

A Comprehensive Review of Contactless Sanitization Systems Using Robotics, IoT, and Artificial Intelligence

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Abstract: *The global landscape of public health and institutional hygiene has undergone a profound paradigm shift, transitioning toward automated and contactless technologies to ensure safety and operational resilience. This review synthesizes current research on the integration of autonomous mobile robots (AMRs), the Internet of Things (IoT), and Artificial Intelligence (AI) across the healthcare, hospitality, and transportation sectors. Central to this analysis is a comparative evaluation of disinfection modalities, specifically manual wiping versus touchless fumigation; findings indicate that while manual methods currently excel in fungal eradication and reaching "micro shadows," automated vaporized hydrogen peroxide (VHP) systems offer superior scalability for high-risk environments. The paper further explores AI-driven smart gateways, which utilize hybrid CNN models to achieve up to 97% accuracy in face mask detection and 99% in face shield verification with sub-second processing latency. In the hospitality sector, predictive analytics and IoT sensors are shown to reduce resource wastage by 30% while significantly enhancing guest satisfaction. However, the adoption of these systems is hindered by technical challenges, including material degradation from UV-C/VHP exposure, high initial investment costs, and an expanded cybersecurity attack surface involving sensor jamming and data poisoning. Finally, this review addresses critical ethical and legal concerns, emphasizing the need for robust frameworks to manage data privacy (GDPR/HIPAA) and legal liability for autonomous agents. By examining resilient design and emerging trends like 5G-based Tactile Internet and Digital Twins, this paper provides a roadmap for transitioning from crisis-driven responses to sustainable, fully autonomous public health infrastructure.*

Keywords: Contactless sanitization, autonomous mobile robots, robotic disinfection, Internet of Things (IoT), artificial intelligence, smart healthcare systems, UV-C disinfection, robotic sanitization, contactless disinfection, smart hospitals, IoT-based monitoring

I. INTRODUCTION

Definition and Scope: Contactless sanitization refers to the integration of automated, sensor-based, and non-manual methods to eliminate pathogens from surfaces and hands without physical contact. This scope includes technologies such as touchless hand sanitizer dispensers that utilize microcontrollers like Arduino Uno and ultrasonic sensors to detect proximity and actuate dispensing mechanisms. Furthermore, the field encompasses large-scale non-contact fumigation processes, such as the use of low-temperature vaporized hydrogen peroxide (VHP) combined with silver cations to decontaminate high-risk environments. These systems represent a shift toward a "sense-think-act" loop where sensors identify a sanitization need and act autonomously to execute the process.

Drivers of Adoption: The rapid adoption of these robotic and automated systems was significantly accelerated by the global COVID-19 pandemic. The pandemic highlighted critical gaps in traditional hygiene practices, as the virus



primarily spreads through respiratory droplets and contact with contaminated surfaces. This necessitated a transition from "high-touch" manual procedures to "high-tech" solutions to reduce the risk of infection for medical personnel and the general public. In sectors such as hospitality and tourism, the crisis drove the adoption of contactless services and sanitization protocols to rebuild guest trust and ensure safety. The need for prevention, rapid detection, and monitoring became a priority for both public health safety and economic resilience.

Importance of the Field: Implementing contactless sanitization is vital for reducing human error and the probability of errors associated with manual cleaning tasks. In high-pressure, high-exposure environments such as emergency departments (EDs) and intensive care units (ICUs), these systems help minimize cross-infection risks and shield staff from multi-drug-resistant organisms. Beyond clinical safety, automated systems effectively reduce physical and mental fatigue for nurses and healthcare workers, who often spend up to 40% of their time on non-clinical tasks like transportation and manual cleaning. In public transportation and communal spaces, the integration of IoT and machine learning for automated screening and sanitization provides a robust framework for managing airborne transmission risks in crowded urban settings. These technologies enable real-time monitoring and efficient resource use, which are essential for long-term public health resilience

II. CORE TECHNOLOGIES IN CONTACTLESS DISINFECTION

1-Non-Contact Chemical Methods

Non-contact chemical disinfection has emerged as a primary alternative to traditional manual cleaning, aiming to provide comprehensive coverage while minimizing human exposure to pathogens. These methods are often integrated into automated systems or robotic platforms to ensure consistency and efficiency in high-risk environments like emergency departments and isolation wards.

Fumigation with Vaporized Hydrogen Peroxide (VHP): One of the most widely utilized non-contact chemical methods is fumigation using low-temperature vaporized hydrogen peroxide, often combined with silver cations. This process, such as the one implemented by the Noco spray system, involves dispersing a fine mist (e.g., 6% hydrogen peroxide solution) to decontaminate large volumes and surfaces. In comparative studies involving the HOSBOT logistics robot, VHP fumigation was shown to be significantly effective in reducing bacterial contamination, achieving a large effect size in bacterial reduction. However, it demonstrated limitations in eradicating fungal growth and frequently failed to meet CDC cleanliness standards in hard-to-reach or shadowed areas. Furthermore, while effective for surface sterilization, VHP is considered an aggressive chemical compound that may pose a risk to the electronic components, optics, and hardware of the very robots it is intended to disinfect.

Electrostatic Spraying: This technology utilizes charged particles to ensure that liquid disinfectants are distributed evenly over complex surfaces. By charging the disinfectant droplets, the spray is naturally attracted to surfaces, enhancing coverage in hard-to-reach areas that traditional sprays might miss. This method is categorized as a vital component of automated disinfection systems, providing a more robust alternative to manual application.

Automated Decontamination Chambers and Stations: Beyond mobile units, non-contact chemical methods are employed in dedicated decontamination stations. These stations utilize chemical sprays, often in tandem with UV-C light, to sanitize robots and equipment before they transition into sterile areas. Such systems can be programmed to provide a predefined amount of liquid and return to a resting position, ensuring adequate coverage while minimizing chemical waste.

Challenges and Optimization: Despite the benefits of non-contact chemical methods, current research suggests they are not yet a total replacement for manual intervention in all scenarios. To achieve fully autonomous, human-free disinfection, studies recommend increasing disinfectant concentrations or exploring alternative chemical agents to better address resistant pathogens like fungi and to improve efficacy in shadowed regions. Additionally, the material compatibility of these chemicals must be carefully evaluated to prevent the gradual degradation of interior finishing materials and sensitive equipment.



2-Light-Based Disinfection

Ultraviolet germicidal irradiation: (UVGI) is a long-standing contactless method used to prevent the transmission of infectious diseases by treating air, water, and surfaces. This technology primarily utilizes low-pressure mercury (Hg) discharge lamps that emit shortwave ultraviolet-C (UV-C) radiation, most commonly at a wavelength of 254 nm.

Biological Basis of UV-C (254 nm): The germicidal effectiveness of UV-C light stems from its ability to inactivate microbes by damaging their deoxyribonucleic acid (DNA). When a microorganism absorbs a UV-C photon, pyrimidine dimers form between adjacent thymine bases in the DNA strand, structural changes that render the microbe incapable of replicating. While the standard output for germicidal lamps is 254 nm, the peak of analytical bactericidal effectiveness actually occurs at 265 nm. Despite its high biological activity against pathogens, UV-C radiation is considered less dangerous to human health than deeper-penetrating UV-A or UV-B because it is almost entirely absorbed by the outer dead layer of human skin.

Application Modes: UVGI is deployed through several specialized modes to ensure efficacy while managing safety risks:

Upper-Room Irradiation: This mode is specifically designed for occupied spaces. Louvered or shielded UVGI fixtures are mounted on walls or suspended from ceilings to confine radiation to the area above people's heads, minimizing direct exposure. The system relies on vertical air movement—created by natural convection, ceiling fans, or HVAC systems—to cycle contaminated air from the lower breathing zone into the upper irradiated zone for continuous disinfection.

