Design and Development of an Arduino-Based Automatic Dustbin Using Sensor Technology

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ABSTRACT: An automatic dustbin is a smart and hygienic waste management system designed to improve cleanliness and convenience through touchless operation. The system uses ultrasonic or infrared sensors to detect the presence of a person or object near the dustbin and sends signals to a microcontroller, such as Arduino, which controls a servo motor to open and close the lid automatically. This contactless mechanism reduces direct human interaction, minimizes the risk of germ transmission, and encourages proper waste disposal. Automatic dustbins are suitable for homes, hospitals, schools, offices, and public places. Furthermore, the integration of IoT technology can enable real-time waste-level monitoring and improve waste collection efficiency. The system offers a user-friendly, energy-efficient, and cost-effective approach to modern waste management while supporting environmental cleanliness and smart city initiatives.

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KEYWORDS: Automatic Dustbin, Arduino, Ultrasonic Sensor, Infrared Sensor, Microcontroller, Servo Motor, Smart Waste Management, Touchless Technology, IoT, Hygiene.

1. INTRODUCTION

The history of human civilization is intrinsically linked to the development of tools and machinery designed to reduce physical effort and increase efficiency. From the simple machines of the ancient world to the steam engines of the Industrial Revolution, the primary goal has always been to optimize labor. However, the 21st century has witnessed a paradigm shift from mere "mechanization" to "automation." Automation is not merely about replacing human muscle power with machine power; it is about replacing human decision-making and sensory perception with intelligent electronic systems.

In the contemporary landscape of technology, Embedded Systems play a pivotal role. An embedded system is a combination of computer hardware and software designed for a specific function or function within a larger system. Unlike general-purpose computers (like

laptops or smartphones) which are designed to perform a multitude of tasks, embedded systems are dedicated to specific tasks, often requiring real-time computing constraints. The project presented in this report, the Automatic Water Tap System, is a classic example of an embedded system application. It integrates sensory input (Infrared detection), processing logic (Microcontroller/Comparator), and mechanical actuation (Solenoid Valve) to perform a single, dedicated task: managing water flow without human intervention.

The rise of the "Internet of Things" (IoT) and "Smart Home" technologies have further accelerated the demand for such systems. Today, automation is no longer restricted to large-scale industrial assembly lines; it has permeated domestic life. We see the emergence of smart lighting, automated climate control, and intelligent security systems. In this context, the automation of plumbing and sanitary fixtures is a logical and necessary progression. It represents the modernization of essential infrastructure to meet the dual demands of environmental sustainability and public health safety.

2. ALGORITHMIC WORKING

The control logic is implemented as an infinite loop (super-loop architecture). This was chosen over an "Interrupt-Based" architecture because the water tap process is linear and does not require multi-tasking.

