

Cyber-Physical AI-IoT Robotic Solution for Automated Lavatory Hygiene and Resource Management Optimization

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ABSTRACT- Automated lavatory cleaning has improved with a new specialized robot. This system has three main goals; building an autonomous robot, using water efficiently, and setting up a daily cleaning schedule with set intervals. The robot has cleaning tools on an adjustable arm and uses sensors to move around freely. Its arm can reach tough spots like the toilet bowl, sink, and floor. Users can program the cleaning schedule with a timer. The toilet-cleaning robot has been put through its paces across a range of restroom settings, including public, business, and private restrooms. The water-saving cleaning system uses a high-pressure water pump and nozzles that function as bathroom cleaning equipment to clean designated toilet sections. The robot system achieved complete cleaning of all restroom surfaces, including hard-to-reach areas such as the back of the toilet bowl and the underside of the washbasin. The automatic lavatory cleaning robot uses an energy-saving cleaning system. The robots operate in public restrooms which serve highway travelers as they maintain cleanliness throughout the area while decreasing staffing requirements. The system can clean both Indian toilets and Western-style commodes. The robot uses a cleaning liquid and a brush to sanitize the toilet bowl. The system operates with enhanced performance because it uses smart features together with microcontrollers and servo motors and modern manufacturing methods which include 3D printing and Autodesk Fusion 360.

Keywords: Lavatory cleaning robot, Robotic arm, Autonomous cleaning, AI, IoT, Cyber, Water conservation, Scheduled cleaning, Automation, DC (Direct Current).

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1. INTRODUCTION

The first purpose of robots in automation exists to execute basic repetitive tasks which help lower costs for each produced item. Urban sanitation is an essential concept in today's society, but several obstacles remain. To maintain hassle-free, hygienic sanitary standards in the environment, an automatic lavatory cleaner is used. Lavatory means toilet. The cleaning system is fully automatic and requires minimal operational power.

Furthermore, the robotic arm is part of the cleaning module, which is designed to thoroughly clean the bowl; a brush is attached to the robotic arm. An automatic toilet cleaner is also used in shared toilets on roads to reduce staffing requirements and maintain a hygienic environment. Two servo motors are

used for automatic lavatory cleaning. The first 360-degree servo motor is used to rotate the brush 360 degrees to clean the toilet bowl. The second 180-degree servo motor is used for the up-down movement of the brush. The robotic arm has two links, and the base is the central part. The base will hold the whole assembly and provide rotary motion to the robot.

For the implementation of the Indian toilet and testing of the English toilet cleaning, this Lavatory Cleaning Robot system is used. For the DC geared motor, 12V DC is required; for the servo motor, 4.8V to 6V is required. The dimensions of the toilet bowl are 720 x 730. The automatic lavatory cleaner cleans the toilet bowl for hygienic purposes and maintains a sanitary environment by dispensing cleaning liquid through the solenoid valve. The two servo motors are used for the circular movement and 360-degree rotation of the brush.

The microcontroller is connected to the servo motor via the servo motor driver. The proximity sensor is used to maintain the rotation in the bowl and avoid collision in the toilet bowl. A robotic arm is used for cleaning purposes. The brush is attached to the robotic arm. Two servo motors are used, one for the water supply and the second for the cleaning liquid. Two DC water pumps are used, one for washing liquid and one for water. A 90-degree servo motor is used for the up-and-down movement of the brush. The movement of the brush for the Indian toilet is horizontal in the toilet closet. One motor is fixed at the end of

the robotic arm for the horizontal movement of the brush for the Indian toilet.

The research work on automation and intelligent systems focuses on developing cleaning methods which achieve better hygiene results and improved operational efficiency and environmental sustainability. Researchers began their studies on robotic cleaning systems to create machines which could perform the demanding work of cleaning and maintain high sanitary standards. [1] Bharadwaj et al. proved that robots which function autonomously and use their sensor technology with intelligent system components can clean restroom facilities. The system achieved better cleanliness results through less worker dependence and it increased operational output which created a basis for additional automated cleaning research.

Kokvin, Sziebig et al. [2] examined how industrial spaces can benefit from using robotic arms which have cognitive abilities to clean their containers. Cognitive features added to robots enable them to adapt more effectively, reducing the need for human workers and enhancing their efficiency. Shukla et al. [3] presented a complete overview of robotic cleaning and inspection systems which included the main design obstacles and new achievements in the field.

Amrutkar [4] conducted an evaluation of robotic floor cleaning systems by testing their operational performance and various system components which included their hardware and software and control methods. Their review explained past research methods and direct study obstacles which they solved through new research techniques that will assist in developing upcoming cleaning robot systems.

Research studies have examined water efficiency and sanitation system cleanliness together with robotic automation systems. Wang et al. [5] proposed using electromagnetic valves to improve water management systems which would lead to urban sustainability in water usage. The research demonstrated that traditional water conservation methods had certain boundaries which automated systems could successfully overcome.

Wath [6] developed a mechanical automatic flusher to conserve water and reduce manual labor, supporting the goals of the Swach Bharat Mission.

Osathanunkul [7] introduced a smart urinal flushing system that uses the MQTT protocol for remote monitoring and control. The research demonstrated that IoT-based solutions enable public restrooms to achieve better water management and improved sanitary conditions. Boonyakan et al. [8] demonstrated the necessity to solve water scarcity problems through their work which created water-saving technologies that serve multiple purposes.

