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Mini Project

Smart Greenhouse System Performance Analysis

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https://github.com/Udara-Sampath/Smart-Greenhouse-System-Performance-Analysis

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1 Introduction

1.1 Background

Smart greenhouse systems utilize Internet of Things (IoT) technology to monitor and control environmental conditions for optimal plant growth. These systems collect sensor data and trigger actuators based on predefined thresholds, creating a closed-loop control system [1].

1.2 Problem Statement

As IoT systems scale, understanding their performance characteristics becomes critical. Key concerns include response latency, system stability, and resource utilization. This project applies performance modeling techniques to evaluate a smart greenhouse control system.

1.3 Objectives

The main objectives of this project are:

- Model the greenhouse IoT system using queuing theory
- Apply M/M/1 queuing model to analyze system performance
- Verify system behavior using Little's Law
- Analyze correlations between environmental parameters and actuator states
- Evaluate system stability and identify potential bottlenecks

1.4 Scope

This study focuses on the control latency and throughput analysis of a greenhouse monitoring system using a dataset of 30 sensor readings collected over 30 minutes.

2 System Description

2.1 System Architecture

The smart greenhouse system comprises sensors and actuators connected through an IoT controller.

Sensors:

- Temperature sensor (measuring in °C)
- Humidity sensor (measuring in %)
- Soil moisture sensor (measuring in %)
- Light intensity sensor (measuring in lux)

Actuators:

- Cooling fan (binary state: ON/OFF)
- Water pump (binary state: ON/OFF)

Control Logic:

- Fan activates when temperature exceeds threshold (typically 30°C)
- Pump activates when soil moisture falls below threshold (typically 40%)

2.2 Data Flow

Sensor readings are collected every minute. Each reading is processed by the control system, which decides whether to activate actuators. The control latency measures the time from sensor reading to actuator response.

3 Methodology

3.1 Data Collection

The dataset contains 30 sensor readings collected over 30 minutes on October 31, 2025. Each record includes timestamp, environmental measurements, actuator states, and control latency. The dataset is available in the project repository [5].

3.2 M/M/1 Queuing Model

The M/M/1 queuing model is applied to analyze system performance [2]. The model assumes:

- Arrivals follow a Poisson process (M - Markovian arrivals)
- Service times follow exponential distribution (M - Markovian service)
- Single server (1)

3.2.1 Arrival Rate (λ)

The arrival rate represents sensor readings entering the system:

$$\lambda = \frac{1}{60} = 0.0167 \text{ readings per second}$$

3.2.2 Service Rate (μ)

The service rate is calculated from mean processing latency:

$$\mu = \frac{1}{\text{Mean Latency}} = \frac{1}{0.1298} = 7.70 \text{ per second}$$

3.2.3 Traffic Intensity (ρ)

Traffic intensity indicates system utilization:

$$\rho = \frac{\lambda}{\mu} = \frac{0.0167}{7.70} = 0.00216$$

For system stability, $\rho < 1$ is required. Our system has $\rho = 0.00216$, indicating a highly stable system.

3.2.4 Average Queue Length (L)

The expected number of requests in the system:

$$L = \frac{\rho}{1-\rho} = \frac{0.00216}{1-0.00216} = 0.00217$$

3.2.5 Average Waiting Time (W)

The expected time a request spends in the system:

$$W = \frac{1}{\mu-\lambda} = \frac{1}{7.70-0.0167} = 0.130 \text{ s} = 130.11 \text{ ms}$$

3.3 Little's Law Verification

Little's Law [3] provides a fundamental relationship:

$$L = \lambda \times W$$

Verification:

$$L = 0.0167 \times 0.130 = 0.00217$$

This matches the calculated queue length from M/M/1 formulas, confirming model validity.

4 Data Analysis

4.1 Descriptive Statistics

Table 1 presents the environmental parameter statistics.