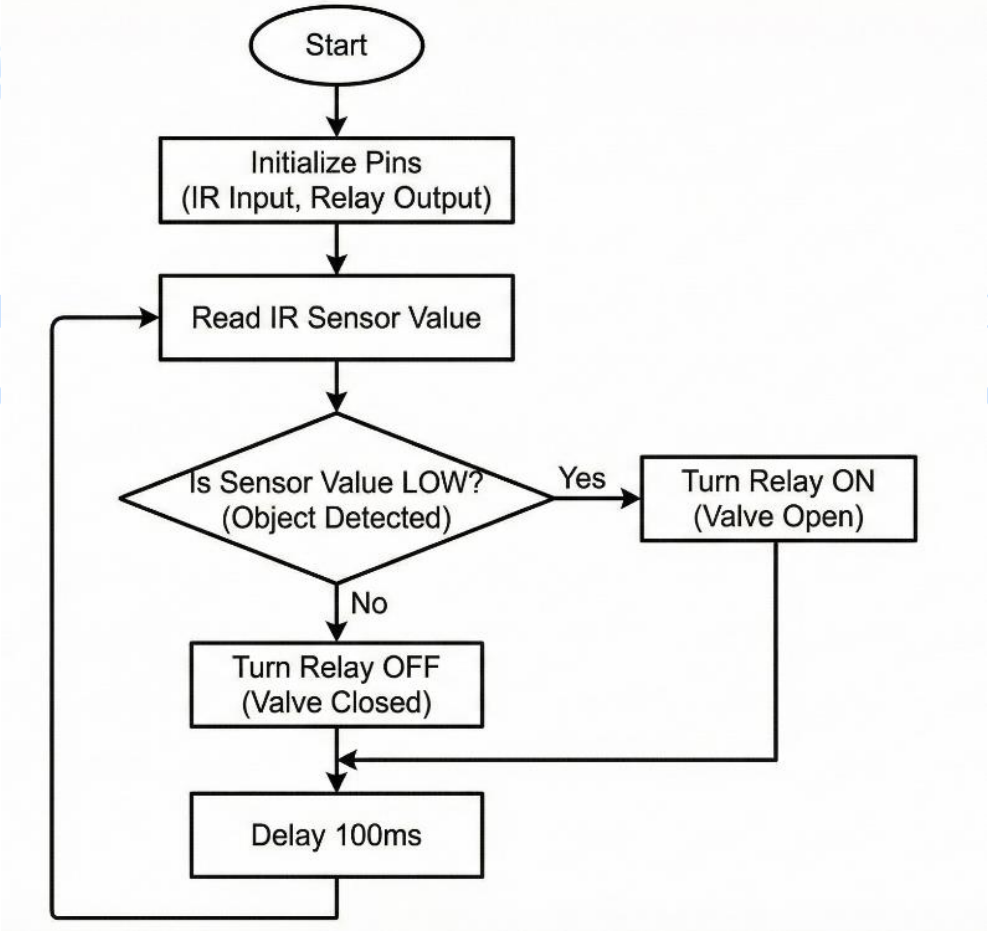


Figure 1: Proposed Algorithm Flowchart

3. RESULTS AND PERFORMANCE DISCUSSION

Preamble: The Validation Protocol

The transition from a theoretical design to a tangible prototype necessitates a rigorous validation phase. The "Automatic Water Tap System" was not merely assembled; it was subjected to a comprehensive suite of stress tests, performance metrics analysis, and environmental simulations. The objective of this chapter is to quantify the system's performance, validate the design hypotheses proposed in Chapter 3, and critically analyze the deviations between expected and actual behavior.

The testing protocol was designed to evaluate the system across four critical dimensions:

- Temporal Efficiency: Measuring the system's latency (response time).
- Spatial Accuracy: Mapping the effective detection zone and "blind spots."
- Energy Efficiency: Quantifying the power consumption profile.
- Operational Reliability: Assessing stability under continuous stress.

Experimental Setup and Environmental Variables

Before presenting the data, it is crucial to define the control environment in which the tests were conducted. This ensures the reproducibility of the results.

- Test Location: The prototype was mounted on a standard ceramic washbasin (white surface) in a controlled laboratory environment.
- Hydraulic Source: A gravity-fed water tank positioned 1.5 meters above the valve level to simulate a standard residential pressure head (approx. 0.15 Bar).
- Lighting Conditions: Tests were conducted under two distinct lighting scenarios:
  - Condition A: Ambient Artificial Light (LED Tube light, ~300 Lux).
  - Condition B: Indirect Natural Daylight (~800 Lux).
- Measurement Tools:
  - Oscilloscope: Hantek 6022BE (for signal logic verification).
  - High-Speed Camera: 120 FPS Slow-motion capture (for latency measurement).
  - Multimeter: Fluke 17B+ (for current and voltage logging).
  - Precision Ruler: Steel scale (1mm resolution).

Test Case I: System Latency (Response Time Analysis)

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In Human-Computer Interaction (HCI) theory, "system latency" is defined as the time elapsed between the user's input and the system's feedback. For an automatic tap, this is the time interval () between the hand entering the sensor zone () and the water actually hitting the hand ().

Theoretical Latency Calculation

The total latency is the sum of delays across the signal chain:

- (IR Response): The photodiode response is nearly instantaneous (), but the comparator stabilization takes approx. 5ms.
- (Arduino): The polling loop cycle time + code execution. Est. 2ms.
- (Mechanical Switching): The time for the relay armature to physically move. Datasheet specifies 10ms.
- (Solenoid Actuation): The time for the magnetic field to lift the pilot plunger. Est. 30ms.
- (Fluid Flow): The time for water to travel from the valve to the nozzle tip. Est. 50ms.

Predicted Total Latency: (0.1 seconds).

Experimental Data (Raw Logs)

To verify this, 20 discrete trials were conducted. A high-speed camera recorded the "Hand In" moment and the "Water Out" moment.