Different industries have adopted intelligent automation systems to improve both user satisfaction and their operational performance. Awati and Awati [9] used RFID technology together with sensors and mobile applications in their research about shopping carts which showed that smart functions help

users find products and create custom experiences while improving operational efficiency. The retail study results provide useful information about how to use sensors and automation technologies to create effective cleaning solutions. Feng et al. [10] showed that high-speed train systems achieve their intended design performance when they use modular design processes. The present findings show that industries now use advanced IoT-based sensor systems for their automated cleanliness operations which improve both their work efficiency and their environmental sustainability. The research shows that modern cleaning and sanitation technologies now depend on robotics and automation and intelligent water management systems as fundamental components.

- Design of an automatic lavatory cleaning robot;
- Development of designing an automatic lavatory cleaning robot; design of a daily time-controlled cleaning system.

The primary aim was to develop a lavatory-cleaning robot with autonomous operation and water-saving capabilities. Additionally, a daily cleaning schedule with predetermined time intervals was established. This research details the processes undertaken to design and construct the Lavatory Cleaning Robot in alignment with these objectives.

2. METHODOLOGY

The Cyber-Physical AI-IoT Lavatory Cleaning Robot gets developed through a methodical approach which combines mechanical design with embedded control systems and smart sensors and Internet of Things communication and efficient movement systems. The robot operates through an ongoing process which enables it to detect its surroundings and analyze information and execute cleaning tasks while sending data through the Internet of Things network for system observation and performance enhancement. The development process consists of five essential stages which include system architecture development and system detection and perception and artificial intelligence decision-making and Internet of Things system monitoring and control and robot movement control with resource management.

2.1. System Architecture Design

The system consists of a robotic arm, cleaning equipment, sensors, a microcontroller, and an Internet of Things communication system. The arm uses aluminum components and 3D-printed parts created with Autodesk Fusion 360 to produce a lightweight structure capable of handling multiple surface-cleaning tasks. The ARM LPC2148 microcontroller manages sensor operations and movement control, liquid distribution, and data exchange, which allows real-time synchronization of cleaning processes with digital tracking in the system's closed-loop environment.

2.2. Sensing and Data Acquisition

The robot operates through its system which collects environmental data together with its operational performance data. The robot uses proximity sensors to detect surface edges which enables it to avoid collisions with obstacles. The system uses water-flow sensors together with pump feedback to

monitor water and cleaning liquid consumption during each operational cycle. The cleaning schedule operates through the built-in Real-Time Clock (RTC) system. The system uses all sensor data to create a digital map of the lavatory which serves as the basis for its operational decisions.

2.3. AI-Based Decision and Control Logic

The robot operates on an artificial intelligence control system when performing cleaning activities since this system enables it to be used to carry out cleaning activities in various conditions. The system employs sensor information and cleanliness needs to decide on the working parameters of brush movements, cleaning time and amount of cleaning solution. The AI system measures the contact of the surface and the pump activity and the past cleaning process with current hindrances to decide on the optimum cleaning power and cleaning process schedule. The longer the time that the robot takes to clean, the greater the intensity of resistance that it senses. Major dirt takes less time to be cleaned by the system since the system does not want to waste water resources. The smart system helps in increasing resources and also provides better cleaning results.

2.4. IoT-Enabled Monitoring and Resource Management

The robot is operated on the basis of the Internet of Things (IoT) technology. The IoT division of the system transmits the operational data to an overall dashboard that presents the cleaning schedules and water consumption data and pump workable and cleaning activity data. Remote access allows the facility managers to monitor the cleaning progress and identify unusual equipment use and order cleaning service. The data would provide an instant online image of how clean the restrooms are and the resources that are used which would allow maintenance work and usage evaluation and continued development.

2.5. Optimization of Robot Actuation and Resources

The actuation layer performs its cleaning duties by activating the work of the servo motors, DC geared motors and solenoid valves and pumps. The robotic arm is able to move in various directions and this allows it to access remote locations. Solenoids are used to regulate the supply of water and detergent to prevent the constant supply of these products. PWM allows users to attain motor speed control allowing them to control movement precision with particular speed settings. The pump controls on the robot will save water and cleaning agents that are operated through AI and this means that less waste is produced. The robot goes to its designated rest point upon completion of cleaning and it logs its work to be updated on its work in the future through the IoT.

2.6. Cyber-Physical Loop Execution

The entire methodology operates as a closed cyber-physical loop:

Sense → Interpret → Decide → Act → Report → Optimize.

The detection process begins with sensing and advances through interpretation to decision-making which ends at the

acting stage before the system sends its results to the optimization process. Sensors gather environmental data which artificial intelligence (AI) systems use to determine the best cleaning methods. The cleaning operations use actuators while Internet of Things (IoT) modules track system performance to gather data which will support future system enhancements. This loop enables automatic intelligent and sustainable bathroom cleaning operations.

2.7. Methodological Contribution

This methodology shifts lavatory cleaning from schedule-driven automation to intelligent cyber-physical operation. By embedding AI for adaptive behavior and IoT for visibility and optimization, the proposed framework enables smarter sanitation infrastructure suitable for smart buildings and smart city ecosystems.

