the building. Communication with the existing BAS/BMS of the building will take place using standard industry protocols such as BACnet or LonWorks and/or through cutting-edge IoT protocols such as MQTT to sustain high level compatibility and interoperability.[23] The actuators controlled by this layer include HVAC units, motorized windows for natural ventilation, and automated door mechanisms for access control.

3.2. Thermal-Based Crowd Detection Module

The crowd detection module is the core sensing component of ThermoSense, deriving real-time counts of occupation through raw thermal data. The whole process consists of two steps.

- Data Acquisition & Pre-Processing: The first step in the module is to acquire data from low-resolution thermal sensors such as Melexis MLX90640 or similar thermopile arrays from other manufacturers like Heimann Sensor or Seek Thermal.14 The thermal sensor captures a continuous sequence of low-resolution thermal images. Then, these raw images are fed through a pre-processing pipeline to increase the signal-to-noise ratio. This involves the use of noise filters such as a Kalman Filter with elimination of random fluctuations and enhancement of measurement stability.30 Afterwards, the dynamic background subtraction algorithm is used to model the thermal environment of the empty room in real time so that it can distinguish between the heat signatures of human occupants showing as foreground objects.[14]

- Occupancy Estimation Model: Preprocessed thermal images are presented to a lightweight, U-Net-like Convolutional Neural Network (CNN) that has been optimized for a specific deployment onto embedded hardware.1 As far as the literature describes, this model is a regression engine rather than a classification engine. It takes the 32x24 pixel thermal image as input and gives a corresponding 32x24 density map as output. The intensity of each pixel here represents the probability that this position is occupied by a portion of a person. The total occupant count will then finally be summed from all the pixel values in the density map and will be rounded up to the nearest integer. The regression mechanism based on the density map is highly advantageous because it has no upper limit on the count of individual persons that can be detected and can amicably handle the case of partial occlusions or overlapping occupants, thereby rendering itself a better and a more flexible solution in comparison to the classic classification models.[21]

3.3. Context-Aware Environmental Control Algorithm

The main novelty of the ThermoSense system consists of its context-aware environmental control algorithm. This makes the system more than just a reactive control system, since it is capable of making intelligent holistic decisions based on inputs from a large number of disparate data streams. On a different level, it embodies an energy management ideology that tries to combine the dynamics of the active mechanical systems (such as HVAC) with a working interference of passive strategies (such as natural ventilation). The intelligence of the system will not be the ability to specify different modes of the HVAC but rather to decide when it would be more energy-efficient not to use HVAC at all. By evaluating external environment context, the system will bring in great outdoor weather conditions to provide comfort for occupants at a cost far less than energy-based alternatives, a feat unavailable to pure occupancy-based systems.[12]

Decision logic is based on a rule framework that brings into consideration the following input variables:

- OccupancyCount: The integer value given by the crowd detection module.
- IndoorTemperature, IndoorHumidity: The real-time reading from sensors indoors within the monitored space.
- OutdoorTemperature, OutdoorHumidity: Real-time data from an external weather feed.

The heavy lifting of the control logic can be represented as follows in pseudocode:

```
// Define environmental thresholds
FavorableTempRange = [18°C, 24°C]
FavorableHumidityRange = [30%, 60%]
HighDensityThreshold = 10 // Example value
// HVAC and Ventilation Control Logic
IF OccupancyCount > 0 THEN
  // Space is occupied; prioritize comfort and efficiency
  IF (OutdoorTemperature IN FavorableTempRange) AND (OutdoorHumidity          IN
FavorableHumidityRange) THEN      //     Favorable  outdoor     conditions: passive, energy-free natural ventilation
    SET HVAC_Mode = OFF
    OPEN Windows
  ELSE
    // Unfavorable outdoor conditions: active mechanical HVAC        SET HVAC_Mode = ACTIVE
    CLOSE Windows
    // Modify HVAC setpoint based on thermal loads due to occupants        ADJUST HVAC_Setpoint based on
OccupancyCount
  END IF
ELSE
  // Space is empty; maximize energy savings
  SET HVAC_Mode = SETBACK // Deep energy-saving mode
  CLOSE Windows
```

```
END IF

// Automated Access Control Logic
IF           OccupancyCount       >
HighDensityThreshold THEN     // High crowd density: improve safety, airflow, and ease of egress
   SET Door_Mode = OPEN_AUTOMATIC
ELSE
   // Normal occupancy: revert to standard door operation
   SET Door_Mode = NORMAL_OPERATION
END IF
```

The importance of this algorithm is that it can adapt its operations dynamically and intelligently. The HVAC systems that tend to consume more energy are only turned on when required; in all other instances, energy will invariably be saved through whichever means of energy efficiency exist according to the complete context of the environment. Further, by providing access control, it adds to building safety and their effective functioning during active hours.

