Intelligent IoT-Based Smart Umbrella System for Real-Time Thermal Regulation and Heat Stress Prevention during Hajj Pilgrimage

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Abstract

The annual Hajj pilgrimage brings millions of Muslims to Makkah, where extreme heat and humidity create severe health risks, including heat exhaustion and heat stroke. While large-scale cooling infrastructure has reduced mass-level risks, a critical gap remains in providing mobile, personalized, and adaptive thermal protection for individual pilgrims. This study introduces an AI- and IoT-enabled smart umbrella designed as a proof of concept to mitigate heat stress through real-time climate regulation. The system integrates temperature and humidity sensors with a reinforcement learning (RL) framework trained using the Soft Actor–Critic (SAC) algorithm. The RL agent autonomously adjusts fan speed and cooling mechanisms based on environmental feedback, achieving dynamic thermal regulation. Deployment is carried out on ESP32 microcontrollers optimized with TensorFlow Lite, ensuring low-latency, offline inference without reliance on cloud connectivity. Sustainability and mobility are enhanced through full solar_powered operation. Evaluation involved benchmarking SAC against other RL algorithms, including Deep Q-Network (DQN) and Proximal Policy Optimization (PPO), across training and deployment phases. In addition, a real-world field test and user study with 49 participants assessed the system's effectiveness. Results demonstrated significant improvements in thermal comfort, stable inference speed, and high user satisfaction, confirming the feasibility of deploying embedded RL systems for outdoor climate control. This work contributes a scalable, energy-efficient, and user-centered approach to adaptive cooling, highlighting its potential for enhancing safety during Hajj and extending to other extreme outdoor environme.

Keywords

Reinforcement Learning, Smart Umbrella, Embedded AI, Heat Stress, Hajj, Climate Adaptation, IoT.