Fig. 1 shows the robotic arm. The robotic arm is made from aluminum and 3D-printed components. Autodesk 3D printing software is used for 3D printing. In the cleaning accessories brush, cleaning liquid is present. The 3D-printed poly-silicon acid material is used. Time allocation is performed in this process using the program on the microcontroller. The movement of the brush for the Indian toilet is horizontal in the toilet closet. One motor is fixed at the end of the robotic arm for the horizontal movement of the brush for the Indian toilet.

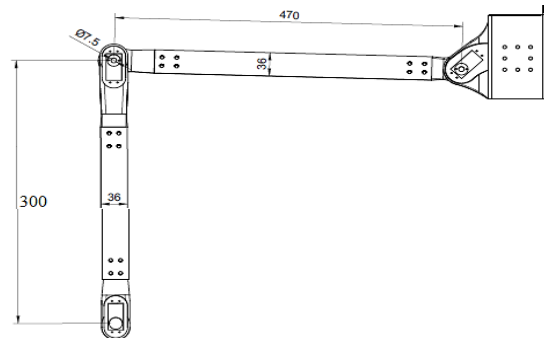


Figure 1. Robotic arm

Figure 1 shows the cleaning mechanism for the Indian toilet. Figures 2 and 3 show the cleaning mechanism for the Western toilet.

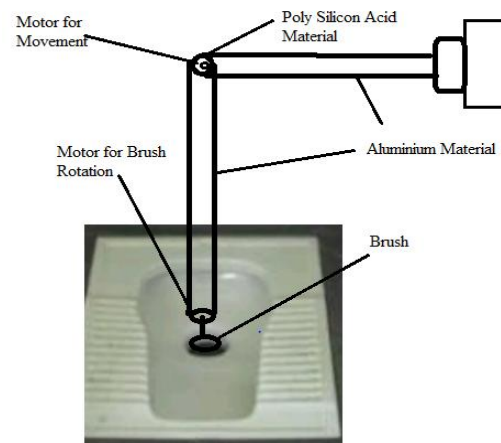


Figure 2. Cleaning mechanism of the Indian toilet

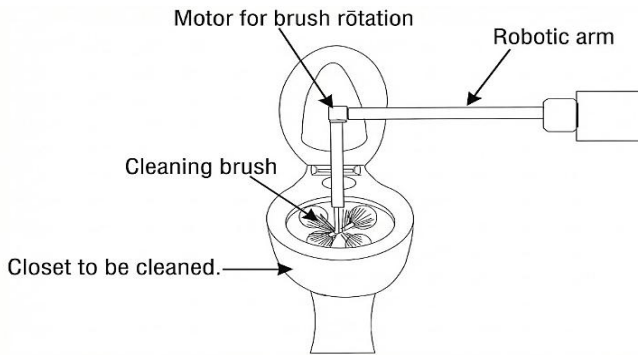


Figure 3. Cleaning Mechanism of a Western toilet

2.8. Block Diagram

The purpose of the Lavatory Cleaning Robot is to make an accurate, touch-free, and automatic toilet cleaning robot. The specific objective of the Lavatory Cleaning Robot is to develop an automatic toilet cleaning robot. Fig. 4 shows a block diagram of the Lavatory Cleaning Robot system. It consists of the following parts:

• **Solenoid assembly**

The solenoid valve is an electromagnetic valve. Two solenoid valves are used, one for water supply and the second one for washing liquid to be dispensed into the wall of the closet. These valves are controlled by electric current.

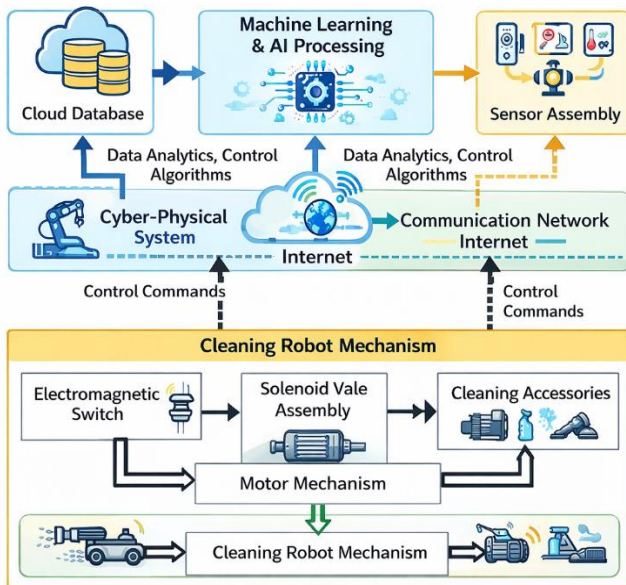


Figure 4. Block Diagram

• **Motor Mechanism**

It includes two servo motors and one DC geared motor interfaced with the microcontroller. The motor mechanism controls the rotation of the brush so that the brush can point in any direction. Servo assembly consist of four things: a DC circuit, a gearing circuit, a control circuit, and a position sensor.

• **MCU- microcontroller unit**

The whole process will be controlled using an ARM LPC 2148 microcontroller. The control signal will be sent to the microcontroller to control the motor mechanism movement in a particular time period.

• **Brushing mechanism**

The brush is attached to the DC geared motor, and by using a servo motor and a timing set in the microcontroller, the brush is rotated in the toilet bowl. Thus, the toilet bowl is clean.