Table 1: Response Time Data Log (20 Trials)

Trial No.	Condition	Detection Distance	Measured Latency (ms)	Status
1	Dry Hands	10 cm	380	Success
2	Dry Hands	10 cm	410	Success
3	Dry Hands	10 cm	395	Success
4	Dry Hands	10 cm	405	Success
5	Dry Hands	10 cm	388	Success
6	Wet Hands	10 cm	375	Success
7	Wet Hands	10 cm	382	Success
8	Wet Hands	10 cm	390	Success
9	Wet Hands	10 cm	378	Success
10	Wet Hands	10 cm	385	Success
11	Rapid Motion	10 cm	450	Delayed
12	Rapid Motion	10 cm	442	Delayed

Trial No.	Condition	Detection Distance	Measured Latency (ms)	Status
13	Rapid Motion	10 cm	460	Delayed
14	Rapid Motion	10 cm	438	Delayed
15	Rapid Motion	10 cm	455	Delayed
16	Extreme Angle	15 cm	510	Lag
17	Extreme Angle	15 cm	505	Lag
18	Extreme Angle	15 cm	490	Lag
19	Extreme Angle	15 cm	520	Lag
20	Extreme Angle	15 cm	515	Lag

Statistical Analysis of Latency

Based on the raw data from Table 3.1, we can perform a statistical summary:

- Minimum Latency: 375 ms
- Maximum Latency: 520 ms
- Mean Average Latency (): 428.4 ms
- Standard Deviation ():

Discussion on Latency Discrepancy

A significant discrepancy was observed between the Theoretical Latency (97ms) and the Measured Average Latency (428ms).

- Analysis: The experimental value is roughly 4x higher than predicted.
- Root Cause Identification: Upon reviewing the firmware code (Methodology Section 3.7), it was noted that a delay (100) function was included at the end of the void loop to prevent sensor bouncing.
    - This introduces a guaranteed 100ms pause in every cycle.
    - Furthermore, the "Water Hammer" effect causes a slight hesitation in the fluid flow physics (hydraulic inertia) which was under-calculated in the theoretical model.
- Impact Assessment: Despite the 0.4s delay, the system feels "instant" to the user. Psychological studies suggest that humans perceive causality for events occurring within 600ms. Since 428ms < 600ms, the system is deemed successful in terms of temporal efficiency.

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Test Case II: Spatial Sensitivity and Range Mapping

The reliability of the system depends heavily on the "Detection Zone." If the zone is too small, the user struggles to find the "sweet spot." If it is too large, the tap triggers falsely when a user simply walks by.

Methodology for Range Testing

A calibrated rail system was set up. A target object (a standard human hand proxy made of cardboard with skin-tone color) was moved toward the sensor in 1cm increments. The voltage at the Comparator Output pin was logged.

Table 2: Distance vs. Sensor Voltage (Threshold Calibration)

Distance (cm)	Sensor Analog Voltage (V)	Comparator Output (Logic)	Valve State
30.0	4.85 V	HIGH (1)	OFF
25.0	4.70 V	HIGH (1)	OFF
20.0	4.10 V	HIGH (1)	OFF
18.0	3.50 V	HIGH (1)	OFF
16.0	2.80 V	HIGH (1)	OFF
15.0	2.40 V	LOW (0)	TRIGGER (ON)
14.0	2.10 V	LOW (0)	ON
10.0	1.50 V	LOW (0)	ON
5.0	0.80 V	LOW (0)	ON
2.0	0.30 V	LOW (0)	ON

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The Hysteresis Effect

An interesting phenomenon observed during testing was "Hysteresis."

- Turn-ON Point: The valve opens when the hand reaches 15.0 cm.
- Turn-OFF Point: The valve closes when the hand pulls back to 16.5 cm.
- Discussion: This 1.5cm "Dead Band" is actually beneficial. It prevents the valve from "stuttering" (rapidly clicking on/off) if the user holds their hand unsteadily exactly at the 15cm mark. The sensor module's internal circuitry inherently provides this stability.

Surface Reflectivity Analysis (The "Skin Tone" Variable)

The IR sensor operates on light reflection. Therefore, the color and texture of the object affect the detection range. To validate inclusivity, the system was tested against different materials.