Table 1: Environmental Parameter Statistics

Parameter	**Min**	**Max**	**Mean**	**Std Dev**
Temperature (°C)	25.6	32.8	28.9	2.1
Humidity (%)	55.0	79.0	67.8	7.4
Soil Moisture (%)	35.0	68.0	49.4	11.3
Light (lux)	2549	5929	4492	1032

Table 2 shows the latency performance metrics.

Table 2: Latency Statistics

Metric	**Value**
Mean Latency	129.8 ms
Minimum Latency	93 ms
Maximum Latency	170 ms
95th Percentile (P95)	165.6 ms

4.2 Correlation Analysis

Table 3 presents key correlations between system variables.

Table 3: Key Correlations

Relationship	**Correlation**	**Interpretation**
Temperature vs Fan State	0.858	Strong positive
Soil Moisture vs Pump State	-0.912	Strong negative
Temperature vs Humidity	0.049	Weak/None

The strong correlation between temperature and fan state (0.858) indicates reliable fan activation when temperature rises. The strong negative correlation between soil moisture and pump state (-0.912) shows appropriate pump activation when soil moisture is low.

5 Results and Visualizations

5.1 Environmental Monitoring

Figure 1 displays the environmental parameters over the monitoring period.

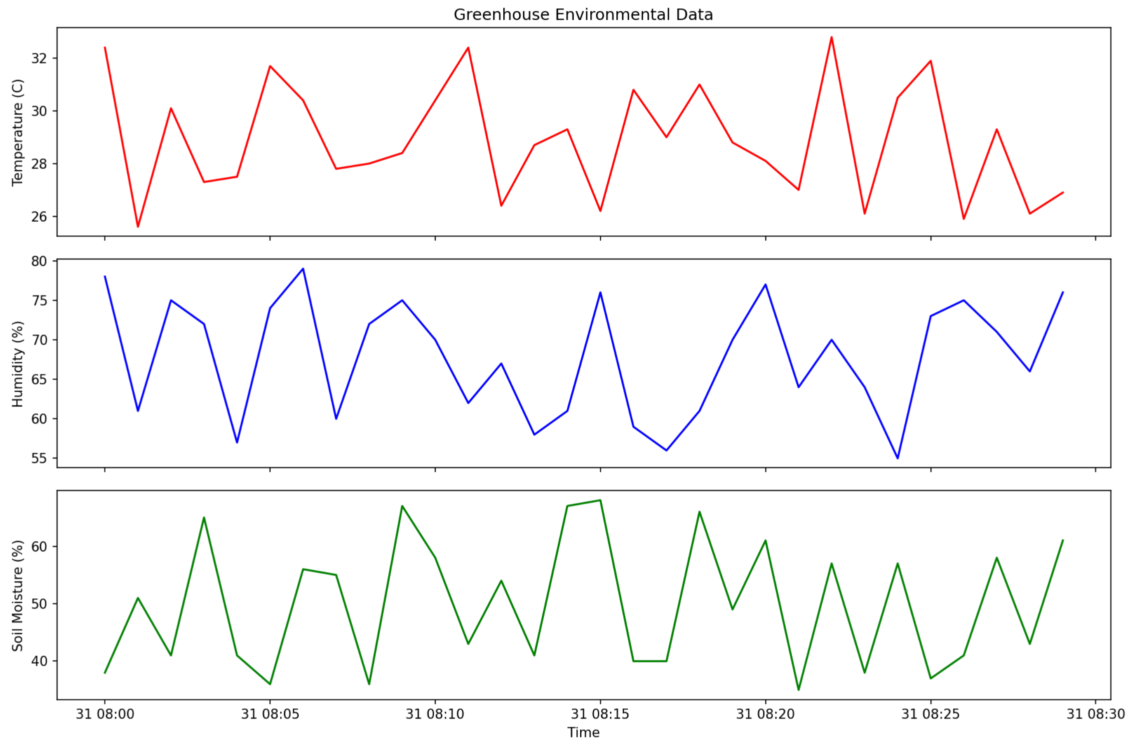

Figure 1: Environmental parameters over the 30-minute monitoring period showing temperature, humidity, and soil moisture variations.

