UV Disinfection Robots: A Review

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Abstract

The novel coronavirus (COVID-19) pandemic has completely changed our lives and how we interact with the world. The pandemic has brought about a pressing need to have effective disinfection practices that can be incorporated into daily life. They are needed to limit the spread of infections through surfaces and air, particularly in public settings. Most of the current methods utilize chemical disinfectants, which can be laborious and time-consuming. Ultraviolet (UV) irradiation is a proven and powerful means of disinfection. There has been a rising interest in the implementation of UV disinfection robots by various public institutions, such as hospitals, long-term care homes, airports, and shopping malls. The use of UV-based disinfection robots could make the disinfection process faster and more efficient. The objective of this review is to equip readers with the necessary background on UV disinfection and provide relevant discussion on various aspects of UV robots.

1. Introduction

The COVID-19 outbreak has been classified as a global public health emergency. According to a recent report from WHO [1], more than 624 million cases and over 6.57 million deaths have been reported since the start of the pandemic. COVID-19 is caused by the severe acute respiratory syndrome coronavirus 2, SARS-CoV-2. Enormous efforts have been devoted by nations worldwide to contain this disease. The virus can either be transmitted directly through respiratory droplets and aerosol particles in the air or indirectly through infectious droplets that are deposited onto surfaces [2, 3, 4]. Studies have shown that the virus can remain active and contagious on surfaces from hours to days depending on the surface material [5].

Although vaccines are being used to tackle the current pandemic, there is a need to develop more efficient decontamination procedures for the current pandemic and the post-pandemic world. Cimolai [6] presents a systematic review of environmental issues and decontamination strategies for COVID-19. The conventional method of decontamination is through manual cleaning followed by disinfection with chemicals. These procedures are labor-intensive, error-prone, could increase exposure risk for cleaning personnel, and do not provide consistent and effective results. Chemical disinfectants, including household bleach and quaternary ammonium compounds, can also be harmful to humans, leave unwanted residue, and be resisted by certain pathogens over time [7, 8].

On the other hand, ultraviolet radiation exposure is used as a no-contact decontamination method. There is a wealth of evidence indicating the effectiveness of ultraviolet (UV) germicidal irradiation as a disinfection and sterilization approach for the prevention of various infectious diseases, including COVID-19, influenza, and tuberculosis [9]. Short-wavelength ultraviolet light, known as UVC

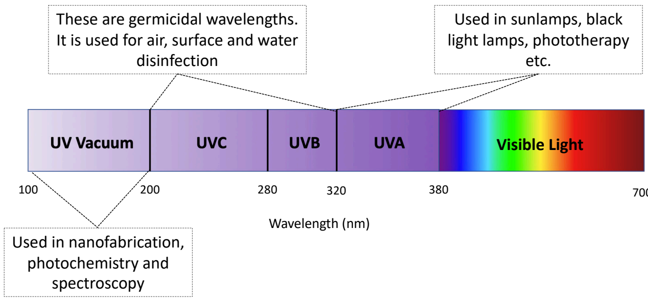

Figure 1: The ultraviolet spectrum and its applications: UVC and UVB light (200-320 nm) are known to have germicidal capabilities. UVA radiation (320–400 nm) is not germicidal, and vacuum UV (100-200 nm) is absorbed in air rapidly and is not used for surface disinfection [11].

(200–280 nm, Fig. 1), disrupts the DNA/RNA of micro-organisms and terminates their cellular activities and reproductions. UVC disinfection can be achieved by mounting UVC lights on the ceiling or using portable UVC lamps to disinfect various surfaces and the air [10]. However, these modes are not very efficient in practice, as they could require long operating times and a lot of manual supervision.

There is a rising interest in using autonomous disinfection systems like UV robots, due to their potential for more efficient disinfection [12] These robots have been deployed to disinfect hospital rooms against COVID-19 through the use of intense radiation [13]. Although the routine application of UV robots in public places could significantly limit the spread of infections, the intense UV radiation from these devices is hazardous to human skin, and thus human presence should be avoided. This may limit the operating time of such devices, and modifications to existing UV systems may be required to further improve the safety and performance of disinfection.

With the onset of the COVID-19 pandemic, there has been an increased focus on UV disinfection technology. Abajo et al. [14] and Raeiszadeh and Adeli [24] present critical reviews on UV disinfection, and their discussions cover a broad range of UV disinfec-

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Table 1: List of review papers on ultraviolet germicidal irradiation (UVGI)

Author/Year	Disinfection Fundamentals	UVGI Systems	UVGI Robots	Efficacy Analysis	Limitations of UVGI	Irradiance Modeling	Open Problems
García de Abajo et al./2020 [14]	✓	✓	×	✓	✓	×	✓
Raeiszadeh et al./2020 [15]	✓	✓	×	✓	✓	×	✓
Ramos et al./2020 [16]	✓	✓	×	✓	✓	×	×
Chiappa et al./2021 [17]	×	✓	×	✓	×	×	×
Dancer et al./2021 [18]	✓	✓	×	✓	×	×	✓
Holland et al./2021 [19]	✓	×	✓	✓	✓	×	✓
Kwok et al./2021 [20]	×	×	×	✓	×	×	×
Kumar et al./2022 [21]	✓	✓	×	✓	×	×	✓
Martins et al./2022 [22]	×	×	×	✓	×	×	✓
Scott et al./2022 [23]	×	✓	×	✓	✓	×	✓
This paper	✓	✓	✓	✓	✓	✓	✓

tion methods and the efficacy and safety of UV devices. Chiappa et al. [17] provided a review that demonstrates the efficacy of a variety of UV disinfection systems against different strains of coronavirus, while Martins et al. [22] explored the validity of different disinfection methods for SARS-CoV-2 in various settings. Some works have also covered the response of the robotics community [25, 26, 19, 27]. They gave an overview of robots, including disinfection, cleaning, and COVID-19 testing robots, that are being used to address problems faced during the pandemic. Kumar et al. [21] gave a brief overview of the basics of UV disinfection, and Guettari et al. [28] provided a discussion on the efficacy of UV robots and devices. However, most of the existing reviews focus solely on classical ultraviolet germicidal irradiation (UVGI) systems, and none of these works provide discussion regarding the autonomy systems of UV robots. Recently published reviews on UV disinfection systems and robots have been compared in Table 1.

Although the COVID-19 pandemic has led to significant growth in UV disinfection and robotics research, their uses are not limited to the current pandemic. Other existing and future infectious diseases could also be combated with the derived research. The contagious nature of pathogens poses a problem in various public spaces. For example, Hospital-Acquired Infection (HAI) has been a major concern. HAIs may occur in hospitals, clinics, surgical centers, and long-term care facilities. It is estimated that there are more than 440,000 HAIs per year in the US [29]. UV robots can be used as additional tools to combat HAIs.