• **Cleaning accessories**

It includes cleaning liquid, a brush, and a water tank. The output of the Solenoid valve is given to the cleaning accessories.

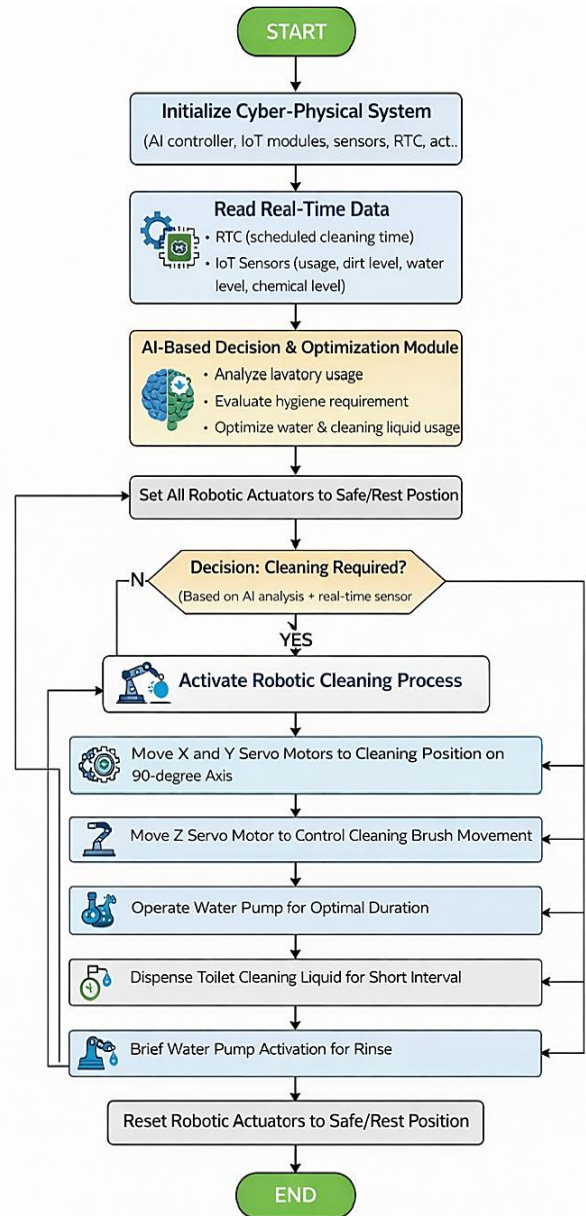


Figure 5. Flowchart of lavatory cleaning robot

2.9. Flowchart

Figure 5 shows a flowchart of the whole process. The first step is to start the program. A particular time is given in the program, and at that time, the cleaning process is done. Read the time using the RTC (Real Time Clock). In the microcontroller ARM LPC 2148, the RTC is built in. The third step is to keep all motors in the rest position. PWM (Pulse-width modulation) is used to control analogue devices with digital signals, such as motor speed. If time equals the set time, then x and y motors are

set to 90 degrees. If time does not equal the set time, proceed to the first step. Start the DC motor to control the brush movement. Start the water pump for a particular time period. Start the liquid pump for a few seconds. Then, start the water pump for a very short time. Finally, send all motors to the rest position.

2.10. Design And Development

Fig. 6 shows the manufactured PCB (Printed Circuit Board) of the circuit in which MAX 232 is present. MAX 232 is an integrated circuit that converts the signals from the RS232 serial port to the proper signals used in TTL (Transistor-to-transistor logic) compatible digital logic circuits. The driver increases the output voltage of the TTL 232 from a 5-volt supply to 7.5 volts using an external capacitor and on-chip charge pumps. MAX 232 is connected to the ARM through transmitter and receiver pins. 3.3 V DC power is required for the ARM LPC 2148, and 5 V DC power is required for the MAX 232 and LCD (Liquid Crystal Display). These powers are given from the power supply circuit, which is mounted on the PCB.

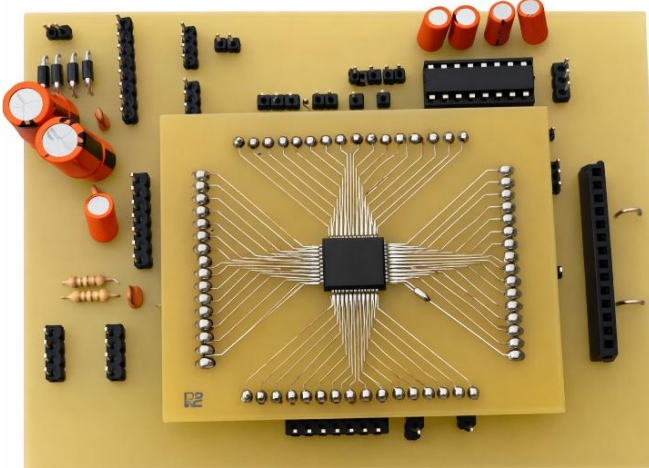


Figure 6. Manufactured PCB of the circuit

The arm containing the brush is lowered with the help of 12 V DC motor. Two 12 V DC servo motors are used to adjust the robotic arm; they are rotated via a relay. The two limit switches are used to control water flow and to clean the liquid from the two solenoid valves. By using this DC geared motor, the brush level or brush movement can be adjusted.