5.2 Latency Distribution

Figure 2 shows the distribution of control latency values.

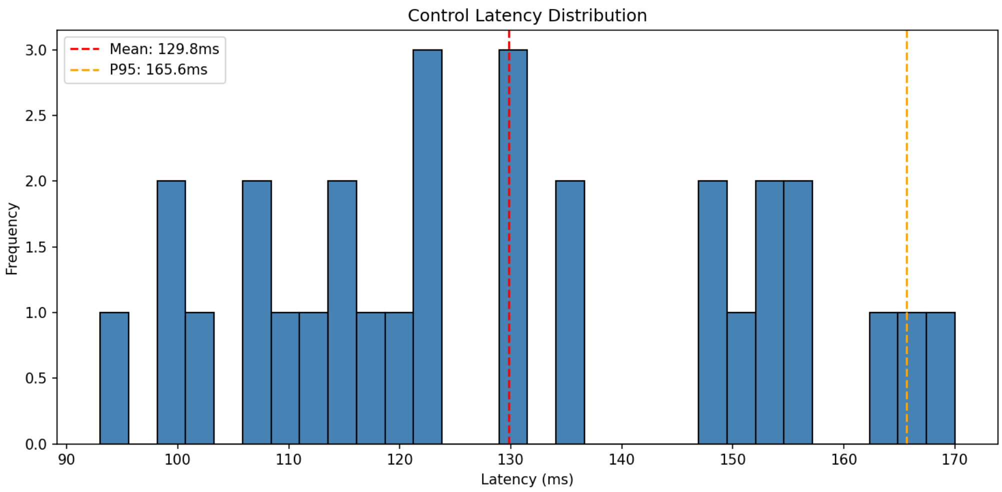

Figure 2: Distribution of control latency with mean (129.8ms) and P95 (165.6ms) markers.

5.3 Parameter Correlations

Figure 3 presents the correlation matrix between environmental parameters.

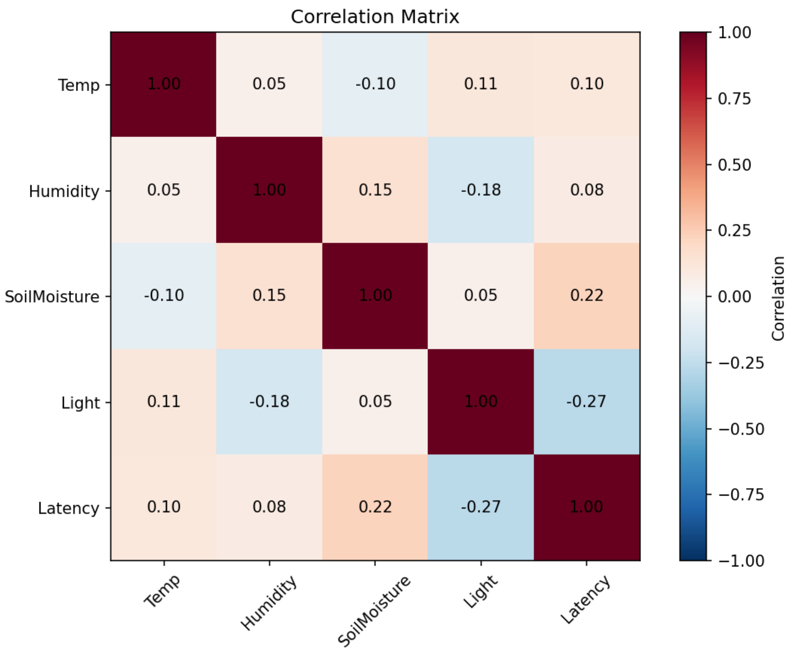

Figure 3: Correlation matrix showing relationships between environmental parameters.

5.4 Queuing Model Analysis

Figure 4 illustrates the M/M/1 queuing model behavior.