In-Duct HVAC Systems: In this configuration, UVGI lamps are installed inside heating, ventilation, and air-conditioning (HVAC) ducts to disinfect air as it passes through the system. Because the radiation is contained within the ductwork and is inaccessible to occupants, these systems can utilize high intensities and UV-reflective materials to increase the kill rate before air is recirculated or exhausted.

Full-Room Sterilization via Portable and Robotic Units: Full-room irradiation is typically used for terminal disinfection in unoccupied rooms, such as patient areas or surgical suites. This is increasingly performed by autonomous mobile robots (AMRs) like the Xenex Lightstrike or Tru-D, which navigate spaces to eliminate pathogens on surfaces and in the air. These units often employ Sensor360 technology to calculate precise UVC doses and motion sensors to automatically shut down if human entry is detected.

Integration and Effectiveness: Modern advancements include UVC sensor modules for human-robot co-localization to ensure safety during the disinfection process. In the hospitality sector, large chains like Marriott International have reported a 25% improvement in hygiene audit scores following the implementation of UV-C light systems in guest rooms and common areas. Additionally, innovative applications like Seoul's glass-panelled bus shelters use UV sterilizers to maintain safe public waiting areas. However, the effectiveness of light-based methods can be limited by shadowed areas or high-humidity environments (above 60-70%), which may protect certain pathogens from the radiation.

3-Automated Dispensing Systems

Automated dispensing systems represent a fundamental shift in personal and public hygiene by eliminating shared contact points that facilitate pathogen transmission. These systems utilize sensors and microcontrollers to deliver sanitizing agents—such as alcohol-based rubs, liquid soaps, or even medications—without requiring physical interaction.

Microcontroller-Based Architectures: The core of modern touchless dispensers often revolves around the Arduino Uno platform, chosen for its affordability and open-source flexibility. These systems typically operate on a closed-loop logic where a microcontroller processes inputs from a proximity sensor to trigger a mechanical response. For example, a common design integrates an HC-SR04 ultrasonic sensor to detect hand presence and a servo motor to actuate the dispensing pump.



Sensor Technologies for Proximity Detection:

Ultrasonic Sensors: Modules like the HC-SR04 emit high-frequency sound waves that bounce off a target; the return time is used to calculate distance regardless of light or surface color. Studies indicate these sensors reliably detect hands within a 5–10 cm range, activating the system in less than one second.

Infrared (IR) Sensors: These sensors detect human intervention by identifying infrared radiation (heat) emitted by the body. When a hand falls within the detectable range, the sensor signals a relay module to pump sanitizer.

Alternative Triggers: Other systems employ pressure resistors, magnetic sensors, or photosensors to trigger dispensing events, depending on the environment.

Integration with Smart Ecosystems and IoT: Dispensing systems are increasingly integrated into smart gateway entrance systems to manage infectious disease risks in communal spaces. These gateways often combine sanitization with temperature monitoring (MLX90614) and vaccine verification via QR codes. Furthermore, IoT-enabled dispensers can synchronize with real-time databases like Google Firebase or Bolt IoT Cloud to track usage frequency, monitor supply levels, and maintain employee health records autonomously.

Sectorial Deployment and Utility:

Public Transportation: Touch-free amenities, including sensor-based soap and water dispensers, have been integrated into AC train coaches and bus shelters to improve travel safety.

Healthcare Facilities: In clinical settings, automated dispensers have been shown to increase compliance with hand hygiene protocols. Some advanced models even feature electronic counters to record the frequency and volume of product used, assisting in hygiene audits.

Vending and Distribution: In regions like Saudi Arabia, the pandemic accelerated the use of electronic drug dispensers and vending machines to provide medications while adhering to social distancing.

Operational Reliability and Security: To ensure continuous operation in high-traffic areas, these devices often utilize an uninterrupted power supply (UPS) or 9V battery systems. However, the digitization of these systems introduces vulnerabilities; the actuator firmware and communication protocols can be potential attack surfaces for malicious actors aiming to disrupt hospital logistics or obtain unauthorized control. Despite these challenges, the modular design of these systems facilitates easy maintenance and scalability for long-term public health resilience.

Table: 1 Taxonomy of Decontamination and Sterilization Techniques for Hospital Robots

Technique Category	Definition	Specific Methods	Description and Application
Decontamination	The removal of contaminants such as pathogens, toxins, and other harmful agents to specified levels, including cleaning, sanitization, disinfection, or sterilization.	Automated Decontamination Chambers	Enclosed stations utilizing UV-C light and chemical sprays to clean robots before they enter sterile clinical areas.
		Self-Decontaminating Surfaces	Use of antimicrobial coatings, such as copper or silver ions, to naturally inhibit bacterial growth on high-contact robot components.
		Ozone-based Decontamination	Utilization of ozone gas to inactivate microorganisms in hard-to-reach or complex areas; requires careful handling due to potential toxicity.
Disinfection	The elimination of most pathogenic microorganisms (excluding bacterial spores) to a level that does not pose a risk of	UV-C Light Disinfection	UV lamps that inactivate pathogens on surfaces; effectiveness is highly dependent on proper calibration and the avoidance of shadowed areas.
		Chemical Sprays and Wipes	Application of EPA-approved disinfectants (e.g., hydrogen peroxide, sodium



	infection.		hypochlorite) either manually or through automated robotic systems.
		Electrostatic Spraying	The use of charged particles to ensure disinfectants are evenly distributed, significantly enhancing coverage in difficult-to-reach geometric areas.
Sterilization	A thorough process that results in the removal of all viable microorganisms, including highly resistant bacterial spores.	Low-Temperature Vaporized Hydrogen Peroxide (VHP)	A method effective for heat-sensitive materials; often requires specialized chambers to contain the vapor.
		Ethylene Oxide Gas Sterilization	Suitable for moisture- or heat-sensitive materials, though implementation is limited by gas toxicity and lengthy processing cycles.
		Autoclaving (Steam Sterilization)	High-temperature steam treatment for detachable, heat-resistant robot parts processed in specialized autoclave chambers.
Complementary Protocols	Techniques that enhance existing primary strategies to ensure consistent hygiene.	Regular Maintenance Schedules	Standardized cleaning intervals to ensure the robot does not become a carrier of pathogens during daily logistics or care tasks.
		Disposable Covers	Protective layers for high-touch areas that reduce contamination and simplify the cleaning process for frequently handled parts.
		Sensor-Based Detection	Use of specialized sensors to detect residues or contamination and automatically alert personnel when a cleaning cycle is required.

III. AUTONOMOUS MOBILE ROBOTS (AMRS) IN SANITIZATION

1-Robotic Platforms

Autonomous Mobile Robots (AMRs) have become integral to hospital logistics and high-risk environments like Emergency Departments (EDs), designed to streamline operations and minimize infection risks. These platforms operate using a "sense-think-act" loop, where sensors perceive the environment and actuators execute complex tasks such as delivery or disinfection. Key robotic platforms currently in use or research include:

HOSBOT (Hospital Robot): This is a modular, cost-effective AMR system developed under the ODIN project to enhance internal hospital logistics. It consists of a mobile base from Robotnik Automation S.L., a Smart Rack cart for carrying Smart Boxes filled with diagnostic samples or medications, and a web-based Human-Machine Interface for staff management.

TUG: Developed by Aethon, this intelligent autonomous robot is widely used for the delivery of medicines, lab samples, and surgical supplies. At facilities like St. Olav's Hospital, it autonomously navigates corridors to transport bed linens and critical equipment, thereby reducing the probability of human error.



2-Disinfection-Specific Platforms:

Xenex Light strike: A high-intensity robot that utilizes UV-C light to perform terminal disinfection of patient rooms and surgical suites.

Tru-D: A portable UV-C system that employs Sensor360 technology to calculate precise germicidal doses, ensuring effectiveness even in shadowed areas.

Sterilray: An autonomous vehicle designed for continuous disinfection of large, difficult-to-reach areas like hospital corridors and common spaces.