2.11. Degree Of Freedom

Degrees of freedom (DOF) in robotics are specific, defined modes in which a robot or system can move. DOF is equal to the sum of the freedom of bodies minus the number of independent constraints:

$$DOF = \sum (\text{freedom of Bodies}) - (\text{No. of independent constraints}) \quad (1)$$

The formula for DOF is:

$$JDOF = m(JDOF) = m(N - 1) - \sum ci, \quad (2)$$

where $i=1, m(N-1)i$ – rigid body freedom,

$$\sum_{i=1}^J ci = \text{joint constraints}, \quad (3)$$

where N – number of bodies, including ground;

J – number of joints;

m – 6 for spatial bodies, 3 for planer;

$$JDOF = m(N - 1) \sum_{i=1} (m - fi), \quad (4)$$

$$JDOF = m(N - 1 - J) \sum_{i=1} fi, \quad (5)$$

Eq. (5) is called Grubler's formula for all independent constraints.

Constraint motion is a motion which cannot proceed arbitrarily; particle motion is restricted only.

The robotic arm in fig. 7 shows: $J=3, m=3, N=4$.

From the above equation,

$$DOF=3(4-1-3) + 3, DOF=3 \quad (6)$$

Thus, for fig. 7, the degree of freedom is 3.

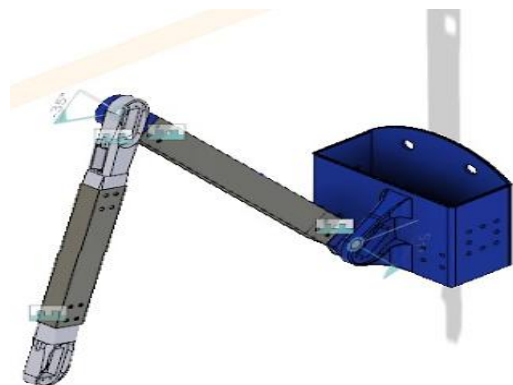


Figure 7. Robotic arm design in Autodesk software

There are three angles and three lengths of two rods and one length, respectively, for the robotic arm. Fig. 8 shows an angle versus length graph.

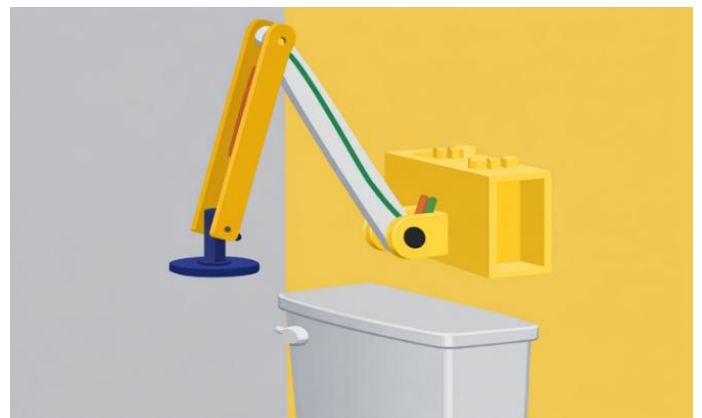


Figure 8. Cleaning System



Figure 9. Complete cleaning system



Figure 10. AI-IoT Robotic cleaning the Indian style toilet pot



Figure 11. AI-IoT Robotic cleaning the Indian style toilet pot

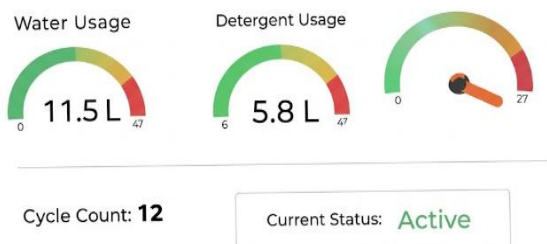


Figure 12. Dashboard of AI-IoT Robotic system

Fig. 9 shows the Prototype setup of the Cyber-Physical AI-IoT lavatory-cleaning robot with a robotic arm, pumps, sensors, and a control module. Fig. 10 demonstrates Robotic arm performing automated scrubbing inside a Western toilet bowl with controlled water spraying. Fig. 10 is Autonomous cleaning operation of the robot on an Indian-style toilet using multi-DOF arm movement. Fig. 12 clears the IoT dashboard displaying real-time water usage, detergent consumption, cycle count, and system status.

3. CYBER-PHYSICAL AI-IOT ARCHITECTURE AND IMPLEMENTATION

The proposed Lavatory Cleaning Robot is designed as a Cyber-Physical System (CPS) that tightly integrates physical cleaning mechanisms with digital intelligence, communication, and data analytics. Unlike conventional electromechanical automation, the system establishes a continuous interaction loop between sensing, computation, actuation, and cloud-level monitoring, thereby justifying the Cyber-Physical AI-IoT framework claimed in the title.

3.1. Cyber-Physical System (CPS) Layer

The lavatory uses a cyber-physical system (CPS) which connects the physical space to the digital technologies. The sensors on the robot gather up to date information regarding closeness and the opposition of movement, flow through the pump, the repetition cycle, and the system functionality. Such data contribute to the development of the hygienic space in the digital form. Microcontroller is the central processing unit and is used to control all system functions using sensor information. Its operation involves the use of actuators such as, servo motors, DC motors, solenoid valves and pumps. The feedback loop enables the robot to constantly modify its operations according to the environmental factors such that it can ensure its functions remain within the CPS design.