In this work, we aim to provide a complete guide for UV robots that covers relevant background on UV disinfection and classical UVGI systems. We also point out the open problems and potential directions of research to address the operational issues of UV robots. This paper is organized as follows: Section 2 presents all the relevant background for UV disinfection. Section 3 presents a discussion on commercially available UV robots and autonomous UVGI systems under research, while Section 4 explores non-UVGI disinfection robots. Finally, future directions and the conclusion are included in Sections 5 and 6 , respectively.

2. Background on UV Disinfection

Decontamination is the process of removal, inactivation, and destruction of pathogens, including bacteria, viruses, prions, fungi, and other microorganisms, to prevent the spread of infections [30]. It consists of three steps: cleaning, disinfection, and sterilization.

Cleaning involves the physical removal of infectious material through mopping, vacuuming, and scrubbing. Disinfection is the process of eliminating pathogens (except for bacterial spores), while sterilization eliminates all microorganisms. Both chemical disinfectants, such as hydrogen peroxide and bleach, and UV radiation are utilized for disinfection, and sterilization [30]. There are stringent sets of guidelines and policies that are typically used to ensure sufficient decontamination [31]. This paper focuses primarily on methods of disinfection and sterilization through UV-based strategies.

Ultraviolet germicidal irradiation (UVGI) is a proven way of disinfection. In this section, we provide relevant background on UV disinfection and various essential factors associated with designing and developing the large variety of available UV disinfection devices.

2.1. *UV Disinfection Mechanism*

UVGI can induce photochemical effects in cells to have a germicidal impact. Ultraviolet light in the wavelength range of 200–320 nm possesses such germicidal properties and is further categorized into germicidal wavelengths of UVC (200–280 nm) and UVB (280–320 nm). UVB and UVC lights are absorbed by the DNA, RNA, and proteins of the cells, which prevent them from replicating and surviving. UVA ($320-400\,nm$), around 95% of what sunlight on earth is composed of, does not have germicidal properties [11]. In this paper, "UVGI" and "UV" will be used interchangeably for simplicity, with both terms referring to UV light with a germicidal wavelength of 200–320 nm.

UVGI systems have been widely used in the disinfection of air, surfaces, water, and food. Some of these systems are enlisted in the following:

- **Air Purification**: For air disinfection, in-duct UV systems are commonly adopted. They consist of arrays of UV bulbs installed in air ventilation ducts to inactivate pathogens in moving air streams [32]. In addition, there are upper room UV systems that primarily create a zone of germicidal irradiation in the upper region of rooms to disinfect bio-aerosols [33].

- **Surface Disinfection**: Surface disinfection can be achieved by exposing the target surface to an appropriate UV dose. Typically, it is used for the sterilization of equipment and rooms using portable disinfection UV devices or overhead UV fixtures that encompass certain areas [34].
- **Water Disinfection**: UV chambers in which the water is irradiated are integrated into many water purification systems [35, 36].
- **Food Safety**: UV irradiation has been approved for inactivation of pathogens in various food products [37]. It is typically used for inactivating microbes to enhance the shelf life of liquid foods, fruits, and vegetables [38].

2.2. *UV Safety Consideration*

UV exposure from sunlight and artificial sources, such as UVGI systems, could be hazardous. It is important to consider the probable phototoxic effects of these systems to avoid accidental harm prior to implementation.

- **UV Exposure**: UV wavelengths ranging from 200 – 320 nm have the most severe side effects to humans. Although UV light is undetectable to the human eye, exposure to intense UV rays could lead to cataracts and vision loss [24]. In addition, potential effects of UV exposure on the skin include erythema, photoaging, immuno-suppression, and skin cancer [39]. In some recent works, it was observed that far-UVC light (207 – 222 nm) effectively kills various strains of human coronaviruses without any harmful effects on exposed human skin [40, 41]. This is primarily due to the limited penetration distance of far-UVC from the outer layer of the mammalian skin [42]. On the other hand, UVB (280 – 320 nm) rays, which are often also present in UVGI systems, can penetrate deeper into the skin and eye to potentially cause cancer and DNA damage similar to UVC [43]. According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the effective UV exposure dose on human eyes and skin should not exceed 30 $[J/m^2]$ in a period of 8 hours [44]. This recommendation has been adopted as a regulation by the US Food and Drug Administration (FDA) and the European Union [24].
- **Ozone Production**: Another risk associated with UV disinfection is the production of ozone. UV radiation of wavelength less than 240 nm can produce ozone and other oxides [11]. As a corrosive gas, ozone could lead to fire hazards. Ozone is also a strong oxidant and toxic air pollutant. Health Canada limits ozone exposure to no more than 20 ppb (parts per billion) in the span of 8 hours [45]. Similarly, the FDA limits the amount of ozone from indoor medical devices to 50 ppb [24]. Manufacturers of UV lamps usually mention the amount of ozone the lamp may produce. Depending on the spectral range and the lamp type of the UVC light source, it may or may not produce ozone. Many such lamps have doped glasses to block ozone-generating wavelengths [46]. It is worth mentioning that ozone gas also has a germicidal effect. For instance, ozone generators, which use UV lamps to generate ozone, are used in the ozonization of water for its disinfection [47].
- **Presence of Mercury**: Mercury-based UV lamps are of concern due to the heavy metal's known harm to the environment and human health. Inhalation of mercury vapor via UV lamp breaks can lead to accumulation within the body, and damage to the neurological and renal systems [48]. In addition, improper disposal of mercury lamps pollutes the environment and adversely affects aquatic life and the soil quality. Other UV light sources mentioned in Sec. 2.1, including UVC LEDs, PXL, and excimer lamps, do not experience safety concerns for mercury presence.

Various countries have regulations to limit the adverse effects of UV devices. For example, in the US [49] and Canada [50], UV devices must comply with the laws on radiation-emitting devices. International Organisation for Standardization (ISO) provides guidelines on minimum requirements of human safety of UV devices as well [51]. Further, they elaborate on the use of protective equipment, such as UV shields and reflectors, that should be used when operating such devices. Nenova et al. [52] presents a systematic approach to improve the safety of UV devices.