3-Multi-Functional Assistive Platforms:

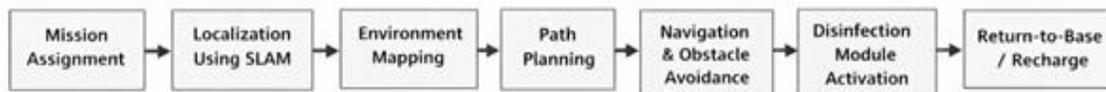
Robotnik RB1: A versatile platform adaptable for delivering medications, moving medical equipment, and performing waste removal.

Terapio: A prototype designed to support medical rounds by following healthcare professionals, transporting supplies, and recording electronic health data.

Virobot and Aido-Bot: IoT-enabled robots designed to provide medication reminders and delivery while incorporating UV sterilization or environmental monitoring for isolated patients.

Emerging Sustainable Designs: Platforms such as HARVi and various Automated Guided Vehicles (AGVs) utilize solar-rechargeable batteries to improve energy efficiency while performing contactless medicine supply and waste disposal tasks.

These platforms leverage a combination of LiDAR, 3D depth cameras (Kinect), and ultrasonic sensors to achieve precise localization and obstacle avoidance in the dynamic and crowded environments of modern healthcare facilities. Despite their success, high upfront costs and a lack of commercial modularity remain barriers to the widespread adoption of these systems.



Autonomous Mobile Robot (AMR) Sanitization Workflow

4-Navigation and Perception

Modern autonomous mobile robots (AMRs) are built upon a fundamental architectural framework consisting of perception, navigation and planning, and control. These systems typically operate within a "sense-think-act" loop, a hierarchical paradigm where the robot first perceives its environment through sensors, processes that data to plan an optimal trajectory, and finally executes physical movement via actuators.

- **Core Sensor Technologies:** **LiDAR:** This is a critical sensor for AMRs, operating on the principle of emitting laser pulses and measuring their time-of-flight to calculate distances with high precision. LiDAR allows robots to generate high-resolution 2D or 3D maps of hospital environments and perform real-time collision avoidance. **3D Depth Cameras (Kinect):** These sensors provide rich semantic information by combining RGB data with depth sensing, enabling the robot to recognize complex environments and perform tasks like human skeleton tracking. Algorithms can use this data for head detection to identify individuals in a crowd even when their bodies are partially occluded. **Ultrasonic and Infrared Sensors:** These are primarily used for short-range proximity detection and act as a "last line of defense" to prevent physical contact with low-lying obstacles or people that primary sensors might miss.

- **SLAM Technology: Simultaneous Localization and Mapping (SLAM)** is the essential process that enables an AMR to enter an unfamiliar indoor space and build a map while simultaneously determining its own position within that map. This technology is vital for navigating dynamic hospital corridors where pre-existing maps may not account



for moving equipment or people. SLAM uses probabilistic models and optimization techniques to solve the interdependent problems of positioning and mapping in real time.

• **Path Planning and AI Integration:** Once a position and map are established, robots use path planning algorithms such as A* or Dijkstra's method to calculate the shortest and most efficient route to a destination. In environments with unpredictable human movement, probabilistic sampling-based planners like Rapidly-exploring Random Trees (RRT) are preferred because they can quickly adapt to changes without recalculating an entire grid map. Advanced AI-driven pipelines further enhance these capabilities by using Convolutional Neural Networks (CNNs) for object recognition, allowing robots to distinguish between static furniture and moving patients.

5-Collaborative Roles

- **Supply Delivery:** Autonomous robots play a vital role in streamlining hospital logistics by efficiently handling the transportation of essential supplies, including sterile equipment, food trays, bedding, and diagnostic samples. This automation is a significant factor in reducing staff fatigue and addressing personnel shortages, as studies indicate that nurses often spend up to 40% of their time on non-clinical tasks like logistics. Specialized systems such as the HOSBOT have been successfully piloted for the delivery of biological samples, specifically transporting blood samples from emergency departments to central laboratories to minimize the physical burden on medical teams.
- **Waste Removal:** The transportation of medical waste is an increasingly prominent collaborative role for AMRs, serving as a critical component of Infection Prevention and Control (IPC) protocols. In high-risk environments like operating rooms, which generate substantial volumes of hazardous and infectious materials, autonomous robots can minimize staff exposure to infectious substances and multi-drug-resistant organisms (MDROs). Versatile platforms like the Robotnik RB1 are designed to perform these tasks autonomously, ensuring that hazardous waste is handled according to strict sanitary standards without requiring manual labor.
- **Automated "Curtain" Barriers:** To prevent respiratory cross-infections, robotic and environmental systems have been utilized to create UVGI "light curtains" or barriers. These systems historically involved using configurations of high-intensity direct ultraviolet grids to sanitize the air and create a protective barrier around sensitive areas, such as infant wards, effectively inactivating pathogens before they could spread to other patients.
- **Telepresence and Therapeutic Assistance:** AMRs also collaborate with medical teams and families through telepresence and social assistance roles. Telepresence robots, such as UBBO, provide a virtual presence for families in COVID-19 isolation rooms, reducing the need for physical entry into contagious areas while maintaining social connection. Furthermore, socially assistive robots (SAR) like PARO and NAO collaborate with clinicians to provide affective therapy for dementia patients or distract children during stressful medical procedures, thereby enhancing the overall quality of care.

IV. INTEGRATION OF AI, IOT, AND SMART GATEWAYS

1-Contactless Screening

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) has facilitated a shift from manual health checks to automated smart gateway entrance systems. These gateways serve as centralized screening points in communal spaces, utilizing a "sense-think-act" logic to monitor, authenticate, and track health parameters in real-time.

- **AI-Driven Recognition Systems:** Modern screening gateways leverage computer vision and deep learning to ensure compliance with safety protocols. A prominent approach involves a hybrid model combining MobileNetV2 and VGG19 architectures. This combination utilizes MobileNetV2's computational efficiency and VGG19's depth for feature extraction, achieving an overall accuracy of 97% for face mask recognition and 99% for face shield detection. These systems are capable of identifying masks even when worn improperly or when the user is moving in real-time.
- **Thermal Imaging and Fever Detection:** Contactless temperature monitoring is a core component of these gateways, primarily utilizing MLX90614 infrared sensors. Interfaced with microcontrollers like Arduino Uno, these sensors provide non-contact thermal screening with an accuracy of $\pm 0.5^{\circ}\text{C}$ (and up to $\pm 0.1^{\circ}\text{C}$ in optimized systems). If a user's



temperature exceeds a defined threshold (typically 98.6°F), the system triggers an automated alert to supervisors and denies entry. Similar technologies have been deployed globally, such as in Seoul’s glass-paneled bus shelters, which use thermal cameras to restrict entry for symptomatic individuals.

- **QR-Code and Vaccine Verification:** To enhance public safety, smart gateways incorporate QR code-based authentication for vaccination certificates. Algorithms using OpenCV and Pyzbar libraries decode employee or visitor metadata—such as vaccination status and dose dates—and cross-check them against secure, official databases like CoWIN. This automated verification ensures a 99% authentication success rate, significantly reducing the risk of fraudulent credentials at points of entry.
- **IoT and Real-Time Data Management:** The "Smart Gateway" framework relies on Google Firebase or similar real-time NoSQL databases to synchronize health records instantly. Using a Tkinter-based Graphical User Interface (GUI), the system maintains a digital audit trail of entry times and health metrics, allowing organizations to ensure all personnel follow daily screening protocols. By scraping data in real-time and uploading it via HTTPS-secured API calls, these systems minimize latency, often processing an individual's entire health screen in less than one second.
- **Computer Vision-Equipped Entrances:** Beyond standalone devices, large-scale infrastructure like Argentina's train network has adopted integrated systems combining facial detection, rapid temperature screening, and ticket validation using thermal and light imaging. These technologies can be adapted for broader use in metros, airports, and workplaces using locally available materials and simplified AI models to ensure economic viability.