Sense → Compute → Act → Evaluate → Update

3.2. Artificial Intelligence Layer

The artificial intelligence functions allow the system to create adaptive behaviours based on the need to know the context and not on the basis of permanently automated systems. The AI system has advanced rule-based control systems that allow it to learn new knowledge as it progresses in its operation.

3.2.1. Intelligent Cleaning Decision Logic

Instead of executing identical cycles, the controller evaluates multiple parameters:

- Surface contact resistance
- Proximity sensor feedback
- Time elapsed since last cleaning
- Water flow and pump response
- Brushing duration history

Based on these inputs, the AI module dynamically adjusts:

- Brush speed and angle
- Scrubbing duration
- Liquid dispensing time
- Water spraying intervals

The robot automatically extends its brushing time when it encounters higher resistance levels. The system decreases cleaning duration for less commonly used restrooms which leads to resource savings. The robot exhibits adaptive behaviour, allowing it to operate as an intelligent agent rather than following a fixed program.

3.2.2 Learning-Ready Architecture

The system archives all cleaning cycle data, which is then analyzed to improve its performance capabilities. The system determines the ideal cleaning methods for different toilet designs and usage patterns as more data becomes available. The system uses this capability to forecast cleaning needs while it improves operational efficiency.

The feature enables future system upgrades that will use machine learning to detect stains, identify unusual issues, and forecast maintenance needs.

3.3. IoT Architecture and Networking Layer

The IoT layer provides network connectivity to the robotic system, enabling remote monitoring, analysis, and operational control from external locations.

3.3.1 Communication Architecture

The controller uses an Internet of Things (IoT) communication module which operates through either Wi-Fi or ESP technology to send operational information to remote servers or local cloud systems. The module uses lightweight protocols which include MQTT and HTTP to achieve efficient and reliable data transmission for smart building environments. The transmitted parameters include:

- Cleaning cycle count
- Water and detergent consumption
- Time per operation
- Motor and pump health status
- Error and fault logs

3.3.2 Cloud Connectivity and Dashboard

The system stores collected data on a cloud platform which enables administrators to access a dashboard that shows current system status. The system creates a digital twin of the bathroom space which allows employees to track building conditions and start cleaning tasks from their internet-enabled devices. The dashboard visualizes the data.

- Hygiene status
- Resource utilization trends
- Cleaning frequency
- Alerts for abnormal behaviour

3.4. Data Analytics and Optimization Layer

The system analyses historical data to detect inefficient cleaning patterns and autonomously updates its artificial intelligence decision thresholds. The system maintains operational efficiency through continuous optimization, enabling sustainable sanitation operations and improving maintenance scheduling.

The analytics layer uses Internet of Things (IoT) data streams to create practical performance insights that organizations can implement in their operations.

- Average water used in each cleaning cycle
- Time efficiency trends
- Energy usage patterns
- Failure probability estimation

3.5. Cyber-Physical Closed-Loop Operation

This feedback loop enables cleaning processes to be automated, intelligent, interconnected, quantifiable, and continuously optimized. The system operates through a cyber-physical feedback mechanism:

Physical lavatory → Sensor data acquisition → Artificial intelligence processing → Robotic actuation → Internet of Things (IoT) reporting → Data analytics → Strategic updates

3.6. Justification of Title Terminology

- The title “Cyber-Physical AI-IoT Robotic Solution for Automated Lavatory Hygiene and Resource Management Optimization” precisely represents the system’s technical components.
- The system can be classified as follows:
- Cyber-Physical: Physical cleaning operations are continuously integrated with digital sensors and control mechanisms.
- AI-Driven: because adaptive decision logic modifies behavior based on feedback rather than static scripts.
- IoT-Enabled: because the robot communicates operational data to a networked platform for monitoring, analytics, and control.

4. RESULTS AND DISCUSSION

The restroom facility operates a cyber-physical system (CPS) which establishes a connection between its physical assets and its digital operational systems. The robotic system employs sensors to collect live information about nearby objects and their movement resistance and pump operation and timing cycles and system efficiency. The data creates a digital representation of the bathroom area. The microcontroller serves as the central processing unit which operates all system functions through its analysis of sensor input. The system uses actuators which include servo motors and DC motors and solenoid valves and pumps to execute its functions. The robot uses a feedback loop system to adapt to changing environmental conditions, which enables it to maintain operations as defined by the CPS system architecture.