2.3. *UV Light Sources*

UVGI systems utilize ultraviolet radiation of varying wavelengths produced from different sources. Each light source poses distinct advantages and disadvantages. It is essential to select a suitable light source to ensure desired disinfection performance. UV light sources currently used are classified into four categories, described below:

- **Mercury Gas Discharge Lamps**: These lamps are made of electrodes containing plasma sealed within a glass body. They are filled with inert gas (e.g. argon) and mercury. When a high voltage is applied, electrons get excited and emit UV light on returning to ground state [53]. These lamps can be classified depending on the pressure of the gas. Low-pressure (LPM) and medium-pressure mercury (MPM) lamps are most commonly used for germicidal applications. MPMs produce a broad spectrum of UV radiation, while LPMs have a narrow emission spectrum band centered at 254 nm.
- **UVC light-emitting diodes (LEDs)**: These are compact semiconductor devices. Typically the semiconductor material for UVC LEDs is Aluminium Gallium Nitride [54]. They produce monochromatic light and generally are available in the range of 255 – 285 nm. Unlike conventional mercury UV lamps, UV-LEDs can selectively combine multiple UV wavelengths for potentially more effective disinfection [55].

Table 2: Comparison of UVGI light sources

Property	UVC-LED	LPM	PXL	Excimer Lamp
Instant On/Off	Yes	No	Yes	Yes
Small Footprint	Yes	No	No	No
Mercury Free	Yes	No	Yes	Yes
Ozone Generation	No	No	Yes	Yes
DC Operation	Yes	No	No	No
Tentative Life Span (hrs)	10K	10K	2K	6K
Wattage Range* [W]	0.5	8-335	10-8000	5-500
Price range per unit * (USD)	1-10	20-1200	50 - 750	600-5000
Wall Plug Efficiency (%)	< 5 [59]	15-35 [59]	12 -17 [60]	40 [61]

* Based on data from [62, 59]

- **Pulsed Xenon Arc Lamps (PXL)**: In these lamps, a broad spectrum UV light (with a greater UVC component) is released in the form of short duration high intensity pulses [56]. Xenon gas flash bulbs used in the lamps can emit a UV spectrum of 200 to 280 nm and light in the visible light spectrum [57]. They are a nontoxic alternative to mercury lamps.
- **Excimer Lamps**: These lamps produce UV radiation via the decomposition of a complex of excited gases [38]. Recently proposed far-UVC lamps use krypton-chlorine (Kr-Cl) gas mixture and are examples of excimer lamps [40, 41]. Excimer lamps produce a monochromatic spectrum [38].

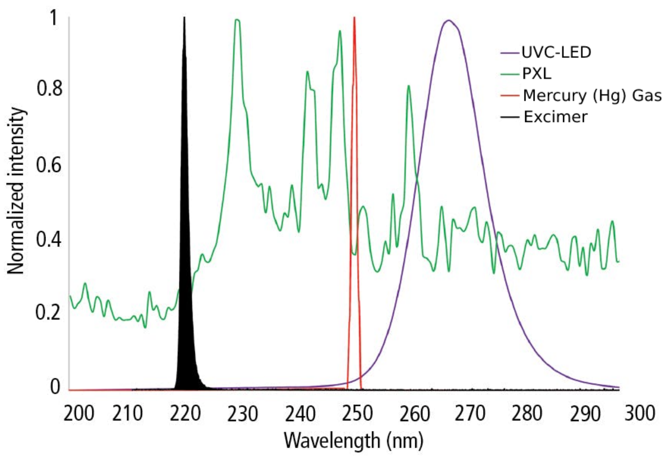


Figure 2: (Plot of Normalized Intensity (arbitrary units) Vs Wavelength (nm) [58]. Spectral Distribution of UV Light sources. LPM and UV-LEDs have narrow emission spectrum. MPMs have a wider spectrum which extends in ozone producing wavelenghts as well.

The emission spectrum of different light sources is depicted in Fig. 2. Most of these light sources have a monochromatic spectrum except for the PXL. There are a limited amount of studies comparing the effectiveness of these different light sources; as a result, it is hard to present a fair comparison.

Gas discharge lamps are the most commonly used. A large variety (in terms of wattage, UV output, size, fixtures, etc.) of these lamps are commercially available. These lamps have greater wall plug efficiency than PXLs and LEDs; however, they suffer from some limitations [60, 63]. The main concerns are health and environmental risks due to mercury contamination, and long warm-up times of the lamp that lead to excessive power consumption [60]. Some studies suggest that disinfection by PXLs lead to more significant inactivation of microbes in shorter exposure times [56], making them a popular choice in surface disinfection.

UVC-LEDs are relatively new to the UV market. It is mainly used in water disinfection applications [64]. They offer many advantages, including a smaller footprint, unlimited on-off cycles, no warm-up time, environmentally friendly, and longer lifetimes [59] when compared to the traditionally used mercury lamps. However, UVC-LEDs have low wall plug efficiency and lower power outputs. More UVC-LED bulbs are required to achieve similar power outputs as systems that utilize mercury UVC lamps, making UVC-LED systems more expensive [63]. UVC-LEDs still hold great potential due to the flexibility in the design of these LED-based reactors [59].

Far-UVC light generated from excimer lamps has been demonstrated to eliminate methicillin-resistant S. aureus (MRSA) bacteria while avoiding skin-related damage, such as erythema, skin cancer, and UV-associated premutagenic DNA lesions, unlike regular UVC, UVB and UVA radiation [42, 65]. A comparison on some properties for these light sources is given in Table 2.

2.4. *UV Irradiance Dosage and Modelling*

In order to determine the effectiveness of UVGI systems quantitatively, UV irradiance dosage and modeling are required. The inactivation of pathogens depends on the supplied UV dosage and duration of light exposure. The UV dosage, D $[J/m^2]$, for microbes subjected to UV radiation is given by [10]:

$$D = E_t \cdot I_r, \tag{1}$$

where E_t is the exposure time in seconds and I_r is the radiant flux received by a surface per unit area (a.k.a irradiance) with SI units $[W/m^2]$. The effectiveness of a dose is classified in terms of log reduction of the microorganism population:

$$log_{10}(r) = log_{10}(\frac{N_0}{N}), \tag{2}$$

where N_0 and N represent the pathogen population before and after UV exposure and r represents the reduction factor. Reduction factor can take values 1,2,3 and 4 which corresponds to pathogen population reduction rate of 90%, 99%, 99.9% and 99.99% respectively. Different pathogens have varied susceptibility to UV radiation; hence, the required UV dose for an application should be selected based on the targeted microbes. Detailed data on exposure dosages for different reduction rates (e.g., D_{90}, $D_{99.9}$) for various bacteria and viruses are provided in [10]. A few doses are included for reference in Table 3.

Table 3: Required D_{90} UV Doses for Surface Disinfection

Pathogen	Dose $[J/m^2]$
Bacteria (Average UV Dose) [10]	54
Viruses (Average UV Dose) [10]	73
SARS-COV-2 (COVID-19 virus) [66]	27

Irradiance Models: The modeling of irradiance fields for UV light sources is essential for determining the UV doses delivered by a system to a target surface or airborne microbes. These models can be utilized to simulate the dosage distribution by a UV-robot, which in turn can be used for path planning of the robot [67, 68].