2-Performance Metrics of Smart Gateway Screening Subsystems

The following table synthesizes the performance and accuracy of AI-driven contactless screening systems based on integrated framework data. These systems utilize a hybrid MobileNetV2 and VGG19 architecture to balance computational efficiency with high detection precision.

Table 2: Performance Metrics of Smart Gateway Screening Subsystems

Subsystem	Metric	Achieved Result
Face Mask Detection	Accuracy	97%
Face Shield Detection	Accuracy; Recall (Sensitivity)	99%; 99%
Temperature Monitoring	Measurement Accuracy; Precision	±0.1°C; ±0.1°F
Vaccine Verification	Authentication Success Rate; Successful Scan Rate	99%; 98%
System Integration	Real-time Processing Latency	<1 second
AI Model Performance	Average Inference Time	90ms per image
User Interaction	Input Processing Time	<2 seconds
Heart Rate Monitoring	Measurement Accuracy	±2 BPM

V. SECTORAL APPLICATIONS

1-Healthcare Facilities

The adoption of contactless sanitization and robotic systems in healthcare was significantly accelerated by the COVID-19 pandemic, primarily to reduce the risk of infection for medical personnel in high-exposure environments like Emergency Departments (EDs) and Intensive Care Units (ICUs). These technologies are deployed across diverse healthcare settings, including care homes for dementia support, primary care for temperature and mask screening, and tertiary hospitals for complex logistics and disinfection.

Hospital Logistics and Supply Chain: Contactless processes are critical for streamlining hospital operations by handling the autonomous transportation of sterile equipment, diagnostic samples, medications, and linens. Systems such as the HOSBOT have been validated for transporting blood samples from EDs to laboratories, effectively relieving staff of non-patient-facing tasks. Similarly, the TUG autonomous robot is utilized in facilities like St. Olav’s



Hospital to transport supplies, which helps reduce human error and allows nurses to spend up to 40% more time on direct patient care.

Terminal Disinfection and Environmental Control: Healthcare facilities utilize specialized robotic platforms for terminal disinfection of patient rooms and surgical suites. High-intensity systems like the Xenex Lightstrike and Tru-D use UV-C light to eliminate pathogens, with Tru-D utilizing Sensor360 technology to ensure effective dosing even in shadowed areas. For large or hard-to-reach areas like corridors, autonomous vehicles like Sterilray provide continuous disinfection without human intervention. These systems are essential for preventing nosocomial infections (hospital-acquired infections) by maintaining high hygiene standards in critical zones.

Telepresence and Remote Monitoring: In infectious disease wards, telepresence robots like UBBO and Giraff provide a virtual presence for family members and healthcare providers within isolation rooms. These systems enable remote medical consultations and patient monitoring, which minimizes physical contact and the need for medical staff to frequently don and doff personal protective equipment (PPE).

Socially Assistive and Rehabilitation Robotics: Contactless interaction is also applied through Socially Assistive Robots (SAR), such as PARO, which is used in affective therapy for dementia patients to reduce the need for psychotropic medications. Other robots, like NAO, are used in pediatric wards to distract and entertain children during stressful medical procedures. Furthermore, rehabilitation robots assist patients with physical disabilities—such as those resulting from a stroke or spinal cord injury—by providing programmed, contactless motor support during recovery exercises.

Entry Screening and Hand Hygiene Compliance: Modern healthcare facilities implement smart gateway entrance systems that integrate AI-driven face mask recognition, thermal imaging for fever detection, and QR code-based vaccine verification. To ensure clinical safety, hospitals also deploy electronic hand hygiene monitoring systems. These systems utilize RFID tags, cameras, or sensors to track compliance with the WHO 5 moments for hand hygiene and the 6-step handwashing technique, providing real-time feedback to staff to minimize the transmission of multi-drug-resistant organisms.

WASH Programs and Infrastructure: Water, Sanitation, and Hygiene (WASH) programs within hospitals focus on providing clean water access and decentralized sanitation systems to improve maternal health and reduce the physical burden on female healthcare workers. Advanced architectural designs, such as negative pressure isolation rooms and specialized PPE doffing areas with high-efficiency air filtration, further support the containment of aerosolized pathogens within the clinical environment. The following table synthesizes the financial and operational aspects of modernizing sanitization and public health infrastructure in India based on recent technological proposals.

Table 3: Advanced Technological Measures and Implementation Costs (Indian Context)

Modern Technology	Primary Sector	Economic Aspects	Estimated Installation Costs
Digital Health Monitoring (e.g., Aarogya Setu, CoWIN)	Healthcare / Public Safety	Stabilizes the labor market and allows businesses to continue operations during health crises by tracking infection patterns.	Development: ~60,000; Maintenance: 80,000. Large platforms like CoWIN estimated at \$7.8 million.
Telemedicine and IoT	Healthcare (Rural & Urban)	Facilitates job creation in the IoT sector, develops a skilled workforce, and provides affordable healthcare distribution at a lower long-term cost.	Overall estimated at \$2.5–3 billion with an expected growth rate of 31–33%.
Robotic Systems (UV Disinfection & Telepresence)	Healthcare & Hospitality / Airports	Reduces infection risks for professionals, lowers overall sanitation and maintenance	UV Robots: ₹10–15 lakhs (12,000–18,000); Telemedicine Robots: ₹5–10 lakhs (6,000–



		costs, and maintains economic stability.	12,000).
Drone Technology	Logistics / Agriculture / Healthcare	Coverage of large areas in less time, reducing manpower needs and significantly saving on operational labor costs.	Overall estimated at \$1.2–1.5 billion for the Indian business industry.
Holographic Switches and Menus	Hospitality / Transportation	Curtails virus transmission at high-touch points, improves sanitation, and reduces wear and tear on physical hardware.	₹20–30 lakhs (24,000–36,000) for customized setups depending on scale.
Advanced Air Conditioning (HEPA/UVGI/Plasma)	Public Transportation (Trains/Buses)	Enhances commuter safety, provides long-term sterilization without manual labor, and minimizes chemical use.	Plasma Purifiers: ₹40,000–₹60,000 per unit; Antimicrobial Coatings: ₹15,000–₹30,000 per coach.
Artificial Intelligence (AI) and ML	Urban Planning / Diagnostic Centers	Enables targeted interference in hotspots to avoid massive lockdowns and optimizes medical resource utilization.	Overall estimated at \$0.7–1 billion with rapid growth potential.
Rapid Genome Sequencing (NGS)	Medical Research / Testing Labs	Serves as a long-term asset for managing diverse infectious diseases and guiding vaccine updates early.	Machine Setup: ₹3–7 crores (360,000–840,000); Per Sample: ₹10,000–₹30,000 (120–360).

2-Operational Synthesis

Cost-Benefit Balance: While initial investments for advanced robotics and sequencing facilities are high, they are justified by reduced healthcare costs, lower infection rates among workers, and increased efficiency in managing national health challenges.

Infrastructure Adaptation: Technologies like thermal cameras and basic UV sanitizers can be made more affordable by using locally available materials and simplified AI models, ensuring they remain viable for high-traffic public infrastructure.

Sustainability: Adoption of antimicrobial materials, such as copper-coated handrails (₹15,000–₹30,000 per coach), naturally degrades viruses on contact and provides a low-maintenance solution for public transit.