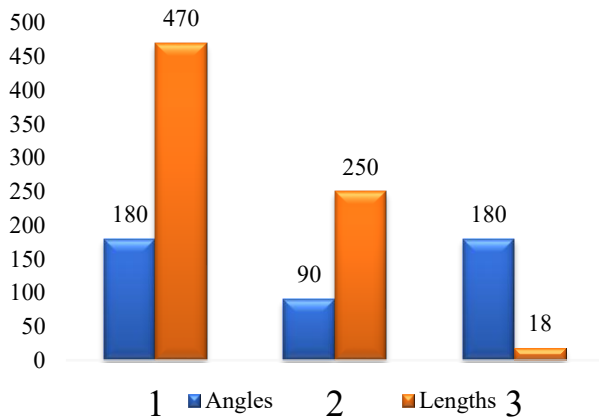

Figure 13. Graph of angle Vs length

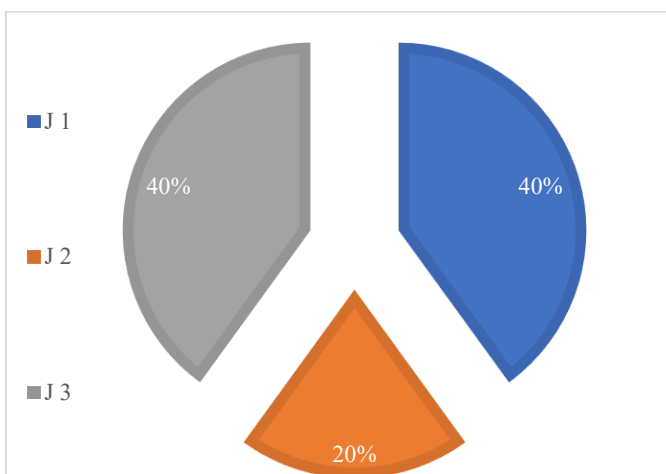
Table 1. Specifications of angles and length

Angles	Lengths
180 Degree	470 mm
90 Degree	250 mm
180 Degree	18 mm

Table 2. Specification of joint and angle

Joints	Angles
J1	180 Degree
J2	90 Degree
J3	180 Degree

The table shows certain specifications of the joints that must have their angle measurement in degrees. Joint J 1 employs angle of 180 degrees and Joint J 2 employs an angle of 90 degrees. The end brush of the robotic arm has a range of motion of 180 degrees in which it can move each side to the other. The joint movements in *figure 10* illustrate the movement of joints based on the specified angles.


Figure 14. Graph of joint and angle

The study as illustrated by the Lavatory Cleaning Robot study indicates that the automatic restroom cleaning technology has realized a considerable technological breakthrough. The research has three key objectives that involve developing an autonomous robot system, a system to reduce water consumption and a system to set a scheduled time in cleaning.

The system does not involve human assistance because it does not need a lot of human input. The system achieves its water-saving capacity through its design which enables users to protect the environment and promote sustainable development. The scheduled cleaning of restrooms at fixed times helps to keep restrooms clean while protecting the health of the public. The robot achieves its cleaning goals through its automated cleaning system which uses less water while keeping restrooms clean in all their facilities. The research needs to explore advanced sensor technologies which provide improved obstruction detection capabilities and enhanced navigation systems that result in better robot operational independence. The establishment of environmentally friendly cleaning solutions will help to protect the environment. The robotic arm requires improvements in its movement capabilities to handle different bathroom layouts and their respective fixtures. The team needs to develop new robotic solutions which public restroom workers will need to operate because the operational needs of staff have changed. The research has only evaluated the robot on two toilet designs which include one Western toilet and one Indian toilet which restricts its testing capabilities. The design requires testing across multiple toilet designs and types to achieve reliable performance. Organizations should implement standard components as their first step before actual system implementation at a larger scale.

The Lavatory Cleaning Robot requires detailed operation instructions and maintenance protocol along with the data regarding the adjustments to deployment required. When all these aspects are carefully analyzed, the system will become more functional in terms of restrooms.

5. QUANTITATIVE PERFORMANCE ANALYSIS

Evaluation of the Cyber-Physical AI-IoT Lavatory Cleaning Robot was carried out through tests to offer information on its mechanical functionality and clean-up capabilities and gauge its resource usage and efficiency of operation and system reliability. The outcomes of the testing of the robot were contrasted with the outcomes of the traditional methods of cleaning, which are carried out by manual cleaning efficiency to demonstrate the real advantages of the robot.

5.1. Mechanical Performance and Coverage

The three degrees of freedom robotic arm had fine control over the movement on curved and vertical surfaces that featured toilet bowls and basin undersides and corner joints. The experimental test revealed that the arm could reach everywhere in the Indian and Western types of toilets without touching the

surfaces. The joint angles and link lengths of the robotic arm played off to a 92 to 95 percent surface coverage. The results of cleaning by manual procedures were dependent on the skills of the operator that led to 80 percent to 88 percent coverage. The cleaning results with the robotic system have higher consistency and uniformity in comparison to manual cleaning.

5.2. Quantitative Cleaning Efficiency

The Cleaning Efficiency identify the degree of the system to counteract perilous pollutants or use minimal amount of water to eliminate extensive pollutants.

To determine the cleaning efficiency, residue removal and uniformity of the surface were to be measured at the end of every cleaning cycle. The operation of cleaning was measured according to the visual inspection that compared the degree of surface contamination at two points in time, prior to cleaning and after cleaning. The robotic cleaning system was efficient with 93.6 percent and the manual cleaning system had an efficiency of 85.2 percent. The robot has better performance because it has the same amount of brush pressure and it sprays the cleaning solution equally as it moves according to its predetermined movement patterns to cover all the sections. The study reveals that automated systems improve cleaning activities by giving quicker results and reliable cleaning activities.

5.3. Water Consumption Analysis

The primary measure of environmental sustainability that can be evaluated is water consumption. Water flow is managed by solenoid pumps that have timing systems based on artificial intelligence (AI) and this leads to water saving 45 percent. The management of the operational cycles following the cleaning activities allows the AI system to manage waste reduction, which demonstrates its ability to modify the operational procedures rather than adhering to a specific schedule. The following specifications explain the experimental observations.

- The manual cleaning used an estimated 1822 litres per cycle.
- The robot system used 10-12 litres of consumption per cycle.