The inverse square law (ISL) model is a commonly used method, where irradiance at a point is inversely proportional to the distance ρ from a point light source with radiant power ϕ [W]:

$$I \propto \frac{\phi}{\rho^2} \tag{3}$$

ISL can be easily extended to non-point light sources. Jacobm and Dranoff [69] used ISL for cylindrical lamps by approximating it as a line source, where each line source can be represented as an aggregation of multiple point sources. ISL is a simple model, but it is only valid in cases where the irradiated surface is far from the light source [70]. Further, ISL doesn't accurately account for the geometry or the type of light source. Many models have been proposed for cylindrical gas discharge lamps. Kowalski and Bahnfleth used thermal view factors to model the near fields for cylindrical light sources [71]. These view factors account for radiation transmitted from emitting surface to the receiving surface. Detailed calculations of view factors for different light sources are given in [71]. The irradiance is computed using:

$$I = \frac{\phi}{2\pi \cdot r \cdot l} \cdot F_{total} \tag{4}$$

where r is the radius of the cylindrical lamp, l is the length of the lamp, and F_{total} is the view factor. They demonstrated superior accuracy compared to ISL for short and far distances. The view factor model can easily replace the ISL for dosage simulation in a robotics application. In many cases, UV lamps are mounted in reflective housing. This changes the irradiance field and should be accounted for while designing a system. Various reflectivity models based on the type of reflectivity are presented in [10].

A UV-LED can be treated as a point light source for far-off distances; hence, ISL model, e.g. Eq. (3), can be used in such cases. The irradiance field due to a complete LED module can be generated by aggregating the contribution of irradiance from each LED in the module. As mentioned before, ISL does not hold [72] for closer distances. An exact expression for irradiance is deduced for rectangular LED in [73]. This method can be used to model the dosage by UV-LEDs for closer distances accurately.

There are models that more accurately account for additional factors, including target surface geometry, the reflectance of surfaces and fixtures, and refractivity. These models are typically more complicated than the simple models presented above. For instance, irradiance models for UV-LEDs for water treatment were derived and incorporated in computational fluid dynamics packages to generate irradiance fields [74, 75]. However, these models are more applicable to small-scale systems and are likely to be computationally expensive for modeling a 3D environment of the world. Ahmed et al. [76] used ray tracing software to accurately model UV irradiance in a UV photo-reactor. Ray tracing software simulates the trajectories of electromagnetic rays emitted from a light source while accounting for laws of optics, refraction, reflection, and shadowing. Ray tracing tools can accurately model the irradiance, but these models are highly computationally expensive.

2.5. Efficacy of UVGI systems

The effectiveness of UVGI systems has been compared to manual cleaning and disinfection. Justification for redesigned decontamination strategies with UV-based systems can be acquired with such studies. The disinfection performance of UVGI systems with varying light sources and UV wavelengths has also been validated under research and real-world environments. This sub-section discusses the capability of UVGI systems to disinfect various pathogens.

Table 4 displays some recent studies that have analyzed various UV disinfection setups against commonly encountered pathogens. Buonanno et al. [78] observed the efficacy of far-UVC light (222 nm) against aerosolized alpha HCoV-229E and beta HCoV-OC43 in a laboratory setting. They found that there was 99.9% inactivation (3-log reduction) for the pathogens at low UV light doses of 1.2 to 1.7 mJ/cm^2. Gerchman et al. [79] and Heilingloh et al. [80] examined UVC-LED (267-297 nm) and UVC lamp (254 nm) respectively in a laboratory setting instead. The UVC-LED system achieved 3-log inactivation of HCoV-OC43 at irradiation of 6-7 mJ/cm^2 after 60 seconds. In addition, the UVC lamp was able to completely inactivate SARS-CoV-2 at 1047mJ/cm^2 after 9 minutes.

Unlike the previously discussed laboratory studies, Morikane et al. [81] inspected the performance of a PX-UV device (200-280 nm) in a Japanese hospital's intensive care unit (ICU) over 2.5 years. They discovered a significant decline in incidences of newly acquired methicillin-resistant Staphylococcus aureus (MRSA) and drug-resistant infections. Nerandzic et al. [57] also conducted their PX-UV device analysis in a hospital. A reduction of 0.55-log to 1.85-log was demonstrated for C. difficile spores, MRSA, and VRE on high-touch surfaces within the hospital after 10 minutes of disinfection. Newer efficacy studies, such as [77], that feature UV robots in real-world settings have also begun to emerge. Detailed reviews of published studies evaluating the efficacy of UVGI systems are presented in [16] and [22].

2.6. Limitation of Classical UVGI systems

Classical UVGI systems, such as the previously introduced fixed UV lamps, upper room UV germicidal systems, and portable UV lights, are effective in complementing and improving existing decontamination procedures; however, there are certain limitations:

- **Shadowing**: Pathogens are protected when engulfed by shadows from objects (e.g. equipment, chairs, beds), since the UV radiation cannot reach such pathogens. The issue of shadowed regions can be addressed by reflecting UV radiation for indirect disinfection [82]. Another solution could be to manually maneuver the UV fixture and lamp around the room to increase the surface exposure to the UV source.

- **Pathogen Coating**: Pathogens within respiratory droplets and aerosol particles, such as sputum and blood, have been proven to block the effects of UV radiation partially. The

Table 4: Non-exhaustive list of recent efficacy studies on UVGI systems

Author/Year	Study Location	UV Light Type	Pathogen Type	Disinfection Method	Results
Astrid et al./2021 [77]	Outpatient hospital clinic (Austria)	Clean Room Solutions' UVD Robot (254 nm)	Four strains of Candida auris	UVC irradiation was done on high-touch surfaces after the standard cleaning and disinfection procedure.	Reduction in target pathogen concentration in irradiated areas and negative effects in shadowed regions were observed.
Buonanno et al./2020 [78]	Laboratory (Israel)	Far-UVC light (222-nm)	Aerosolized alpha HCoV-229E and beta HCoV-OC43	Target pathogens inactivated in an aerosol irradiation chamber.	99.9% inactivation observed for UV doses of 1.2-1.7 $[mJ/cm^2]$
Gerchman et al./2020 [79]	Laboratory (USA)	UVC-LED system (267 -297 nm)	HCoV-OC43 virus	Irradiance dosages were up to 60 seconds for 267 and 279 nm and up to 90 seconds for 286 and 297 nm UV.	Shorter UV wavelengths were more effective at inactivating the virus (3-log inactivation at irradiation 6–7 mJ/cm2).
Heilingloh et al./2020 [80]	Laboratory (Germany)	UVC (254 nm) and/or UVA (365 nm)	SARS-CoV-2	The emitted light was at a distance of 3 cm and viral samples were taken at 3-minute intervals for 30 minutes.	The emitted dose required for a complete inactivation of SARS-CoV-2 was 1048 mJ/cm2 after 9 minutes of exposure.
Morikane et al./2020 [81]	Hospital ICU (Japan)	PX-UV device (200-280 nm)	MRSA	Effects of adding PX-UV device to manual terminal cleaning in the hospital was evaluated for 2.5 yrs	Cases of newly acquired MRSA and Antinobector reduced significantly.
Yıldırım et al./2015 [57]	Acute-care hospitals (USA)	PX-UV device (200 - 280 nm)	C. difficile, MRSA, and VRE	Pathogen contamination on high-touch surfaces was assessed before and after 10 minutes of PX-UV irradiation.	PX-UV device lowered the recovery of C. difficile spores, MRSA, and VRE.