VI. SECTORAL APPLICATIONS

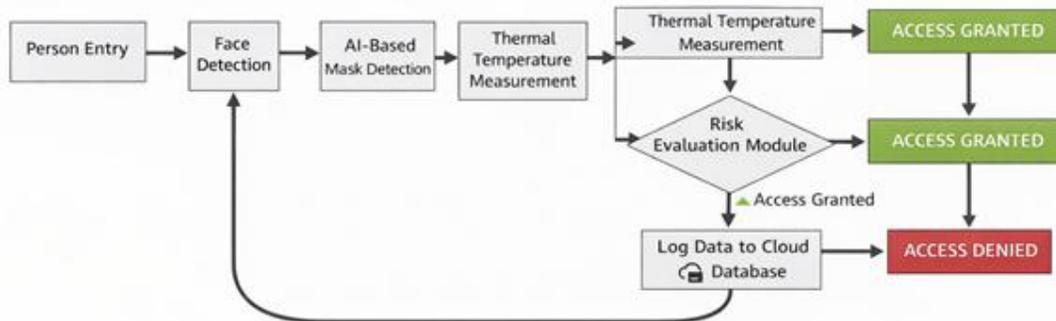
1-Public Transportation

The public transportation sector faces unique challenges in implementing contactless processes due to its inherently crowded nature and high passenger turnover. Mitigation strategies focus on four primary pillars: air quality improvement, automated surface sanitization, contactless service interfaces, and AI-driven crowd management.

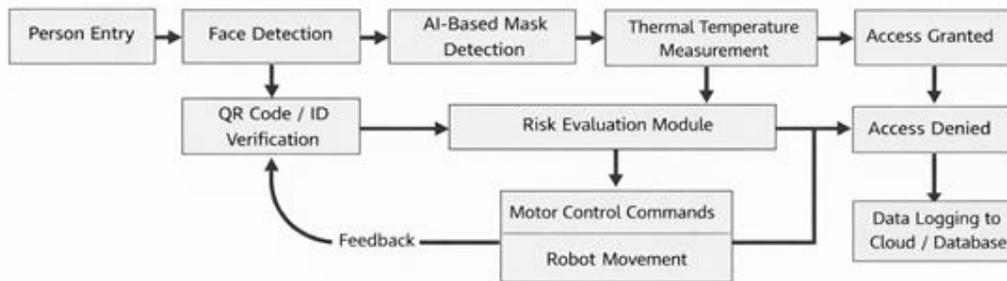
- **Air Quality and Ventilation:** Enhanced ventilation is a critical countermeasure for reducing viral loads in enclosed environments like buses and trains. The integration of High-Efficiency Particulate Air (HEPA) filters into HVAC systems allows for the trapping of virus-carrying droplets as small as 0.3 microns. Furthermore, some systems incorporate Ultraviolet Germicidal Irradiation (UVGI) technology directly into air ducts to inactivate airborne pathogens before the air is recirculated. Studies have shown that utilizing natural ventilation, such as opening windows, can reduce infection risks by up to 92% compared to completely closed environments.



- **Automated and Antimicrobial Surface Sanitization:** Contamination levels are historically higher on frequently touched surfaces than in ambient air, necessitating rigorous sanitization of handrails, latches, and seats. To automate this process, UV-C light technology is deployed in high-traffic hubs to disinfect station entrances, gates, and escalator handrails without manual labor. In India, strategies for "future-proofing" transport include replacing standard fittings with copper-coated handrails or applying titanium dioxide coatings, both of which serve as antimicrobial materials that degrade viruses upon contact.
- **Contactless Service and Screening Gateways:** To minimize physical interaction with contaminated surfaces, transport agencies have prioritized the rollout of contactless payment systems and sensor-based sanitizer dispensers. Many hubs have implemented computer vision-equipped entrances that use thermal imaging and AI to scan commuters for fever and mask compliance in real-time. Additionally, speech recognition systems are being integrated into ticket vending machines and elevators, allowing for voice-activated, touch-free operation in crowded stations.
- **AI-Driven Crowd Screening and Response Optimization:** Effective scheduling and health regulations are vital to avoid the congestion that facilitates transmission. Modern systems leverage AI and IoT to calculate crowd densities at depots by analysing Wi-Fi and internet data from travellers' mobile devices. This data allows for automated response optimization, where simulation tools refine train or bus schedules in real-time to manage passenger surges and ensure safe distancing thresholds are maintained.
- **Infrastructure and Economic Viability:** While the initial investment in these advanced technologies can be high, they are increasingly viewed as essential for long-term operational resilience and passenger safety. By adapting basic thermal cameras, UV sanitizers, and simplified AI models using locally available materials, these systems can be made economically viable for large-scale deployment in high-traffic public infrastructure.



Smart Gateway Contactless Screening System



Smart Gateway Contactless Screening System



2-Hospitality and Tourism

The hospitality and tourism sector, which contributes significantly to the global economy and accounted for approximately \$194 billion of India's GDP in 2019, faced a sharp revenue decline of nearly 47% in 2020 due to pandemic-related restrictions. To rebuild guest trust and ensure operational resilience, the industry has rapidly adopted contactless sanitization and service technologies.

- **Contactless Guest Journey:** Traditional "high-touch" interactions are being replaced by digital alternatives such as contactless check-ins, digital room keys, and mobile ordering for dining, which are now becoming industry standards. In high-end markets like the Middle East, "Contactless Hospitality" features now include in-room digital assistants and mobile keys to reduce physical contact points. Peer-to-peer accommodation platforms like Airbnb have also seen a lasting shift toward mobile check-ins, keyless entry, and virtual concierge services to meet evolving guest safety expectations.
- **Advanced Sanitization and Monitoring Technologies:** Hotels have integrated specialized hardware to maintain and verify hygiene standards. Marriott International reported a 25% improvement in hygiene audit scores after deploying UV-C light disinfection systems in guest rooms and common areas. Hilton's Clean Stay program utilizes IoT sensors to monitor air quality and high-traffic areas, while some properties use "cleaned and sanitized" seals on doors to reassure guests of a room's status. Furthermore, robotic vacuum cleaners and automated mopping systems are increasingly used to reduce human labour while ensuring consistent hygiene.
- **Contactless Dining and Interactive Interfaces:** Innovations in food and beverage services include holographic menus and switches, which allow users to select options via hand gestures without touching physical screens or surfaces. These 3D interactive interfaces are especially useful in restaurants and airports to curtail virus transmission. Additionally, voice-activated controls for elevators and floor selection are being integrated into public kiosks and hotels to provide safer alternatives to high-touch buttons.
- **Smart Entry and Screening Gateways:** To manage health risks at scale, restaurants and hotels have implemented computer vision-equipped entrances. These systems utilize thermal imaging, AI, and visual analytics to rapidly scan guests for fever and mask compliance without requiring manual checks. Hybrid deep learning models have achieved an accuracy of 97% for face mask recognition and 99% for face shield detection, facilitating efficient and non-intrusive screening at entry points.
- **Predictive Analytics and IoT Integration:** Luxury chains like Taj and ITC Hotels use predictive analytics and IoT devices to optimize cleaning schedules based on occupancy and traffic patterns. This data-driven approach allows staff to address cleanliness issues proactively, with some properties reporting a 30% reduction in resource wastage through predictive maintenance and scheduling. IoT-enabled smart trash bins also notify staff when disposal is required, preventing overflow and maintaining a hygienic environment.

Table 4: Classification of Robotic Systems in Healthcare

The following table summarizes the primary roles, technical features, and current development status of various robotic platforms utilized within clinical environments, as documented in the sources.

Category	Specific Platforms	Key Features	Current Developmental Stage
Surgical	da Vinci Surgical System	Supports partial automation of surgical subtasks; utilizes AI to enhance safety, precision, and targeting.	Operational.
	STAR (Smart Tissue Autonomous Robot)	Vision-guided system with a powered laparoscopic suturing tool; calculates stitches autonomously based on incision contours.	Experimental.
	Preceyes Surgical System	Designed for delicate intraocular retinal procedures; utilizes pre-programmed surgeon movements to reduce human error.	Clinical Trials.