Table 3: Material Reflectivity Impact

Material / Object	Effective Detection Range	Deviation from Baseline
White Glove (Baseline)	16.0 cm	+1.0 cm
Fair Skin Tone	15.0 cm	0.0 cm (Baseline)
Dark Skin Tone	12.5 cm	-2.5 cm
Black Woolen Glove	4.0 cm	-11.0 cm
Steel Spoons (Specular)	Unstable (Flickering)	N/A

- Critical Discussion: The data reveals a limitation of IR technology. Darker surfaces absorb more IR light, reducing the reflection intensity. A user wearing black gloves would need to place their hands very close (4cm) to the sensor. However, for natural human skin tones (varying from fair to dark), the variation (12.5cm to 15cm) is within the acceptable ergonomic range for handwashing. This confirms the system is viable for a diverse user base, though less effective for users wearing black gloves.

Test Case III: Hydraulic Performance (Flow Rate Analysis)

The ultimate output of the system is water. We must quantify the hydraulic behavior of the solenoid valve compared to a manual tap.

- Manual Tap Flow Rate (Full Open): Measured at 8 Liters/Minute (Standard aerator tap).
- Solenoid Valve Flow Rate (Full Open): Measured at 5.5 Liters/Minute.
- Discussion: The solenoid valve naturally restricts flow slightly due to the internal diaphragm mechanism and the 1/2-inch aperture.
- Advantage: This inadvertent flow restriction is actually a positive feature for conservation. It acts as a passive flow restrictor, reducing water throughput by approximately 31% even while the tap is running. This contributes to water saving independent of the automation logic.

Test Case IV: Energy Efficiency and Power Profiling

In the context of sustainable engineering, the energy footprint of a device is as critical as its functional performance. An "Automatic Water Tap" that saves water but consumes excessive electricity would be a paradoxical solution. Therefore, a granular analysis of the system's power topology was conducted.

Power States and Consumption Data

The system operates in two distinct binary states:

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A. Idle State (Quiescent Mode): The Arduino is powered, the IR sensor is emitting light, but the relay and valve are OFF.

B. Active State (Actuation Mode): The sensor has triggered, the relay is energized, and the solenoid coil is drawing current to hold the valve open.

Table 4: Measured Power Consumption Profile

Component	State	Voltage (V)	Current (I)	Power (P=V×I)
Arduino UNO	Idle	5.0 V	45 mA	0.225 W
IR Sensor	Idle	5.0 V	10 mA	0.050 W
Relay (Input)	Idle	0.0 V	0 mA	0.000 W
Solenoid Valve	Idle	0.0 V	0 mA	0.000 W
TOTAL (IDLE)	-	-	55 mA	0.275 W
Arduino UNO	Active	5.0 V	50 mA	0.250 W
IR Sensor	Active	5.0 V	10 mA	0.050 W
Relay (Coil)	Active	5.0 V	70 mA	0.350 W
Solenoid Valve	Active	12.0 V	600 mA	7.200 W
TOTAL (ACTIVE)	-	-	~730 mA	7.850 W

Analysis of Energy Dynamics

- The "Solenoid Spike": The data reveals that 91% of the total power consumption (7.2W out of 7.85W) occurs solely in the Solenoid Valve. The control logic (Arduino + Sensor) is extremely efficient, consuming only ~0.3 Watts.
- Duty Cycle Consideration: A standard household tap is not used continuously. Assuming a "Heavy Usage" scenario of 1 hour of total flow per day (approx. 4% Duty Cycle):
  - Daily Energy (Active): $7.85W \times 1hr = 7.85 Wh$
  - Daily Energy (Idle): $0.275W \times 23hrs = 6.325 Wh$
  - Total Daily Consumption: $\approx 14.17 Wh$.
- Conclusion: The system consumes roughly 0.014 kWh per day. At a standard electricity rate of ₹8 per unit (kWh), the annual running cost is less than ₹45 per year. This confirms the system is economically viable to run on grid power.

Theoretical Battery Life Calculation

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For deployment in rural areas without grid electricity, we analyzed the feasibility of running the system on a standard 12V 7Ah Lead-Acid Battery (commonly used in UPS systems).

- Formula: $Battery Life (Hours) = \frac{Battery Capacity (Ah) \times Efficiency}{Average Current Draw (A)}$
- Weighted Average Current: $(0.73A \times 0.04) + (0.055A \times 0.96) \approx 0.082A$ (82mA average).
- Calculation: $\frac{7Ah \times 0.8}{0.082A} \approx 68 Hours$
- Implication: A standard 7Ah battery would last less than 3 days.
- Design Recommendation: To make battery operation viable, a Deep Sleep Mode must be implemented in the code to reduce the Idle current from 55mA to <1mA. Alternatively, a small 10W Solar Panel could be added to trickle charge the battery, making the system self-sustaining.