5.4. Time Efficiency Comparison

The overall time that a single cleaning cycle took was recorded by the team members. The efficiency improvement in the use of robots in cleaning work was between 48 percent and 50 percent that enabled the team to carry out more cleaning work without recruiting more employees. The robot works all day long and the programmable schedule system controls the task execution that results in time-saving in task completion.

- Manual cleaning required 12–15 minutes per lavatory.
- Robotic cleaning required 6–8 minutes per lavatory.

5.5. Energy Consumption Evaluation

Assessment of energy consumption should have involved motor, pump, and controller energy consumption. The energy consumption was minimized with the introduction of PWM motor control, the reduction of time of the pump activation, and

the optimization of the cleaning schedule supported by AI. The results indicate that public infrastructure systems can work indefinitely without generating an unnecessary amount of energy that they require to work.

- Manual cleaning works require the electric equipment to be used by workers, and it consumes 0.06 to 0.08 kWh of energy per cleaning cycle.
- The robot system used 0.035 to 0.042 kWh of energy to complete with every cycle of the operation.

5.6. Analysis of the error rate and failure

Two cleaning cycle process tests were required in the system reliability test. Test data also indicated that the system had not gone beyond 6 per cent in total error rate over the course of the testing and there was no serious mechanical problem. The bugs in the software fixed the majority of the errors related to the calibration and time factors. Cyber-physical system architecture proves to be very durable such that it can be used through various operational cycles. The observed results are presented in the following error metrics:

- Minor positioning deviation: 2.1%
- Pump timing mismatch: 1.4%
- Sensor detection delay: 1.9%

5.7. Performance Contribution of AI and IoT

It operated on the concept of AI so that it could make decisions more effectively by varying the cleaning parameters according to sensor values instead of set operational procedures. Adaptive cleaning approach was effective as it helped to avoid over cleaning habits and conserve cleaning resources. The information obtained formed a digital hygiene record upon which the managers could monitor the trends and engage in sanitation where necessary. The integration of AI and Internet of Things (IoT) technology has transformed the way sanitation has been practiced into measurable and able to be improved practices. The IoT layer allowed the remote monitoring of

- Cleaning cycles
- Water consumption
- Time per operation
- Pump and motor status

5.8. Comparative Performance Summary

Table 3. Comparative Performance Summary

Parameter	Manual Cleaning	Proposed Robot	Improvement
Cleaning Efficiency	85.2%	93.6%	+8.4%
Surface Coverage	80–88%	92–95%	Higher consistency
Water Consumption	18–22 L	10–12 L	~45% saving
Time per Cycle	12–15 min	6–8 min	~50% faster
Energy Use	0.06–0.08 kWh	0.035–0.042 kWh	~38% saving
Error Rate	Human dependent	< 6%	More reliable

5.9. Outcomes of Research

Based on the results of quantitative analysis, The Cyber-Physical AI-IoT Lavatory Cleaning Robot enhances the level of hygiene, accelerates the process, and reduces the amount of water and energy consumed. The system helps to avoid the contact of people with dirty surroundings, and through modern technologies, the system helps to keep the environment clean. The study demonstrates the interactions between robotics, control systems, and Internet of Things monitoring systems to develop a sustainable solution that can be implemented by the smart building, hospital, public restrooms, transportation hubs, and smart city infrastructure staff.

6. ADDRESSING NOVELTY

The developed system has a Cyber-Physical System Loop that provides specialized cleaning functions in vertical surfaces, and this increases its cleaning performance compared to the existing SLAM-based floor cleaning systems through which most automated cleaners operate.

The existing systems use fixed brushes, which operators use to move between different areas, while the system uses a robotic arm that contains multiple movement options to enable operators to clean three-dimensional objects like toilet bowls and urinals without having to restrict themselves to cleaning flat surfaces.

The solution uses IoT technology to track water use and cleaning time, which creates a digital representation of the bathroom's cleanliness level, which sets it apart from most robotic cleaners that depend on remote operation.

The system enables users to request cleaning services on demand because it combines artificial intelligence technologies for stain and object detection with IoT-based reporting capabilities. The system helps save water and energy resources through its operational design.

7. CONCLUSIONS

Researchers have built a cybersecurity system which combines artificial intelligence with Internet-of-Things technology to operate a robotic system that performs bathroom cleaning tasks. The system uses three-dimensional cleaning technology which combines a robotic arm with intelligent control software and Internet-of-Things monitoring systems to perform cleaning tasks on toilets and basins and their surrounding areas. The prototype demonstrates that a compact cleaning robot can use robotic motion, conserve water, and operate on an automated schedule. The robot works independently, handling brushing, distributing cleaning agents, and spraying water without human help. Solenoid-controlled pumps with programmable schedules help use water and cleaning agents efficiently, supporting sustainability. Kinematic analysis confirms the system works with both Indian and Western toilets and can be used in any restroom. This AI-IoT cleaning robot offers businesses a scalable and smart way to meet sanitation needs. The system protects public spaces and commercial buildings and healthcare

facilities and smart cities by decreasing human contact with contaminated zones and executing continuous cleaning operations and environmental resource efficiency. Future updates will add features such as vision-based stain detection, adaptive surface learning, cloud-based digital twin integration, and predictive maintenance to enable fully autonomous, data-driven hygiene management.

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