Dentistry	YOMI	Provides physical guidance for drill depth and orientation during dental implantation via vibrational feedback.	Research.
	Yakebot	Performs dental implant surgery with tactile and visual feedback; supports both automatic and manual drilling modes.	Clinical Trials.
	Smart Dental Implant (SDI)	Uses a piezoelectric dental crown to harvest energy from oral motion (chewing/brushing) for photo-biomodulation therapy.	R&D.
Telepresence	Double	Two-wheeled video conferencing robot; features autonomous navigation and obstacle avoidance for remote consultations.	Operational.
	UBBO (AXYN)	Remotely operated; provides virtual family presence inside SARS-CoV-2 isolation rooms without entering the space.	Operational.
	Giraff	Mobile system for remote consultations; prioritizes social connection and assistance for elderly individuals living alone.	Operational.
Logistics	TUG (Aethon)	Intelligent mobile robot for internal logistics; performs automatic docking, loading, and delivery of medicines or linens.	Operational.
	Omron LD Series	Self-navigating platform; requires no modifications to existing infrastructure to transport supplies through complex layouts.	Operational.
	HOSBOT	Modular, cost-effective AMR; utilizes laser scanners for collision avoidance while transporting biological samples.	Validated (Pilot).
Cleaning	Xenex Lightstrike	High-intensity robot for disinfecting critical zones; features sensors that interrupt the device if motion is detected.	Operational.
	Tru-D	Portable UVC system; utilizes Sensor360 technology to calculate precise doses even in shadowed areas.	Operational.
	Sterilray	Autonomous vehicle for large areas (e.g., corridors); operates without human intervention for continuous disinfection.	Research.
SAR	PARO	Baby-seal-shaped robot for affective therapy; uses sensors for touch and sound to calm patients with dementia.	Operational.
	NAO	Humanoid robot; used to entertain and distract children during stressful pediatric medical procedures.	Operational.
	Bandit	Humanoid design; provides encouragement and feedback to patients during physical rehabilitation exercises.	Research.
Nursing Assistant	ARNA (Adaptive Robotic Nurse Assistant)	Multi-directional arm with force-torque sensors to provide physical support to nurses.	Experimental Pilot.
	Terapio	Round-supporting robot; uses laser range finders to track medical staff and record electronic health data.	Prototype.



VII. EVALUATION OF EFFECTIVENESS AND LIMITATIONS

1-Comparative Analysis

The practical efficacy of contactless sanitization is often evaluated by comparing it to traditional manual methods. A primary study conducted in a high-risk tertiary hospital emergency department utilized the HOSBOT autonomous mobile robot (AMR) to compare manual wiping (using Meliseptol Wipes Sensitive) against non-contact fumigation (utilizing the Nocospray system with 6% vaporized hydrogen peroxide and silver cations). The success of these methods was measured against the CDC threshold of <2.5 colony-forming units (cfu)/cm² for critical environments.

- **Bacterial Reduction:** Both manual wiping and non-contact fumigation significantly decreased bacterial contamination across all tested sites on the robotic platform. However, manual wiping proved superior, successfully reducing bacterial counts below the CDC threshold in 100% of the tested areas and achieving total elimination of bacteria in 50% of those sites. In contrast, while fumigation was effective in most cases, it failed to meet the cleanliness standards in two specific areas: the top surface of the Smart Box and the interior of the Smart Rack drawer. Statistical analysis using Cohen's d indicated a higher effect size for manual wiping ($d = 2.08$) compared to fumigation ($d = 1.24$).
- **Fungal Eradication:** A significant performance gap exists between the two methods regarding fungal contamination. Manual wiping effectively eradicated all fungal growth at positive sites. Conversely, touchless fumigation showed no statistically significant decrease in fungal colony counts, yielding a negligible effect size ($d = -0.001$).
- **Reach and "Shadowing" Effects:** The primary limitation of non-contact chemical methods like fumigation is their inability to effectively reach shadowed or complex internal areas of equipment. Manual wiping allows for physical contact and targeted pressure, which ensures better coverage of irregular surfaces that aerosolized mists may miss.
- **Hardware Compatibility and Automation:** While manual wiping is currently more effective, it remains labour-intensive and prone to human error. Non-contact fumigation offers the advantage of easy automation, allowing for a human-free disinfection process that reduces staff fatigue and infection risk. Furthermore, although no immediate damage was observed during trials, vaporized hydrogen peroxide is an aggressive chemical compound that may eventually damage a robot's electronic components, optics, and finishing materials if used frequently.

To achieve a fully autonomous sanitization solution, researchers suggest that non-contact fumigation requires optimization, such as increasing disinfectant concentrations or developing alternative chemical agents that are more effective against resistant pathogens like fungi and spores.

2-Technical Challenges

The implementation of contactless sanitization technologies, while promising, is hindered by several significant technical and operational barriers. These challenges range from environmental factors that reduce efficacy to high costs and systemic vulnerabilities.

Environmental and Operational Limitations:

Shadowing Effects: A primary drawback of both light-based (UV-C) and chemical fumigation (VHP) is the inability to sanitize shadowed or hard-to-reach areas where light cannot penetrate or mists cannot circulate effectively.

Impact of Humidity: The germicidal efficiency of UV-C and various aerosolized disinfectants drops sharply in high-humidity environments, specifically when relative humidity exceeds 60–70%.

Material Compatibility: Frequent use of aggressive chemical agents like vaporized hydrogen peroxide or high-intensity UV-C can cause gradual degradation of electronic components, optics, and finishing materials, such as the disintegration of certain plastics.

Hardware and Design Constraints:

Mobility Barriers: Many autonomous mobile robots (AMRs) are currently limited by irregular terrain, rough surfaces, or the inability to climb stairs, restricting their use to specific indoor layouts.

Power and Maintenance: Automated systems often suffer from inadequate battery life and frequent failures in hardware components like wearable tags or sensors, requiring constant maintenance and specialized technical support.



High Initial Investment: The upfront costs for advanced robotic platforms (e.g., UV-C robots or automated logistics systems) and the supporting infrastructure for IoT networks remain prohibitively high for mid-sized and budget facilities.

Systemic and AI-Driven Challenges:

Data Integration and Latency: Merging heterogeneous data from multiple sensors (sensor fusion) introduces complexities in calibration and synchronization. Furthermore, unoptimized systems may suffer from latency or processing delays that hinder real-time screening effectiveness.

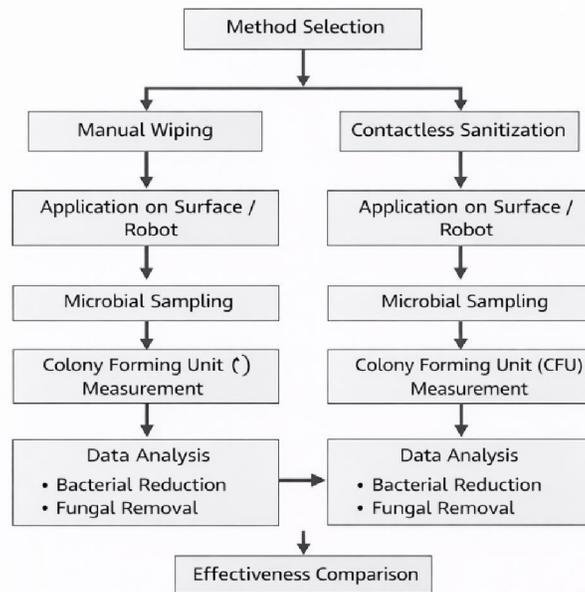
Recognition Accuracy: AI-driven gateways for mask or fever detection face challenges in low-light conditions or when dealing with facial occlusions such as hairstyles or non-standard protective gear.

Interference Issues: There is a persistent risk of radio-frequency interference (RFI) between the wireless communication protocols of sanitization robots and sensitive medical devices in clinical settings, which can lead to equipment failure.

Security and Privacy Risks:

Cyber-Vulnerability: Automated systems are susceptible to diverse security threats, including jamming, spoofing, and malware that can compromise a robot's navigation or control systems.