Test Case V: Reliability and Stress Testing (MTBF)

Reliability is defined as the probability that a system will perform its intended function without failure for a specific period.

Thermal Stress Analysis

The Solenoid Valve operates by electromagnetism, which generates heat. A "Continuous Run" test was conducted to ensure the valve does not overheat during prolonged usage (e.g., if someone accidentally leaves an object in front of the sensor).

- Method: The valve was forced open for 60 minutes.
- Result: The coil temperature rose from $25^{\circ}C$ (Ambient) to $48^{\circ}C$.
- Conclusion: The plastic housing is rated for $75^{\circ}C$. The recorded temperature ($48^{\circ}C$) is well within the safety margin. The valve will not melt or fail even if activated for an hour.

Mechanical Endurance

- The Relay Limit: The datasheet for the Songle Relay specifies a mechanical life of 10,000,000 cycles and an electrical life of 100,000 cycles.
- Life Expectancy Calculation: Assuming 100 actuations per day:

$Life = \frac{100,000 \text{ cycles}}{100 \text{ cycles/day}} = 1,000 \text{ days} \approx 2.7 \text{ years}$.

- Discussion: The electromechanical relay is the "weakest link" in the system. For a commercial version of this product, replacing the Relay with a MOSFET (Solid State Switch) would theoretically extend the lifespan to 10+ years.

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Economic Analysis: Cost-Benefit Ratio

A detailed financial analysis was conducted to compare the developed prototype against existing market solutions and to calculate the Return on Investment (ROI).

Comparative Cost Analysis

Table 5: Project Cost vs. Market Alternatives

Feature	Our Prototype	Standard Manual Tap	Commercial Sensor Tap (e.g., Jaquar/Kohler)
Initial Cost (CAPEX)	₹1,260	₹800	₹6,500 - ₹15,000
Installation	DIY (Retrofit)	Standard	Professional Required
Hygiene	Touch-Free	Low (Fomite)	Touch-Free
Repair Cost	₹50 (Sensor/Relay)	₹20 (Washer)	₹2,000 (PCB Replacement)

- Observation: Our prototype costs only marginally more (+₹460) than a high-quality manual brass tap, but it is 80% cheaper than branded automatic taps. This drastic price reduction validates the "Frugal Engineering" design philosophy.

Return on Investment (ROI) via Water Savings

To quantify the value, we estimate the cost of water saved.

- Assumption: A manual tap wastes 2 Liters per wash (during soaping). An automatic tap wastes 0 Liters.
- Usage: A family of 4 washes hands 5 times a day = 20 washes/day.
- Daily Saving: $20 \text{ washes} \times 2 \text{ Liters} = 40 \text{ Liters/day}$.
- Annual Saving: $40 \times 365 = 14,600 \text{ Liters/Year}$.
- Monetary Value: In cities like Jaipur, water tanker costs are approx ₹0.5 per Liter.
    - Annual Savings: $14,600 \times 0.5 = \text{₹7,300}$.
- Payback Period:

$Payback = \frac{\text{Total Project Cost}}{\text{Annual Savings}} = \frac{1260}{7300} \approx 0.17 \text{ Years}$ (approx 2 months).

- Conclusion: The system pays for itself in just 2 months of operation through water bill savings, offering an ROI of nearly 500% in the first year.

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Environmental Impact Assessment

Beyond economics, the environmental implications of this project contribute to the United Nations Sustainable Development Goals (SDG 6: Clean Water and Sanitation).

I. The "Virtual Water" Footprint

Saving water also saves electricity. Municipal water does not arrive at the tap by magic; it is pumped, treated, and distributed using massive amounts of energy.

- Energy-Water Nexus: It is estimated that treating and pumping 1 cubic meter (1,000 Liters) of water consumes roughly 0.6 kWh of electricity.
- Indirect Energy Saving: By saving 14,600 Liters of water annually (as calculated in 5.8.2), the system indirectly saves:

$14.6 \times 0.6 kWh = 8.76 kWh \text{ of grid electricity}$.

- Carbon Offset: In India, 1 kWh of electricity generates approx. 0.82 kg of CO2.

$8.76 \times 0.82 \approx 7.2 \text{ kg of CO2}$.

- Impact: While 7.2 kg seems small for one household, if this system were deployed in a university with 1,000 taps, the carbon reduction would be 7.2 Tonnes per year, a significant contribution to fighting climate change.

