Environmentally Context-Aware and PSO-GA Optimized Smart Building Sensor Placement

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***Abstract*—Research towards sensor placement within two-dimensional (2D) floor plans often emphasizes optimizing for maximum coverage and minimum overlap between sensors to reduce costs. However, existing solutions tend to overlook additional optimization metrics, including dynamic environmental conditions, which can have numerous practical applications. Our proposal is to take the existing approach and modernize it by creating a two-phase optimization framework to achieve context-aware sensor placement across 2D floor plans, optimized via a hybrid of Particle Swarm Optimization (PSO) and Genetic Algorithms (GA). The first phase entails minimizing the overlap between sensors while maximizing the coverage of a randomly selected floor plan from the HouseExpo dataset to create a PSO + GA optimized sensor layout. The second phase will utilize the optimized layout from phase one and apply real-world environmental data profiles from the HouseZero dataset to simulate dynamic zone conditions. Using the same structure of the PSO + GA algorithm, the optimization loop is repeated across multiple runs, where each run targets a specific environmental variable and activates only sensors of that type to produce the most effective layout for said environmental condition. This phase leverages a fitness function that is weighted based on environmental factors within a room or coverage zone to finalize sensor layouts based on their effectiveness across various time-based environmental conditions. These finalized layouts provide insight into useful sensor usage patterns and can have significant implications for energy-aware IoT applications [1][2]. This also includes reducing long-term costs and energy usage by selectively activating condition-specific sensors and also for forecasting usage cycles to improve maintenance and replacement planning.**

***Index Terms*—Sensor Placement, Hybrid Metaheuristics, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Environmental Sensing, Smart Buildings, Internet of Things (IoT), Context-Aware, Energy Optimization**

I. Problem Statement

The main objective of this proposal is to determine the optimal placement of sensors within 2D floor plan layouts based on a two-phase, environmentally context-aware, optimization strategy. The first phase aims to optimize sensor placement within a 2D layout by maximizing coverage while minimizing deployment cost and redundancy, using layouts randomly selected from the HouseExpo dataset. The second phase adapts the optimized layout from phase one by incorporating environmental conditions (e.g., CO_2 levels, temperature, humidity, activity level, etc.) using real zone-level data from the HouseZero dataset. The optimization is repeated across multiple runs, where each run targets a specific environmental variable and maps only sensors of that type to generate the best positioning layout for the given condition. During both phases, the optimization problem will be addressed using a hybrid PSO and GA approach to explore and refine sensor configurations. Moreover, our aim is to balance trade-offs related to spatial coverage, cost efficiency, energy consumption, and sensor utilization filtered based on environmental conditions within a given layout.

A. Phase One: Optimizing Sensor Placement for 2D Layouts

During this phase, a 2D layout will be randomly generated based on floor plan datasets obtained from HouseExpo or similar highly trusted resources to ensure maximum coverage with minimum cost and sensor detection overlap. This process closely follows the structure outlined by Nasrollahzadeh et al. and is modeled by the following objective function with constraints on cost, coverage, and overlap [3].

The following notation defines the framework for the following objectives:

- $x_{jhk} \in \{0,1\}$: Binary variable, equal to 1 if a sensor of type h is placed at position j with direction k
- C_h: Cost of deploying a sensor of type h
- $g_{ijhk} \in \{0,1\}$: Coverage indicator, equals 1 if sensor jhk covers point i, otherwise 0
- a_i: Minimum sensors amount required to cover point i
- N/O: Set of all coverage-critical points
- p: Candidate sensor positions
- S: Universal sensor types (raidal coverage)
- K: Sensor directions

Objective 1: Minimize Sensor Placement Cost

$$F_1 = \min \sum_{j=1}^{p} \sum_{h=1}^{S} \sum_{k=1}^{K} C_h \cdot x_{jhk} \tag{1}$$

Constraint: Ensure Minimum Coverage at Each Point

$$\sum_{j=1}^{p} \sum_{h=1}^{S} \sum_{k=1}^{K} g_{ijhk} \cdot x_{jhk} \geq a_i \quad \forall i \in N/O \tag{2}$$

Objective 2: Maximize Overall Coverage

$$F_2 = \max \sum_{j=1}^{p} \sum_{h=1}^{S} \sum_{k=1}^{K} g_{ijhk} \cdot x_{jhk} \tag{3}$$

Combined Fitness Function

$$\text{Fitness}_1 = \min\left(\frac{F_1}{F_2}\right) \tag{4}$$

The hybrid PSO-GA algorithm is applied to this objective to ensure optimal spatial layout under deployment cost constraints. The finalized layout highlights the best placement for all sensors throughout the 2D space.