Data Protection: The collection of personal health data and the use of constant video surveillance for hygiene monitoring raise intense privacy and legal concerns, necessitating strict adherence to frameworks like GDPR and CCPA to avoid unauthorized data exposure.



Comparative Evaluation of Sanitization Methods

3-Cybersecurity, Privacy, and Ethical Concerns

Attack Surfaces

In the context of contactless sanitization systems, an **attack surface** is defined as the set of vulnerable points on a system's boundary or environment through which an adversary can compromise its functionality. These surfaces are primarily categorized into **physical attacks**, **digital attacks**, and other network-related vulnerabilities.

Physical Attack Surface: This involves the physical manipulation of hardware, such as tampering, destruction, or theft of sensors to disrupt the system's perception.



Jamming Attacks: Adversaries can use intense light to jam camera sensors or emit light at the same wavelength as LiDAR to render it ineffective in detecting obstacles. Ultrasonic sensors and GPS signals are also susceptible to jamming, potentially leading to Denial-of-Service (DoS) scenarios where the sanitization system becomes unavailable.

Spoofing Attacks: These involve deceiving sensors with false information, such as using laser projection to fool LiDAR-based perception or transmitting false GPS signals to redirect autonomous sanitization robots to incorrect locations.

Sensor Manipulation: Targeted attacks can manipulate Inertial Measurement Units (IMUs), affecting a robot's ability to measure velocity and causing it to lose control or fail in object detection tasks.

Digital Attack Surface: These attacks exploit software vulnerabilities in a robot's operating system, firmware, or algorithms to manipulate its planning and control layers.

Actuator Attacks: Adversaries may target the hardware-level firmware or communication protocols of actuators (the components that move robot arms or wheels) to cause abrupt or harmful movements. Vulnerabilities often arise from hard-coded credentials in user manuals or a lack of access rights configuration, allowing unauthorized remote control.

Malware and Ransomware: Sanitization robots can be targeted by self-learning malware that tracks movements to trigger harmful payloads or ransomware that locks industrial control systems to extort operators.

Attacks on AI Models: Since many contactless systems rely on AI for object recognition and screening, the AI pipeline itself is a critical attack surface.

Training (Poisoning) Attacks: An adversary can poison the training dataset by tampering with sensory data, leading the AI to misclassify objects or misjudge distances.

Inference Attacks: These include model evasion, where input is subtly perturbed to prevent correct classification, and model alteration, where network weights are modified to create hidden "backdoors" that cause the system to fail on specific inputs.

Network and Communication Surface: Vulnerable communication protocols can lead to eavesdropping, traffic analysis, and man-in-the-middle attacks. To mitigate these risks, modern smart gateway systems often implement HTTPS-encrypted data transmission and admin-only access control for real-time databases. Systems may also store authentication metadata, such as QR codes, locally to reduce the risks associated with cloud-based persistence and data exposure.

b- Data Privacy

The deployment of contactless sanitization and AI-robotic systems necessitates the exchange of substantial personal information, raising critical data privacy concerns regarding unauthorized access and information leakage. Systems designed for hand hygiene monitoring and smart entry screening often involve constant video or sensor surveillance, which can be perceived by staff and the public as an invasion of privacy and a pretext for continuous monitoring. Furthermore, there is a significant concern that health adherence data collected by these systems could be misused for punitive purposes rather than exclusively for public safety.

To mitigate these risks, systems must be designed to adhere to strict legal and regulatory frameworks, most notably the General Data Protection Regulation (GDPR) in Europe and the California Consumer Privacy Act (CCPA) in the United States. In healthcare contexts, the development of medical and sanitization robots should ideally align with the Health Insurance Portability and Accountability Act (HIPAA) to ensure the security of sensitive medical information and prevent data breaches.

Modern frameworks address these vulnerabilities through Privacy Enhancing Technologies (PET), which aim to protect user identities through anonymity, pseudonymity, and data obfuscation. Specific technical strategies include:

Differential Privacy (DP): Used to compute a theoretical bound on the effect any particular input has on the output, thereby preventing information leakage.

Selective Forgetting: Also known as "amnesiac machine learning," this technique allows systems to scrub specific private data or arbitrary classes from trained neural networks without using the original dataset.



Decentralized Data Management: Protecting privacy by adopting models where sensitive information, such as vaccination metadata or QR codes, is stored locally on a user's device rather than in cloud databases to limit data exposure.

Ensuring transparent communication and obtaining explicit informed consent are essential ethical requirements to build user trust and ensure individuals are fully aware of what data is being collected and how it will be utilized. Ultimately, stakeholders must strike a careful balance between system utility and privacy, ensuring that the public health benefits of contactless processes do not result in unintended social or legal harm through data misuse.

c- Legal Liability

Navigating liability and responsibility within robotic and automated systems presents a complex legal challenge, as the integration of autonomous decision-making blurs traditional lines of accountability. As contactless sanitization and medical robotics become more prevalent, determining who is at fault when a procedure or process goes awry—such as during remote-assisted telesurgery or autonomous disinfection—requires careful legal consideration.

Determining Accountability: A primary concern in the field is identifying which party should be held liable for malfunctioning or harmful actions. Potential candidates for legal responsibility include the system manufacturer, the software developer, the human operator overseeing the device, or even the autonomous agents themselves. However, assigning liability directly to an AI agent remains difficult under current frameworks because they are not recognized as legal persons.

Risk in Specialized Environments: The use of surgical and sanitization robots in high-risk or hostile environments increases the stakes for unintended events, such as an attack on robot actuators or mechanical failure during a critical task. These liability issues arising from robotic errors serve as a significant barrier to the widespread adoption and trust of these technologies in clinical settings.

Sector-Specific Consequences: Beyond clinical errors, legal liabilities extend to the failure of maintaining hygiene standards in public sectors like hospitality and tourism. Subpar hygiene can expose guests to health risks, leading to legal claims, fines, or facility closures by health authorities. In the context of online services, such as online pharmacies, there is an urgent need for government bodies to implement specific regulations to ensure safe purchases and clear accountability for medicinal vendors.

Frameworks for the Future: To address these concerns, researchers advocate for the development of standards and legal-regulatory frameworks that align with humanitarian laws and medical ethics. While the three laws of robotics proposed in fiction offer some guidance for programming AI agents, their real-world implementation remains a challenge for engineers attempting to ensure that robots do not cause harm through action or inaction. Ultimately, resolving these legal ambiguities is essential for fostering economic resilience and public trust in contactless systems.

VIII. FUTURE DIRECTIONS AND RESEARCH GAPS

1. Optimization

The future of contactless sanitization lies in transitioning from semi-autonomous aids to fully autonomous, human-free disinfection solutions. Current research highlights several critical areas where optimization is required to bridge the gap between experimental success and real-world scalability.

Refinement of Chemical and Light-Based Protocols: While non-contact fumigation using vaporized hydrogen peroxide (VHP) is effective for bacteria, it currently shows limited efficacy against fungal pathogens and struggles to reach shadowed areas. Optimization strategies should focus on increasing disinfectant concentrations or developing alternative chemical agents that are more effective against resistant spores. Similarly, for light-based systems (UVGI), there is a need for innovative fixture designs that increase germicidal efficiency while keeping manufacturing and operational costs low, particularly for resource-limited settings.

Advanced AI and Navigation for Dynamic Environments: Current autonomous mobile robots (AMRs) often operate on preset paths and may require manual intervention when encountering obstacles. Future optimization must focus on



enhancing SLAM (Simultaneous Localization and Mapping) technology and AI-based predictive algorithms. This will enable robots to autonomously reset their paths and navigate the unpredictable corridors of hospitals or high-traffic public hubs without collisions or operational halts. Additionally, integrating Explainable AI (XAI) can help non-expert users understand robot failures, thereby calibrating human trust in these systems.

