APPLICATION OF ULTRAVIOLET GERMICIDAL IRRADIATION TECHNOLOGY IN THE DISINFECTION ROBOT SECTOR: A REVIEW

ỨNG DỤNG CÔNG NGHỆ CHIẾU XẠ DIỆT KHUẨN BẰNG TIA CỰC TÍM TRONG LĨNH VỰC ROBOT DIỆT KHUẨN: ĐÁNH GIÁ TỔNG QUAN

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(Received: July 21, 2022; Accepted: August 29, 2022)

Abstract - Ultraviolet Germicidal Irradiation (UVGI) has grown significantly as an optimistic alternative to chemical disinfection for surface and air disinfection in the healthcare sector. The application of UVGI in robotic technology has led to new opportunities in developing the disinfection robot which allows us to prevent pathogen transmission, reduce human participation and cross infection, then achieve efficient, quick and environmentally friendly sterilization. The aim of this paper is to review the outstanding achievements in UV-C disinfection robot sector. This review is based on the reports on 35 types of UV-C disinfection robots in both academic research and commercial sector. The current and future trends in the UV-C lamp technologies and the technical capacities of the robot are also discussed.

Key words - Ultraviolet Germicidal Irradiation (UVGI); UV-C; Disinfection Robot

Tóm tắt - . Chiếu xạ diệt khuẩn bằng tia cực tím (UVGI) đã có những phát triển đáng kể như là một giải pháp thay thế đầy lạc quan cho phương pháp diệt khuẩn bằng hóa chất để khử trùng bề mặt và không khí trong lĩnh vực chăm sóc sức khỏe. Việc ứng dụng UVGI trong công nghệ robot đã mở ra những cơ hội mới trong việc phát triển robot diệt khuẩn, cho phép ngăn chặn sự lây truyền mầm bệnh, giảm sự can thiệp của con người và lây nhiễm chéo, do đó đạt được hiệu quả diệt khuẩn nhanh chóng và thân thiện với môi trường. Mục tiêu của bài báo này là đánh giá những thành tựu nổi bật trong lĩnh vực robot diệt khuẩn UV-C. Đánh giá này dựa trên các báo cáo về 35 loại robot diệt khuẩn UV-C cả trong lĩnh vực nghiên cứu hàn lâm và thương mại. Các xu hướng hiện nay và tương lai trong công nghệ đèn UV-C và các tính năng kỹ thuật của robot cũng được thảo luận.

Từ khóa - . Chiếu xạ diệt khuẩn bằng tia cực tím (UVGI); UV-C; Robot diệt khuẩn

1. Introduction

Ultraviolet or ultraviolet rays, UV rays are the electromagnetic radiation that are transmitted through waves of different frequencies and wavelengths. The wide range of wavelengths is called the electromagnetic spectrum which is divided into 8 bands: radio waves, microwaves, infrared (IR), near-infrared (NIR), visible light, ultraviolet (UV), X-rays, and gamma rays (Figure 1). The UV radiation is in the portion of the EM spectrum between visible light and X-rays and are generally divided into four subbands: UV-A with a wavelength from 320 to 400 nm; UV-B (280-320 nm); UV-C (200-280 nm) and V-UV (100-200 nm) [1].