shie-lding of the medium encompassing the infectious microbe can hinder disinfection capabilities. The shielding effect increases as the particle size increases and can be significantly reduced when targeted particles are illuminated with UV light equally from multiple directions [83]. This can be achieved by utilizing multiple UV sources, mobile UV devices, or reflective materials and surfaces for uniform illumination on coated pathogens.

- **Logistical Challenges and Cost**: Logistical issues that include the operation, scheduling, and moving of UV fixtures also limit the adoption of these disinfection systems. Unlike when using a traditional chemical disinfectant, UV disinfection systems cannot be used when humans are nearby. This requires additional safety measures, such as emptying rooms, displaying safety signs, and active monitoring. Staff members dedicated to manually moving and monitoring the devices are needed. The increased complexity of the new disinfection approach creates logistical challenges and added costs.

3. UV Disinfection Robots

Significant progress has been made in the speed of adoption for robotic technologies in recent years. Robotics can be incorporated to improve multiple facets of infectious disease management in the future, including disinfection [27, 102]. Classical UVGI systems discussed in Sec. 2.1 integrate fixed devices that often require manual supervision and maneuvering. Limitations of such devices, mentioned in Sec. 2.6, can be addressed with UV robots that are mobile or autonomous. The autonomy offered by UV robotic disinfection systems can result in less labor-intensive and more efficient decontamination procedures. They can also be monitored remotely via tablets and apps for disinfection status and troubleshooting. This section provides an overview of UV robots and explores the effectiveness of these robots. Lastly, limitations of the current generation of robots are identified.

3.1. UV Disinfection Robot Mechanism

In recent years, there has been a growing interest in using autonomous area disinfection UV devices and robots. These devices are used to supplement manual cleaning and are comprised of a mobile base, high-power pulsed xenon lamps or an array of LPM lamps, and motion detectors [103]. These high-powered lamps have a significant irradiance envelope and can disinfect a volume of space in all directions. In health care settings, they are used to disinfect rooms after manual cleaning is completed by staff. Some of these devices have sensors that monitor environmental conditions, such as humidity and temperature. This data is used by the devices to modify

Table 5: List of commercially available UVC disinfection devices

Robot	Cost (USD)	Light Source	Autonomy	Human Safety	Efficacy Study
Xenex Lightstrike [84]	125, 000	PXL	×	×	✓
Tru D Smart UVC [85]	125, 000	LPM	×	×	✓
Sterilray Far-UV Robot [86]	-	Excimer lamp	✓	✓	✓
UVD Robot by Blue-Ocean robotics [87]	90, 000	LPM	✓	×	✓
Surfacide's Helios UVC Disinfection System [88]	-	Amalgam UVC lamps	×	×	✓
Honeywell's UV System [89]	-	LPM	✓	×	✓
Ava Robotics UV Disinfection robot [90]	-	-	✓	×	×
Blue Shift UV's R-Zero Arc [91]	45, 000	-	×	×	✓
BooCax UV1500 [92]	-	Quartz lamps	✓	×	✓
Safe Space Technology's RoverUV [93]	-	-	✓	×	×
BlueBotics's mini UVC [94]	-	-	✓	×	×
Pudu's Puductor 2 [95]	-	LPM	✓	×	×
Prescientx's Violet [96]	-	-	✓	✓	✓
GlobalDWS's DSR [97]	-	-	✓	×	×
TMiRob's Intelligent Disinfection Robot [98]	-	-	✓	×	✓
Aitheon's UVD Robots [99]	-	LPM	✓	×	✓
Lumnicleanse's UV-C robot [100]	-	-	✓	×	✓
The Badger UV Disinfect Robot [101]	-	LPM	✓	×	✓

the UV dose accordingly. Since UV is harmful to human skin, the robot is usually operated in empty rooms. Measures that include using curtains to cover the windows are taken to prevent undesired exposure to UV radiation. In addition, motion detection sensors are used, so that the UV lights can be cut off immediately if any human presence is detected. Classical UV disinfection devices are usually either placed in a single position in the room for a complete disinfection cycle or are moved manually by the designated operator to different parts of the rooms [103].

UV robots can provide automatic and consistent disinfection. Such robots extend classical UVGI devices in which UV lamps are mounted on mobile platforms that offer potential autonomy [104]. The UVGI robots can perform autonomous decision-making by using inputs they receive from sensors. They rely on simultaneous localization and mapping (SLAM) [105] to build the map of the environment and use the map to deliver high-powered UV dose [13].

Multiple studies demonstrate the effectiveness of UV devices and robots. A randomized cluster trial conducted in the US across nine hospitals for over two years demonstrated that adding UV-C robots to quaternary ammonium disinfection decreased the risk of subsequent acquisition of infection [106]. Guettari et al. [28] developed a mobile UVC disinfection robot that is able to eliminate bacteria. However, Dancer and King [18] reviewed efficacy studies of automated decontamination devices that utilized UV light and recommended that more efficacy research of UV autonomous robots with control groups should be done before the overhaul of existing cleaning and disinfection procedures.

3.2. *Existing UV Disinfection Robots*

With the rising interest in using service robots in the healthcare systems and the onset of the COVID-19 pandemic, the research on the development of autonomous UVGI robots has accelerated. Research institutes and companies around the world have been creating, implementing, and testing autonomous UV disinfection. Commercially available UV robots and recent research contributions on UV robots are discussed and assessed in this sub-section.

3.2.1. *Commercially Available UVC Robots*

Companies and research labs have been developing disinfection robots before the COVID-19 pandemic, aiming to improve the efficiency of cleaning and disinfection in areas with a high risk of infections.