Standardization of Performance Metrics: A significant research gap exists in the lack of standardized measurement tools and metrics to evaluate the accuracy and quality of different sanitization systems. Future research must establish industry-wide benchmarks to measure performance differences across diverse technologies, such as the WHO 6-step hand hygiene technique monitoring or UV-C surface coverage accuracy.

Operational and Economic Efficiency: Optimizing these systems for space and time efficiency is crucial for their economic viability. In the hospitality and transportation sectors, leveraging predictive analytics and IoT can optimize resource use—such as water and electricity—while ensuring cleaning schedules are based on real-time occupancy data rather than rigid timers. Furthermore, research should prioritize material compatibility, ensuring that high-intensity UV-C or aggressive chemicals do not degrade the electronic components or finishing materials of the infrastructure they protect.

Sustainability and Integration: Future directions include the development of "smart" buildings equipped with autonomous air quality detection and integrated parallel wastewater systems to prevent cross-contamination. The ultimate goal is a holistic integration where waste, energy, and water systems work in a circular loop, maximizing resource recovery while maintaining a sanitized environment.

2. Emerging Trends

The landscape of contactless sanitization is evolving toward a highly integrated ecosystem where physical hardware, immersive software, and real-time data networks converge to ensure public health safety.

Integration of LLMs and Enhanced HRI: A significant emerging trend is the incorporation of Large Language Models (LLMs) into social and assistive robots to foster more natural and intuitive Human-Robot Interaction (HRI). By enabling robots to engage in natural conversations, healthcare facilities can improve user acceptability among patients and caregivers, transitioning robots from mere tools to interactive partners.

Healthcare in the Metaverse and VR/AR: The metaverse is being proposed as a transformative platform for digital health, integrating Artificial Intelligence (AI), robotics, quantum computing, and IoT. Virtual Reality (VR) and Augmented Reality (AR) are increasingly used for "pre-visit" previews in tourism and for complex medical procedures, such as VisAR, which allows for the virtual superimposition of organs with submillimeter precision during surgery.

5G, Tactile Internet, and Digital Twins: The emergence of 5G-based Tactile Internet (TI) is providing the ultralow latency and high reliability required for real-time robotic control in dynamic environments like crowded hospital corridors. Parallely, the use of Digital Twins—digital representations of physical patients or systems—enables real-time monitoring and predictive modelling to optimize treatment and hospital workflows.

Advanced Materials and Antimicrobial Coatings: To complement active sanitization, there is a growing trend toward "future-proofing" infrastructure with antimicrobial surfaces. This includes applying copper-infused coatings or titanium dioxide to high-touch areas like handrails and elevator buttons, which naturally degrade viruses upon contact.

Swarm Robotics and Collaborative Systems: Future research is leaning toward swarm robotics, where multiple autonomous agents communicate and move like a single organism to perform large-scale tasks such as disinfecting entire airports or hospitals simultaneously. These systems rely on decentralized security solutions and federated learning to protect the swarm from targeted adversarial attacks.

Blockchain for Data Integrity and Transparency: Blockchain technology is emerging as a critical tool for ensuring the transparency and traceability of sanitization efforts and vaccination verification. In the "phygital" (physical plus digital) environment, blockchain can secure health-related transactions and build consumer trust by providing unalterable records of cleaning protocols and guest safety.



Device-Free Monitoring and Advanced Sensing: Innovative research has demonstrated the potential for device-free indoor location tracking using existing commodity Wi-Fi infrastructure, allowing facilities to monitor personnel movement and hand hygiene compliance without requiring wearable tags. Additionally, the adoption of "toe-to-go" elevator systems, voice-activated interfaces, and AI-based facial recognition is expected to become standard in post-pandemic architectural design.

3. Resilient Design

Future research and implementation in the field of contactless sanitization focus on resilient design, which aims to bridge the gap between temporary crisis response and long-term sustainable infrastructure. This involves integrating physical architectural shifts with advanced automated systems to ensure society can withstand future infectious outbreaks without total economic or social shutdown.

Holistic Architectural Adaptation: Future residential and institutional buildings are moving toward flexible, adaptive configurations. This includes designing homes with separate entry spaces where contaminated objects can be left outside living areas and creating rooms that can be easily partitioned for quarantine purposes. In healthcare, resilient design focuses on anterooms serving as buffers between sterile and high-traffic zones, and rooms capable of adjusting airflow direction, pressurization, or hourly air changes based on real-time health risks.

Zonal Isolation and Functional Separation: A critical trend in resilient design is the establishment of dedicated environmental zones—clean, semi-clean, and contaminated—with independent circulation structures and air-conditioning systems. For senior living, this manifests in smaller, homelike settings (such as the "Green House" model) with consistent staff to minimize entry and re-entry risks. Furthermore, large-scale venues like convention centres and stadiums are being future-proofed for swift conversion into auxiliary care sites, incorporating features like wide entrances for hospital beds and optimized ventilation.

Advanced Material Selection and Infrastructure: Future infrastructures are expected to prioritize antimicrobial materials, such as copper-infused handrails and bed rails, to naturally degrade pathogens. In plumbing, the implementation of parallel wastewater systems and sink pipes in U-traps is recommended to prevent cross-contamination through interconnected sewer networks.

Technological and Digital Resilience: The integration of "smart" systems that automatically detect and respond to indoor air quality or surface contamination is a primary research goal. Beyond physical structure, future systems must be cyber-resilient, designed to withstand jamming or spoofing of sensors in automated sanitization networks. There is also an emerging focus on the "phygital" environment, where technologies like Digital Twins are used for real-time predictive modelling of hospital workflows and infection risks.

Standardization and Metrics: A major research gap remains the lack of standardized measurement tools and metrics to evaluate the effectiveness of different technologies. Establishing industry-wide benchmarks for system accuracy and performance is essential to facilitate the broad adoption of these resilient design principles in both resource-rich and resource-limited settings.

IX. CONCLUSION

The rapid global integration of contactless disinfection and autonomous systems marks a **paradigm shift in public health, safety, and economic resilience**, a transition significantly accelerated by the COVID-19 pandemic. Technologies once considered subsidiary, such as **UV-C germicidal irradiation, vaporized hydrogen peroxide (VHP) fumigation, and automated dispensing systems**, have moved to the centres of institutional infrastructure. These tools effectively eliminate shared contact points and human error, providing consistent sanitization in high-traffic and high-risk zones. **Autonomous Mobile Robots (AMRs)** have proven indispensable in streamlining hospital logistics and performing terminal disinfection, thereby **reducing staff exposure to infectious pathogens** and freeing personnel for direct patient care. However, comparative analyses indicate that while automated methods like VHP are highly scalable, they still face technical limitations such as **"micro shadows" and variable efficacy against resilient fungal**



strains, meaning they currently supplement rather than entirely replace manual cleaning. The fusion of **AI, IoT, and smart gateways** has revolutionized screening processes, enabling real-time thermal monitoring, face mask detection, and vaccine verification with minimal latency. Across the **healthcare, public transportation, and hospitality sectors**, these advancements have redefined the "guest journey," transitioning standard operations toward **contactless check-ins, remote monitoring, and automated service interfaces** that meet permanent post-pandemic expectations. Despite these benefits, the digitization of hygiene introduces significant **cybersecurity and ethical challenges**. The expanded "attack surface" of connected sensors and actuators necessitates robust defence strategies against **spoofing, jamming, and data breaches**. Furthermore, the collection of sensitive health metadata requires a careful balance between **system utility and individual privacy**, demanding strict adherence to legal frameworks like GDPR and HIPA A. Looking forward, the future of sanitization lies in **resilient design** and the integration of emerging technologies such as **5G-based Tactile Internet, Digital Twins, and blockchain** to ensure data integrity and real-time response optimization. By evolving from crisis-driven responses to sustainable, fully autonomous systems, society can bolster its preparedness for future infectious threats while safeguarding **both public health and economic stability**.

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