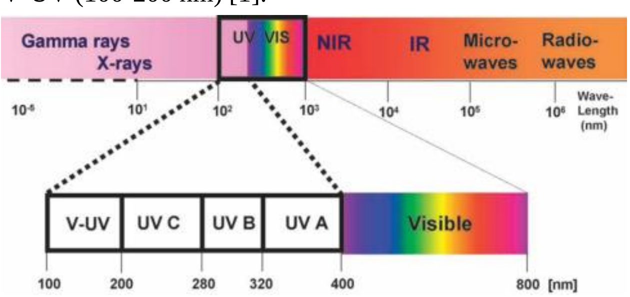

Figure 1. *Light wavelength range [1]*

Ultraviolet Germicidal Irradiation (UVGI) is defined as a germicidal technology using ultraviolet rays with a bactericidal wavelength range from 200-320 nm used to disinfect the air, surfaces, and water. The term UVGI was originally proposed by the International Commission on Illumination (CIE) and then adopted by the Centers for Disease Control (CDC). Nowadays, this concept is used mainly for two types of UV that are capable of killing bacteria, UV-B and UV-C to distinguish it from UV-A (320-400 nm) is not capable of bactericidal. There is also a type of vacuum ultraviolet (VUV) (100-200 nm) but this type is not able to transmit in the air because it is absorbed quickly, so this wavelength range is not used in disinfection applications. Although the wavelengths of UV-B and UV-C both cause some bactericidal photochemical effects, the wavelengths in the UV-C range are particularly harmful to microorganisms since it is absorbed by the proteins, RNA, and DNA. The UV-C radiation is then often used in germicidal applications [2].

Recently, the outbreak of the COVID-19 epidemic has imposed a growing demand for UV-C disinfection robots as an alternative to conducting disinfecting works in the contaminated environments. The UV-C germicidal robots launched in the last few years have proven to be highly effective at killing bacteria and are considered as a quick and environmentally friendly disinfection solution. The UV-C germicidal robot technology is a combination of mobile robot technology and UVGI technology, which is applied to disinfecting surfaces and air. The UV-C germicidal robot performs the disinfection task by moving to the desired locations and shining an UV-C beam for the time required to kill pathogens. Some advantages of using UV-C germicidal robots are: (1) Operating without operators and being standardized, reducing the presence of humans [3]; (2) With the mobility of the robot, it can move to many locations in the workspace, to the hidden corners that wall-mounted UV-

C lighting systems cannot reach, thus improving efficiency; (3) If using a UV-C lamp system with high power, it will save time to disinfect compared to using a fixed germicidal lamp system; (4) Using UV-C disinfection step after manual disinfection to reduce cross-transmission and infectious diseases; (5) Using UV-C light source does not leave any residual chemical residue, which is an eco-friendly solution.

In this paper, we present a review on UV-C disinfection robots launched in the market as well as in academic research. The literature search was carried out in July 2022 with data from commercial websites and scientific journals.

2. Theoretical background of UV-C disinfection

2.1. Mechanisms of UV-C Disinfection

UV-C disinfection does not kill pathogens, it inactivates them so that they cannot reproduce and cause infection. UV-C rays from the light source can pass through the cell walls of microorganisms and are absorbed by proteins, RNA, and DNA. The cell nucleus in bacteria and pathogens contains DNA, which is composed of linked chains of nucleotides to form the double helix. Four nucleotides in DNA include Adenine (A), Cytosine (C), Guanine (G), and Thymine (T). These bases form specific pairs Cytosine (C) with Guanine (G) and Adenine (A) with Thymine (T). Viruses do not have a nucleus but may contain DNA or RNA in their protein coat. RNA also has 4 nucleotides like DNA, but Thymine is replaced by Uracil. The microbial inactivation by UV-C occurs when two Thymine molecules are close together in a DNA strand and one of them is excited by a UV-C photon. This leads to a composition of two adjacent Thymine to create a new molecule known as Thymine Dimer (Figure 2). When large quantities of Thymine are formed, the DNA is inactivated and cannot be replicated [4]. RNA is inactivated when two adjacent Uracil molecules are linked to form Uracil Dimer.

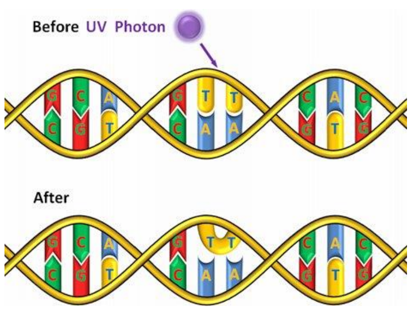

Figure2. *UV-C photon absorption of DNA and formation of Thymine Dimers [5]*

2.2. Factors affecting the efficacy of UV-C

2.2.1. UV-C intensity

Calculating the intensity is essential for determining the bactericidal range of any UV-C lamp. The calculation of the UV-C intensity according to its geometrical shape is implemented through the Radiation View Factor. The Radiation View Factor defines the geometric relationship between the emitting surface and the receiving surface [6]. If the emitting surface is of constant intensity and the receiving surface is a differential element, the Radiation View Factor can be used to determine the intensity at the position of the differential element. If the receiving surface is a finite region or the emitting surface is not uniform, the radiation on the respective surface must be integrated to find the total absorbed radiation.