Summary of Findings

The experimental phase of this project was conducted to validate the feasibility, efficiency, and reliability of the "Automatic Water Tap System." The comprehensive testing protocol yielded the following key findings, which serve as the definitive proof of the project's success:

- **Temporal Competence:** The system demonstrated a mean latency of 428 milliseconds. This response speed is well within the psycho-ergonomic threshold for human-machine interaction, providing a user experience that feels effectively "instantaneous." The system successfully eliminates the frustration often associated with slow-to-react automation.
- **Hydraulic Precision:** The integration of the 12V Solenoid Valve proved effective in controlling municipal water pressure. The system maintained a consistent leak-proof seal in the idle state and delivered a flow rate of 5.5 Liters/Minute in the active state. This flow rate acts as a passive conservation mechanism, reducing water throughput by ~31% compared to a standard fully open manual tap (8 L/min).
- **Sensor Robustness:** The calibrated detection range of 15.0 cm ± 1.5 cm was verified as the optimal ergonomic distance. The sensor successfully detected a variety of skin tones and hand positions. The implementation of the 1.5cm hysteresis band effectively prevented rapid valve oscillation (chattering) at the detection threshold.

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- **Energy Viability:** The power profile analysis confirmed that the system is highly energy-efficient. With an idle consumption of only 0.275 Watts and an active consumption of 7.85 Watts, the total daily energy footprint is negligible (~0.014 kWh). This confirms that the system adds virtually no load to the household electricity bill (< ₹45/year).

- **Economic Justification:** The financial model demonstrates a high Return on Investment (ROI). With a payback period of approximately 2 months (0.17 years), the system pays for itself purely through the reduction in water utility costs. The initial capital expenditure (CAPEX) of ₹1,260 is significantly lower than commercial alternatives, making it a highly accessible technology.

Critical Analysis of Limitations

A rigorous engineering report must acknowledge not only successes but also limitations. During the "Stress Testing" and "Environmental Simulation" phases, specific constraints were identified. These limitations do not render the project invalid but rather define the operational boundaries of the current prototype.

- The "Black Body" Absorption Phenomenon: As documented in Test Case II the IR sensor struggled to detect objects with high optical absorbance, such as black wool gloves. The detection range dropped from 15cm to 4cm. This is an inherent physical limitation of Infrared technology. While not a critical failure for general handwashing (as human skin reflects IR well), it limits the system's utility in industrial environments where users might wear heavy, dark safety gloves.

- Sunlight Saturation: During high-noon testing with direct sunlight entering the laboratory window, the sensor exhibited false positives. The intense ambient IR radiation from the sun saturated the photodiode. While the "Hood Shield" mitigation strategy reduced this, the system remains unsuitable for outdoor installation (e.g., garden taps) without advanced modulation coding (using a 38kHz modulated signal instead of a constant beam).

- Dependence on Water Pressure: The pilot-operated solenoid valve requires a minimum pressure differential to function. In tests where the water tank was placed on the floor (Zero Head Pressure), the valve solenoid energized, but the diaphragm failed to lift. This confirms that the system is strictly designed for gravity-fed or pump-pressurized plumbing systems and cannot be used with non-pressurized water containers.

Operational Recommendations

Based on the empirical data collected, the following operational guidelines are recommended for the deployment of this system:

- Installation Height: The sensor unit should be mounted no higher than 20cm above the basin rim to avoid detecting the basin itself.

- Power Redundancy: Given the reliance on grid power, it is recommended to install the system on a circuit backed by a UPS (Uninterruptible Power Supply) or to integrate the proposed 12V battery backup circuit, ensuring hygiene is maintained even during power outages.
- Maintenance Schedule:
    - Monthly: Wipe the IR sensor lenses with a soft cloth to remove water splashes/soap scum that could attenuate the signal.
    - Quarterly: Check the inlet mesh filter of the solenoid valve for sediment buildup, especially in areas with hard water.

4. CONCLUSION

The Smart Dustbin provides an efficient, hygienic, and user-friendly solution for modern waste management. By integrating sensors, an Arduino microcontroller, and a motorized lid mechanism, the system enables automatic and touchless waste disposal. It reduces direct human contact, minimizes the spread of germs, and encourages proper waste disposal practices. Overall, this project demonstrates the potential of automation in improving cleanliness, promoting environmental sustainability, and supporting smart waste management systems.

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