Xenex Disinfection Services has shown that their Lightstrike robot can significantly reduce SARS-CoV-2 on hard surfaces and N95 respirators with PX-UV [107]. Tru D Smart UVC robots were examined in a tertiary acute care hospital, and they are able to effectively reduce C. difficle and Acinetobacter in patient rooms [108]. Autonomous Disinfection Vehicle Robot (ADV) from Far-UV Sterilray are being advertised, but their production has not begun. They utilize excimer lamps that produce far-UVC [86]. Hospitals in Romania, Croatia, and Italy have begun using Blue Ocean Robotics' autonomous disinfection robots. They claim to be able to disinfect rooms with LPM within 10 minutes [87]. Surfacide's Helios UV-C Disinfection System coordinates multiple robots to overcome shadowed regions of rooms and improve disinfection time. They have

(a) Xenex Lightstrike [84]

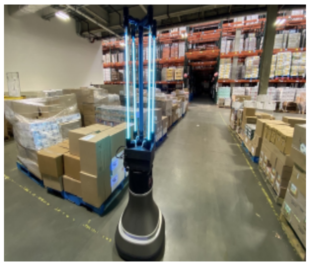
(b) TRU-D Smart UVC [85]

(c) UVD robot by Blue Ocean Robotics [87]

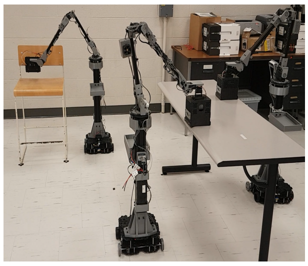
(d) Sterilray Far-UVC robot [86]

Figure 3: Area disinfection units (a-b), and disinfection robots (c-d)

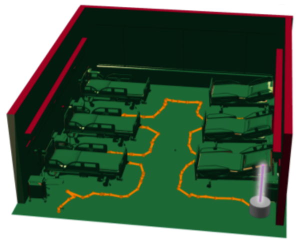
(a) UVGI manipulator motion planning [109]



(b) Autonomous disinfection robot with mounted lamps [110]



(c) G-Robot: Multi-Robot Germicidal System [111]



(d) Optimized coverage planning for UV disinfection [67]

Figure 4: UVGI robotic features in development

also been implemented by multiple hospitals in the USA [88]. Honeywell's UV Treatment System is designed specifically to disinfect aircraft cabins. It is able to sufficiently disinfect 30 rows of seating in 8 to 10 minutes. They have been implemented into Qatar Airways' disinfection practice [89]. Additional UV disinfection robots are included in Table 5 and shown in Fig. 3, and more are under development.

As seen in Table 5, robots that are currently available mostly support autonomy. Although some claim to be able to disinfect within a reasonable time, experiments and set-ups were not standardized; thus, numbers do not offer a fair comparison. They are also expensive, and a cost-benefit analysis should be conducted by users prior to purchase and adoption. With autonomous UV disinfection being a relatively new mode of disinfection, experimentation and analysis on commercially available robots from sources without conflict of interest are greatly needed to verify the claimed effectiveness and safety of available devices. Regulations and standards for autonomous systems should also be introduced as robots inevitably become increasingly intertwined in our daily lives.

3.2.2. UV-Robots and Algorithms in Development

Current research contributions for UV robots focus on hardware development and creating autonomy algorithms to maximize the performance and efficiency of disinfection. The UV robots proposed in the literature either use a mobile manipulator configuration or a typical mobile base with UV lamps mounted on it. Most of these robots use prior maps and target locations specified by a human operator to generate disinfection plans. Furthermore, some works use customized planning algorithms to ensure all the areas in the environment receive desired UV dosage. A detailed discussion of various contributions is described next. A non-exhaustive list of novel designs proposed in the literature and their key features are summarized in Table. 6.

Many proposed disinfection systems adopt a mobile manipulator design. ADDAMS UV robot [112, 113] is a teleoperated semi-autonomous mobile manipulator equipped with an LPM and a UV wand. The LPM is used for generic environment disinfection, and the manipulator uses the UV wand to disinfect target surfaces. A human operator can either drive via teleoperation or specify the desired location to navigate the robot. When the robot is at the desired location, the operator uses a GUI to select target surfaces for the robot to disinfect. Similarly, Conte et al. [115] proposed a teleoperated mobile manipulator where UV lamps are mounted on the mobile base and the manipulator's end effector. The manipulator disinfects regions that are beyond line of sight of the lamps on the mobile base. The robot operates in two stages. First, a coarse 3D map of the environment is created by teleoperating the robot in the environment. Next, the trajectories for the mobile base are generated before disinfection, based on the waypoints specified by the human operator. During the execution of these trajectories, a fine 3D dosage map is continuously updated to monitor the disinfection levels. Upon approaching objects, such as chairs, tables, and cabinets, the mobile base is stopped, and the arm moves to disinfect the object.

A Fetch mobile manipulator equipped with a UV flashlight to disinfect target surfaces in the environment is proposed in [109, 120]. The planner generates the path for the manipulator based on waypoints specified by the human operator. Further, their planner generates the speed of the manipulator based on desired disinfection level and an empirical UV dosage model. Ma et al. [117] proposed a mobile manipulator where the robotic arm is equipped with an array of UVC LEDs. A prior point cloud map of the environment and a graphical interface are used by the operator to select the targets for disinfection. The planning module generates the path for the mobile base and the arm to disinfect the target surface. The quality of disinfection by the robot was evaluated using UVC fast check strips in testing locations that included bookshelves, card readers, and toolboxes.

A limitation of the works mentioned above is the requirement

Table 6: A non-exhaustive list of current UVC robots in research

Robot	Type	Light Source	Human Safety	Efficacy Study	Human Operator Requirements
ADAMMS UV Robot [112, 113]	Mobile Manipulator	LPM and UV Wand	×	×	Select targets to disinfect through teleoperation.
Fetch UV Robot [109]	Mobile Manipulator	UV Flashlight	×	×	Select targets to disinfect through teleoperation.
Ultrabot [114]	Mobile Base	LPM	✓	✓	–
G-Robot [111]	Mobile Manipulator	Far-UVC	✓	×	–
UV-Robot by [115]	Mobile Manipulator	LPM and UV lamp	×	×	Select targets to disinfect through teleoperation.
UV-PURGE [116]	Mobile Base	LPM	×	✓	Drive the robot via teleoperation.
UV-Robot by [117]	Mobile Manipulator	UVC-LED	×	✓	Select targets to disinfect through teleoperation.
UV-Robot by [110]	Mobile Base	LPM	×	✓	Select targets to disinfect through teleoperation.
UV-Robot by [118]	Mobile Base	LPM	×	×	Select targets to disinfect through teleoperation.
UV-Robot by [119]	Mobile Base	LPM	✓	✓	Drive the robot via teleoperation.

for an operator to specify disinfection targets. Hence, the operator should have additional skills to interact with the software to select the target locations. Furthermore, manually setting targets in large spaces may be time-consuming and error-prone. This issue was partly addressed through G-Robot [111], an autonomous mobile manipulator equipped with human-safe Far-UVC. It uses a plane segmentation algorithm to detect target surfaces like tables, chairs, and shelves. The coverage planner uses the map of the environment and detected planar surfaces to generate waypoints for the robot. The disinfection of the surfaces is then done by executing appropriate joint motions determined by the planning module. However, currently G-Robot cannot detect complex non-planar surface in the environment.