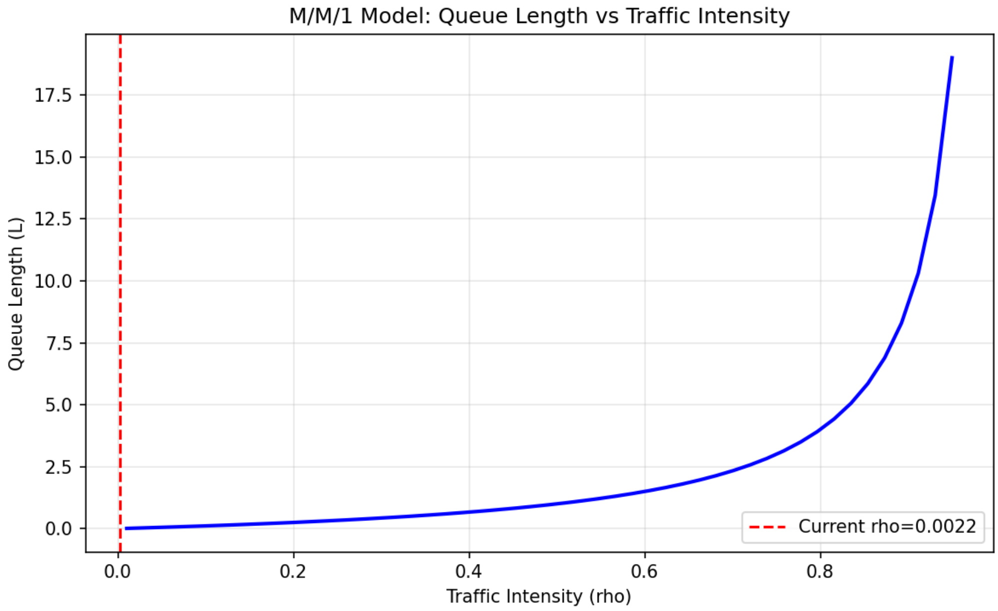

Figure 4: M/M/1 model showing queue length vs traffic intensity. The system operates at $\rho = 0.00216$ (red line), far from the unstable region.

5.5 Actuator Performance

Figure 5 shows actuator utilization and latency patterns.

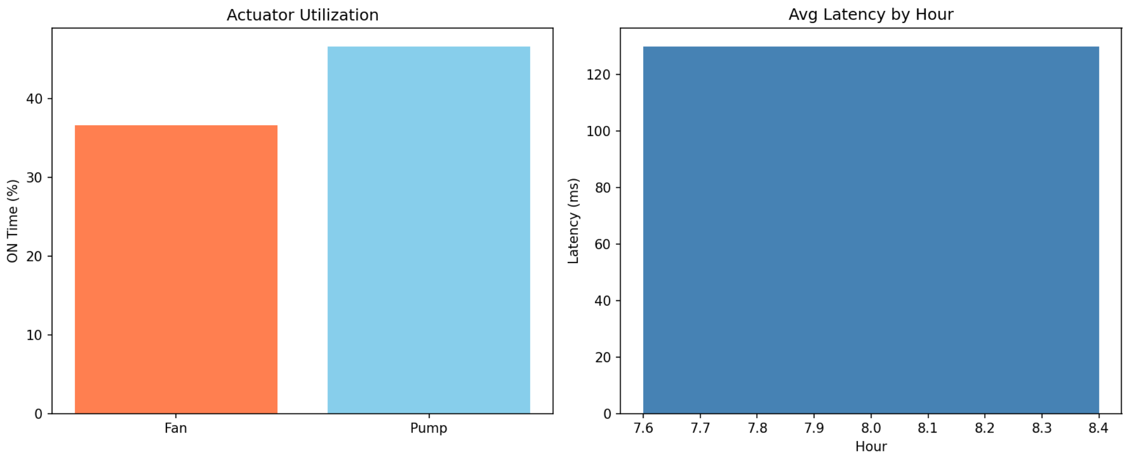

Figure 5: Left: Actuator utilization percentages. Right: Average latency by hour.

