ABSTRAK

Krisis air global akibat perubahan iklim menuntut peningkatan efisiensi pada sistem irigasi pertanian skala mikro. Teknologi *Internet of Things* (IoT) telah banyak diterapkan, namun mayoritas sistem yang ada masih beroperasi secara reaktif berbasis ambang batas statis dan mengabaikan parameter intensitas cahaya yang esensial dalam proses evapotranspirasi. Selain itu, implementasi kecerdasan buatan sering terhambat oleh keterbatasan kapasitas memori mikrokontroler. Penelitian ini bertujuan membangun sistem *Adaptive Digital Twin* untuk memprediksi dinamika kelembapan tanah dengan membandingkan kinerja algoritma *Long Short-Term Memory* (LSTM) dan *Random Forest*. Pengembangan sistem menerapkan arsitektur terdistribusi *Cloud-Edge* IoT, di mana perangkat mikrokontroler ESP32 difokuskan untuk proses akuisisi data sensor dan aktuasi, sementara pemrosesan pemodelan prediktif dieksekusi sepenuhnya melalui infrastruktur komputasi awan. Kualitas data *input* ditingkatkan melalui metode kalibrasi empiris pada sensor kelembapan tanah kapasitif berbiaya rendah. Hasil penelitian membuktikan bahwa pemisahan beban kerja komputasi berjalan secara efektif. Evaluasi algoritma menunjukkan LSTM unggul secara signifikan dengan nilai koefisien determinasi mencapai 0,98, berbanding terbalik dengan *Random Forest* yang gagal memetakan data runtun waktu. Integrasi model prediktif terbaik ke dalam antarmuka kontrol tertutup secara sukses menciptakan mekanisme irigasi proaktif. Sistem secara presisi mampu mengantisipasi tren kekeringan dan mengaktifkan pompa secara otomatis sebelum kelembapan tanah menyentuh ambang kritis 40%, sehingga mengoptimalkan penggunaan air secara berkelanjutan.

Kata kunci: *Adaptive Digital Twin*, *Cloud-Edge* IoT, Irigasi, Kelembapan Tanah, LSTM.

ABSTRACT

The global water crisis exacerbated by climate change demands improved efficiency in micro-scale agricultural irrigation systems. Internet of Things (IoT) technology has been widely adopted, but most existing systems operate reactively based on static thresholds, ignoring light intensity parameters essential to the evapotranspiration process. Furthermore, implementing artificial intelligence is often hindered by the limited memory capacity of microcontrollers. This study aims to build an Adaptive Digital Twin system to predict soil moisture dynamics, comparing the performance of Long Short-Term Memory (LSTM) and Random Forest algorithms. System development applies a distributed Cloud-Edge IoT architecture, where the ESP32 microcontroller focuses on sensor data acquisition and actuation, while predictive modeling is executed entirely through cloud computing infrastructure. Input data quality is improved through an empirical calibration method on low-cost capacitive soil moisture sensors. The research results prove that the separation of computational workloads runs effectively. Algorithm evaluation shows that LSTM is significantly superior, reaching a coefficient of determination of 0.98, inversely proportional to Random Forest which fails to map time-series data. Integrating the best predictive model into a closed-loop control interface successfully creates a proactive irrigation mechanism. The system precisely anticipates drought trends and activates the pump automatically before soil moisture touches the critical threshold of 40%, thereby optimizing sustainable water usage.
Keywords: *Adaptive Digital Twin, Cloud-Edge IoT, Irrigation, LSTM, Soil Moisture.*