4. Analysis of System Impact and Performance

4.1. Projections for Energy Optimization and Efficiency

The implementation of the ThermoSense system is expected to produce considerable improvements in energy efficiency in buildings. The basic tenet is to synchronize HVAC and lighting operations with real-time occupancy, which has a long history of validation in the academic and simulation studies. There is research to prove that occupancy-centric HVAC controls can achieve considerable energy savings, with reported reductions from 914% 33, 10-30% in commercial buildings 34, and ultimately 40% powered by advanced AI strategies.4 Hypothetically calibrated building energy models superimposed on real occupancy data presented potential HVAC energy savings as high as 53-55%.35

The ThermoSense shall place itself in a position to deliver savings at the upper tier of these estimates due to its two-pronged optimization scheme. It fine-tunes the active HVAC system's operation based on strict knowledge of occupant counts; the context-aware algorithm delivers additional savings through harnessing passive natural ventilation. This substitution of mechanical cooling by free, natural airflow when conditions permit is a big plus compared with systems that only modulate HVAC setpoints. Saving energy directly from the building's Energy Use Intensity (EUI), which is in kWh per square meter yearly, is, therefore, expected, when it includes the Energy Use Intensity. Another way is to complement light control to lower its Lighting Power Density (LPD) in watts per square meter.[36]

4.2. Inherent Advantages in Privacy and All-Condition Reliability

Apart from energy savings, the technological choices underpinning ThermoSense provide critical nonfunctional advantages that are paramount for real-world adoption and long-term performance.

- Privacy by Design:

The main advantage of the ThermoSense System, when compared to other competing highaccuracy association systems, is protecting privacy, where the only type of monitoring used are, of course, low-resolution thermal array sensors. Apparently, then, this ought to conserve ThermoSense from capturing any personally identifiable information (PII). Inasmuch as thermal data cannot be used to identify individuals or capture any sensitive activities,17 it also serves to proactively diminish the great risk dominant areas of privacy, security, and legalities that typically accrue to surveillance programmed through camera facilities - hence it guarantees total compliance with existing data protection legislation, such as GDPR. This is an essential ingredient of the system and by doing so utterly conveys to its acknowledgement one of the key barriers to the mass embracing of smart building technology.[9]

- Operational Robustness:

Dependence on thermal imaging ensures extreme operational reliability across a wide range of environmental conditions. Thermal sensors work equally well in bright daylight, low light, and complete darkness and are not compromised by visual obstructions, like smoke or fog, which make RGB cameras inherently light dependent.16 Thus, the ThermoSense system will be exceedingly robust and suitable for continuous 24/7 functioning in a variety of environments: corporate offices, classrooms, public venues, and transportation hubs, with no degradation in performance.

4.3. Modularity, Scalability, and Future Enhancements

The ThermoSense system has been designed following the principles of modularity and scalability in line with agile development and incremental deployment. It is based on an IoT approach to facilitate smaller system installation such as room or floor installation and gradually scale installations over time to the entire building or even campus-wide property portfolios. Each sensor-processor node can operate in a semi-autonomous mode, where it relays final occupancy counts to a central controller; this lessens network traffic on the system, thus allowing easy addition/removal of nodes and easy inclusion/exclusion of its operation mode from the entire system.

In the future, the ThermoSense system generates an extremely rich data stream, which could open exciting improvements and research areas. Integration of predictive analytics is an exciting key area in research. By building and training models from historical occupancy data, machine learning could use this information to extrapolate future occupancy patterns with a high level of accuracy.4 As a result, the building's automation would change from a simple reactive to proactive control strategy, in which spaces would be prepared and pre-conditioned prior to being inhabited to save costs associated with comfort-wasting start-up expenses. The other important enhancement would be connecting this system to organizational scheduling data such as digital calendars for meeting rooms. This add-on would provide even more context in differentiating between a meeting and an informal gathering, thereby informing decisions regarding control actions.[39]

5. Conclusion

Radical change to intelligent, dynamic, responsive automation must be brought to the built environment in terms of a much more improved energy transition.

ThermoSense was introduced in this paper as a comprehensive system designed to meet this extremely urgent demand due to its capabilities in real-time occupancy sensing and full energy management concerning its primary hurdles. This technology can conduct extremely precise crowd counting under any environmental condition, while still assuring the anonymity of building occupants, which is one of the major barriers for acceptance of such technology.

The main scientific contribution of this paper is to offer a novel context-aware control algorithm, which does represent a significant improvement over traditional occupancy-based systems. ThermoSense has since implemented a much more sophisticated and sustainable way of environmental control by mediating between mechanical and passive natural ventilation with intelligent responses to internal occupancies and external atmospheric weather conditions. With its multi-layered IoT architecture and the local processing of data through edge computing, the system ensures low latency, high reliability, and in-built privacy of data. Thus, in strong, scalable, and effective framing for the new generation smart buildings-independent energy consumption but, more important, secure, responsive, and fundamentally-humancentric-smart buildings, is ThermoSense combining privacy-preserving sensing, intelligent edge-processing, and contextaware control logic.

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