6 Discussion

6.1 System Stability

The traffic intensity $\rho = 0.00216$ is significantly less than 1, indicating the system operates in a highly stable region. The control system processes requests much faster than they arrive, ensuring no queue buildup.

6.2 Latency Performance

With mean latency of 129.8ms and P95 of 165.6ms, the system provides acceptable response times for greenhouse control applications where real-time requirements are typically in seconds rather than milliseconds [4].

6.3 Control Effectiveness

High correlations between environmental parameters and actuator states demonstrate effective automated control. The system responds appropriately to environmental changes without manual intervention.

6.4 Bottleneck Analysis

The current bottleneck is the control latency itself. However, with $\rho \ll 1$, this bottleneck does not cause queuing delays. The system has significant capacity headroom for future scaling.

6.5 Scalability Assessment

The system could theoretically handle approximately 400 times the current load before ρ approaches 0.9, where queue lengths would become significant.

7 Conclusions

7.1 Key Findings

1. The smart greenhouse IoT system is **stable** with traffic intensity $\rho = 0.00216$
2. Average queue length is negligible ($L = 0.00217$), meaning requests are processed immediately
3. Little's Law verification confirms the validity of the M/M/1 model application
4. Strong correlations between sensors and actuators indicate effective control logic
5. The system can handle significantly higher loads before approaching instability

7.2 Recommendations

1. Increase sampling frequency (e.g., every 10 seconds) for finer control without stability issues
2. Implement predictive control algorithms to reduce latency
3. Monitor P95 latency as a service level indicator
4. Consider redundant controllers for mission-critical deployments

7.3 Limitations

- Dataset contains only 30 records over 30 minutes
- Single-day data may not capture seasonal variations
- M/M/1 assumes exponential service times, which may not perfectly match real latency distribution

7.4 Future Work

Future studies could extend this analysis with larger datasets, implement predictive maintenance models, and evaluate multi-server queuing models (M/M/c) for distributed greenhouse systems.

References

[1] IoT Analytics, "Smart Agriculture Market Report," 2023. [Online]. Available: https://iot-analytics.com

[2] L. Kleinrock, *Queueing Systems, Volume 1: Theory.* New York, NY, USA: Wiley-Interscience, 1975.

[3] J. D. C. Little, "A proof for the queuing formula: L = λW," *Operations Research*, vol. 9, no. 3, pp. 383–387, 1961.

[4] R. Jain, *The Art of Computer Systems Performance Analysis.* New York, NY, USA: Wiley, 1991.

[5] N. S. U. S. Kavinda, "Smart Greenhouse System Performance Analysis," GitHub Repository, 2024. [Online]. Available: `https://github.com/Udara-Sampath/Smart-Greenhouse-System-Performance-Analysis`

8 Appendices

8.1 Appendix 1: Source Code

The complete Python source code for this analysis is available at:
`https://github.com/Udara-Sampath/Smart-Greenhouse-System-Performance-Analysis`

The main analysis script `greenhouse_analysis.py` performs the following operations:

- Data loading and preprocessing
- Descriptive statistics calculation
- M/M/1 queuing model implementation
- Little's Law verification
- Correlation analysis
- Visualization generation

8.2 Appendix 2: Dataset Description

The dataset `dataset_sample.csv` contains 30 records with the following columns:

- `Timestamp` - Date and time of reading
- `Temperature (°C)` - Ambient temperature
- `Humidity (%)` - Relative humidity
- `Soil Moisture (%)` - Soil moisture level
- `Light Intensity (lux)` - Light level
- `Fan State` - Fan status (0=OFF, 1=ON)
- `Pump State` - Pump status (0=OFF, 1=ON)
- `Control Latency (ms)` - Response time

8.3 Appendix 3: M/M/1 Model Summary

Table 4: M/M/1 Model Parameters and Results

Parameter	**Value**
Arrival Rate (λ)	0.0167 per second
Service Rate (μ)	7.70 per second
Traffic Intensity (ρ)	0.00216
Average Queue Length (L)	0.00217
Average Wait Time (W)	130.11 ms
System Status	STABLE