Some works have focused on improving the classical UVC robot configuration of a mobile base mounted with UVC lamps. Conroy et al. [118] proposed using a UVC lamp on a low-cost mobile base made of off-the-shelf parts. A human operator would drive this robot via teleoperation to create the floor plans of the environment. In the offline planning stage, linear programming is used to determine waypoints and disinfection time for the robot to ensure that sufficient dosage is received by all the locations in the given floor plan. Finally, the robot disinfects the environment based on waypoints and disinfection time generated in the offline planning stage. Pierson et al. [110] proposed using a mobile base mounted with UVC lamps. Their robot uses a map with target locations specified by an operator. They proposed two path planning modules. First, an augmented A* algorithm is used for planning paths in non-changing environments. Second, Voronoi-based coverage control is used to plan paths in cases where the environment may have new static obstacles that are not present on the map. In both cases, the planner uses a dosage map based on irradiance models to ensure that all the locations in the environment receive sufficient UVC dosage. They tested their robot at a food bank facility and were able to deliver desired disinfection dosage. In [116], a cost-efficient mobile robot for UVC disinfection is proposed. The robot was made of off-the-shelf components. It is teleoperated using a mobile app and has no autonomy features. Further, it was tested in an office facility and reported a reduction in bacteria count after using the robot. The downside of using a mobile base mounted with UVC lamps is the lack of human safety due to exposure to UV radiation. Consequently, these robots can only be used when there is no human presence.

Some works have focused on improving safety of classical UVC robots through augmented physical design. McGinn et al. [119] proposed a novel design of the UV robot that controls its UV irradiation through a physical barrier to shield bystanders and equipment from UV rays. Their robotic base uses an open-source robotic mobile base that supports autonomous navigation. An operator drives the robot in radiology labs via teleportation to evaluate disinfection quality. Perminov et al. [114] proposed Ultrabot, an autonomous mobile UV disinfection robot. The UV lamps on Ultrabot are shielded from one side, which effectively limits the field of view of lamps to 180°. This design choice enables the operation of the robot alongside humans. Furthermore, Ultrabot has an ozone-based air purification mechanism in which all the UVC lamps are fully shielded. The ozone generated by UVC lights is redistributed in the environment using a set of fans. Ozone is a toxic gas, so there is a need to ensure that the ozone produced during disinfection does not exceed safety limits for humans. In both cases, for the physical shielding to be effective, the robot must plan its pose so that the bystanders are not exposed to UV rays. This might be a challenging task in a busy environment like a shopping mall.

Some contributions have focused purely on algorithmic development for efficient distribution of UV dosage. Tiseni et al. [121]

proposed a novel motion planner that consists of a genetic algorithm for UV disinfection robots and showed in simulation that it improved disinfection performance, time, and energy requirement. Similarly, an optimized coverage planning algorithm for UV surface disinfection is proposed in [67]. Tazrin et al. [122] proposed schedulers for efficient disinfection by a team of drones equipped with UVC band panels. They developed schedulers based on heuristics, such as the randomized approach, a greedy approach, and genetic algorithm-based scheduling for energy-efficient path scheduling for disinfection drones.

Many proposed autonomous disinfection robots use alternative disinfection mediums like chemical sprays. The autonomy components of such robots can potentially benefit the development of autonomous UV disinfection robots. Some of these robots are discussed in Sec-4.

3.3. Limitations of UV Disinfection Robots

Similarly to classical UVGI systems, UV disinfection robots also possess limitations and drawbacks that require further improvements and research.

- **UV Safety**: One of the biggest issues with current disinfection robots is that they cannot be used in dynamic environments with human presence due to UV's harmful effect on human skin and eyes. As a result, these devices cannot be used in shared patient rooms and public spaces while there is human traffic. Some existing works [119, 114, 111] have addressed this issue. However, stronger safety guarantees should be established to avoid any undesirable exposure.
- **Navigation Difficulties**: Spaces with a heavy human presence or areas occupied with cluttered, dynamic, and large objects, such as hospital receptions, hallways, MRI rooms, and the ICU, could be difficult for autonomous robots to navigate and disinfect efficiently while avoiding any collisions. Furniture and machinery arrangement in the disinfection space could lead to areas that are inaccessible for the mobile robot, causing the issues mentioned in Sec. 2.6. Areas that cannot be reached by the most commonly used ground mobile robots could also include surfaces that are too high and far away or blocked by objects such as tables, chairs, and beds. Reachability issues might be partly resolved by using a mobile manipulator configuration.
- **Logistical Issues and Cost**: Studies have demonstrated that the use of UV technology could be limited in hospitals currently due to required logistics and operational times [123]. These UV robotic systems are more expensive than classical UVGI devices. Additional training and education of staff members and the general public for the safe deployment of UV robots are also time-consuming and resource-intensive.

These potential issues for the integration of UV robots must be considered and examined further for the development of future autonomous UV disinfection robots.

4. Other Types of Disinfection Robots

Disinfection robots that are currently available and in development are not limited to using UVGI as the disinfection medium. Another novel mode for no-touch environmental cleaning and disinfection is to use hydrogen peroxide (H_2O_2).

Aerosolized hydrogen peroxide (AHP) and vapour hydrogen peroxide (H_2O_2) are two forms of hydrogen peroxide used for disinfection. AHP devices have been proven to achieve 4-log reduction of MRSA; however, vapor H_2O_2 systems have been shown to be safer, faster, and better at inactivating pathogens than AHP [124]. Falagas et al. [125] presented a review of multiple studies on the efficacy of vaporized H_2O_2. They conclude that vaporized H_2O_2 can be used as an effective supplement to manual cleaning. Some of the robots, such as XDbot [126], is comprised of a robotic arm equipped with a spray nozzle that is used to spray vaporized H_2O_2. A semi-autonomous quadruped robot for performing disinfection is proposed in [127]. The robot is equipped with a spray-based disinfection system on the robot's back. The system includes an image processing capability to verify disinfected regions. The authors argue that quadruped's control of body orientation results in better accessibility in more complex environments. Additionally, this work uses CNN to verify the disinfection quality. If the disinfection quality is not sufficient, then the robot can spray that particular area again. Thakar et al. [128] used mobile manipulators mounted with a spray nozzle to disinfect surfaces. A branch and bound-based area coverage algorithm is presented to determine spray paths on a point cloud of the surface being disinfected. A spline-based representation of the robot's degrees of freedom and successive refinement-based optimization is used for generating robot motion. Another interesting robot that utilizes spray-based disinfection, from Peanut Robotics, incorporates the ability for both cleaning and disinfection [129]. It houses the required disinfectant and mops on a mobile platform where a 7 DoF gripper can swap and apply each tool for autonomous cleaning.