B. Phase Two: Further Optimization of Sensor Layout based on Environmental Factors

For phase two, the goal is to optimize the layout produced in phase one. Real-world environmental conditions from the HouseZero dataset are applied to rooms randomly assigned within the 2D floor plan. The optimization is executed across multiple runs, with each run focused on a single environmental parameter (e.g., CO_2 levels, temperature, humidity, activity level, etc.). During each run, only sensors of that type are considered active.

The layout is refined per parameter-specific run to determine optimal sensor placement based on zone-level environmental behavior. Each run activates only one sensor type (e.g., CO_2 levels, temperature, humidity, activity level, etc.), with the objective of re-establishing maximum coverage while minimizing energy consumption and operational cost. The resulting layouts are tailored to each environmental factor across real-world time-based profiles from the HouseZero dataset. The multi-objective structure of this optimization follows the formulation adapted from [1], originally developed for IoT service placement, but applicable here due to its focus on balancing sensing utility, cost, and energy trade-offs across dynamic zone-specific inputs.

The following notation defines the framework for the following objectives:

- $x_{ij} \in \{0, 1\}$: 1 if sensor S_i is assigned to sensor coverage zone Z_j, 0 otherwise
- S_i: Sensors
- Z_j: Sensor coverage area (e.g., rooms or layout clusters)
- $S = \{s_1, s_2, ..., s_N\}$: Set of deployed sensors
- $Z = \{z_1, z_2, ..., z_P\}$: Set of sensor coverage zones
- $E_{\text{est}}(S_i, Z_j)$: Estimated energy consumption of S_i in zone Z_j, derived from HVAC power data
- $C_{\text{op}}(S_i, Z_j)$: Operational cost of using S_i in zone Z_j, based on runtime and power draw
- $Q_{\text{env}}(S_i, Z_j)$: Environmental sensing utility score, derived from zone-level variance in environmental readings

Objective 1: Maximize Sensor Coverage

$$f_1(S, Z) = \max \sum_{i=1}^{N} \sum_{j=1}^{P} Q_{\text{env}}(S_i, Z_j) \cdot x_{ij} \tag{5}$$

Objective 2: Minimize Energy Consumption

$$f_2(S, Z) = \min \sum_{i=1}^{N} \sum_{j=1}^{P} E_{\text{est}}(S_i, Z_j) \cdot x_{ij} \tag{6}$$

Objective 3: Minimize Sensor Operation Cost

$$f_3(S, Z) = \min \sum_{i=1}^{N} \sum_{j=1}^{P} C_{\text{op}}(S_i, Z_j) \cdot x_{ij} \tag{7}$$

Normalization Function Overview

$$X' = \frac{X - \min(X)}{\max(X) - \min(X)} \tag{8}$$

Normalized Sensing Coverage

$$f_u(s, z) = \frac{q(s, z) - \min(Q)}{\max(Q) - \min(Q)} \tag{9}$$

Normalized Energy Consumption

$$f_e(s, z) = \frac{e(s, z) - \min(E)}{\max(E) - \min(E)} \tag{10}$$

Normalized Cost

$$f_c(s, z) = \frac{c(s, z) - \min(C)}{\max(C) - \min(C)} \tag{11}$$

Fitness Function (Combined Weights)

$$F(S, Z) = \sum_{z \in Z} x_{ij} \left(\alpha f_u(s, z) - \beta f_e(s, z) - \gamma f_c(s, z)\right) \tag{12}$$

Where:

- $\alpha, \beta, \gamma \in \mathbb{R}$: Randomized weights to emphasize objective importance
- $\alpha + \beta + \gamma = 1$
- $x_{ij} \in \{0, 1\}$: Sensor i is active in zone j
- f_u, f_e, f_c: Normalized sensing utility, energy, and cost

The hybrid PSO-GA algorithm is applied to this fitness function to generate sensor placement layouts that prioritize active regions based on environmental activity levels. For each run, sensors of a specific type (e.g., CO_2 levels, temperature, humidity, activity level, etc.) are activated in response to dynamic conditions, producing optimized layouts that balance sensing utility with energy and operational cost.

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