Robots that use a combination of UV and vaporized H_2O_2 are also in development. For instance, TMI's air disinfection robot is equipped with UVC, an overhead spray nozzle for H_2O_2, and a HEPA filter [98]. Similarly to UV disinfection systems, H_2O_2 devices and robots also require further research to validate their applicability. Problems that include the inability to use H_2O_2 disinfection in human presence, long disinfection time, and the requirement for more safety training make efficient implementations of H_2O_2 systems difficult. Both UVGI and H_2O_2 robots will lead to a need to overhaul existing cleaning and disinfection procedures. Further research that addresses the logistical and safety issues of UVGI and H_2O_2 robots should be explored to aid large-scale implementations of future disinfection approaches.

5. Future Directions and Open Problems for UV Robots

While current issues limit the widespread use of UV robots, there is much ongoing work and scope for improvement in the future. The areas open for improvement include (i) efficient resource management, (ii) accurate dosage modelling, (iii) human safety, and (iv) benchmarking, described next.

5.1. *Resource Management*

UV disinfection is an energy-intensive process; therefore, a more informed usage of these resources can lead to better resource management. For instance, the use of semantic segmentation of the environment to identify high-touch surfaces can be a significant source of the spread of infection [130, 131]. Different surface material can have varied disinfection requirements, and can be identified using deep learning models [132]. Additionally, learning the interaction of humans with various objects in the environment through object affordance [133] can enable the robot to identify critical points to disinfect on a target object. Besides this, planning algorithms should be designed for optimized utilization of resources while maximizing the coverage of disinfection. Different environmental regions can be prioritized based on the concentration of high-touch surfaces. For example, high-traffic and high-risk areas within a shopping mall, including food courts and washrooms, would hold higher priority for disinfection. The planning algorithms can incorporate these priorities and factors like battery charge and environmental traffic to generate robot paths for maximized disinfection coverage. Further, deploying a team of disinfection robots can ensure efficient disinfection operation. Such multi-robot systems can sufficiently disinfect large spaces while being energy efficient. Autonomous UAVs that can emit UV for disinfection can also be utilized to make navigation around cluttered rooms and disinfecting obstructed and more difficult-to-reach areas easier. UAVs could possibly attach themselves to ceilings or other surfaces during fixed point disinfection to conserve energy use. In addition

5.2. *Dosage Modeling*

Many recently proposed UV robots (see Sec. 3.2.2) have adopted dosage maps in their planning modules. These maps help generate optimal coverage routes and track the dosage received by different environmental regions. For computational efficiency, most of the existing dosage maps are 2D, i.e., the dosage footprint on the floor is used as a cue to measure the disinfection quality of the 3D environment. Besides this, approximate irradiance models for different UV lamps are used. These approximations in dosage representation may lead to insufficient or excessive disinfection by the robot. A more accurate 3D representation of the dosage map and accurate irradiation simulation models would be a valuable contributions. An accurate dosage map could be used for auditing the quality of disinfection. Such audits can be used as feedback by the robot for covering any missed or insufficiently disinfected spots in subsequent operations.

5.3. *Human Safety*

There is also an opportunity to use UVGI in human presence. Some UV robots [111] have adopted human-safe far-UVC. However, commercial far-UVC lights are still limited and have not been tested thoroughly to ensure safety. They are also a more expensive light source. On the other hand, Yildirim et al. [134] tried shielding UVC-LEDs in a busy CT scan room with human presence and found that the proposed robot could eliminate microbial air contamination. However, the effect of UV shielding on the skin and eye protection was not thoroughly analyzed. Another way could be to use mobile manipulators equipped with UV modules (mounted on the end-effector) to disinfect various objects and surfaces as presented by Hu et al. [130]. Their system uses a CNN-based detector to identify objects that humans interact with frequently. Human safety in UVGI systems can be ensured by incorporating the information on the irradiance envelope of UV light in the planning module, such that configurations that lead to direct exposure to humans can be avoided. Such a planner can be inspired by the existing literature on the next best view problem [135]. The position of humans in the environment can be gathered using LIDAR data [136].

5.4. *Benchmarking*

It would be worthwhile to conduct additional studies to aid the development of UV robots. Standardised benchmarks should be established to evaluate the performance of UV robots The design requirement analysis based on perspectives from experts in infection prevention and control, and environmental health and safety would help develop practical UV robots. A usability analysis should also be conducted to ensure that UV robots seamlessly integrate with the existing infrastructure of healthcare and other public institutions. Besides this, unbiased efficacy studies should be conducted to make a strong case for UV robots. Lastly, studies on the perception of humans on robots, and GBA+, gender, and cultural-based analysis, should also be conduct-ed since the adoption of autonomous disinfection robots would impact existing decontamination procedures and personnel significan-tly across different cultures and ethnicity. GBA+ studies that examine the impact of UVC light on; for instance, different ethnicity's skin types and decontamination practices could provide valuable insights.

6. Conclusions

In this work, we reviewed the basics of UV germicidal systems and presented various necessary details associated with the development of the technology. A discussion on the effectiveness and current state of classical UVGI systems and UVGI robots was presented. As of now, the use of these robots is limited to healthcare settings where they are used after standard cleaning procedures. Due to the risks associated with UV light to humans, these robots cannot currently be operated in human presence without more examination and development; however, the implementation of such devices is expected to increase in the post-pandemic world.

The future generation of UV disinfection robots needs to possess improved designs that could enable their use in the presence of humans. There are many open research problems in the use of UV robots for disinfection, such as i) path planning to maximize UV irradiance to the surfaces, ii) disinfecting objects and surfaces which are frequently used and touched in hospitals and public places, iii) designing efficient disinfection strategies and devices to minimize UV exposure risks, iv) training robots to identify frequently used spaces, surfaces, and objects for timely disinfection, v) coordinating a team of robots to perform disinfection faster and more reliably , vi) using manipulators and drones to disinfect surfaces that are difficult for UV light to reach, vii) designing disinfection robots that can be used in the presence of humans, and viii) designing robots that can perform both manual cleaning and UV disinfection would be beneficial to develop. .

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