The irradiance at a point outside the UV-C lamp can be calculated using the Radiation View Factor from the differential planar element to the finite cylinder of the lamp when the element is perpendicular to the axis of the cylinder and is at the edge of the cylinder as shown in Figure3. We can divide the lamp into two parts of length l_1 and $l-l_1$. Therefore, the total Radiation View Factor at any point at distance x from the lamp will be defined as follows:

$$F_{total}(x,l_1,l-l_1,r)=F(x,l_1,r)+F(x,l-l_1,r) \quad (1)$$

with $F(x,l,r)$ can be described in the following general form:

$$F(x,l,r)=\frac{L}{\pi H}\left[\begin{array}{l}\frac{1}{L}a\tan\left(\frac{L}{\sqrt{H^2-1}}\right)-a\tan(M)\\+\frac{X-2H}{\sqrt{XY}}a\tan\left(M\sqrt{\frac{X}{Y}}\right)\end{array}\right] \quad (2)$$

where: $H=\frac{x}{r};L=\frac{l}{r};X=(1+H^2)+L^2;Y=(1-H^2)+L^2$ and $M=\sqrt{\frac{H-1}{H+1}}$, l is the length of a lamp segment [m], x is the distance from the lamp to the receiving point [m] and r is the radius of the lamp [m].

Finally, we can determine the radiation intensity of the lamp [W/m^2] according to the following formula:

$$I=\frac{P}{2\pi rl}F_{total} \quad (3)$$

Where P is the power of the UV-C source, [W].

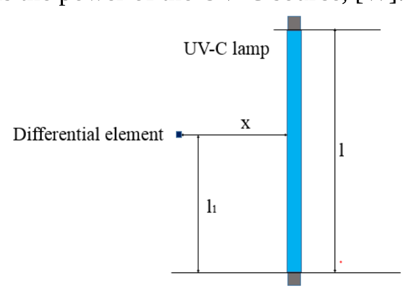

Figure 3. *The illustration for the Radiation View Factor of a UV-C lamp*

2.2.2. UV-C dose

The microorganisms are exposed to UV-C radiation represented by an exposure dose as a function of radiation intensity times exposure time [7], as follows:

$$D=I.t \quad (4)$$

Where: D: UV exposure dose, [J/m^2]; t:Exposure time,[s]; I: Intensity, [W/m2].

2.2.3. Disinfection rate

The bactericidal ability of UV-C devices is represented by the bactericidal coefficient r_d presented in the studies [8], [9]:

$$r_d = (1-s_v)\times 100\% = (1-e^{-kIt})\times 100\% \quad (5)$$

with: r_d: germicidal coefficient, [%]; s_v: survival rate; t: Exposure time, [s]; k: the microbial susceptibility to the UV radiation [m^2/J]

The microbial susceptibility to the UV radiation varies widely among microorganisms. We can estimate the value of the susceptibility coefficient according to the groups of microorganisms as presented in [10].

3. UV-C disinfection robot

The ultraviolet disinfection robots launched in the last few years have proven to be highly effective at killing pathogens and are considered a quick and eco-friendly disinfecting solution. In this session, we will summarize new achievements in the production of UV-C germicidal robots on the market as well as the studies about UV-C robots in academic research.

3.1. Commercial UV-C Disinfection Robot

In recent years, there have been several types of UV-C germicidal robots on the market. The most typical is the UVD robot launched by the Danish company UVD Robotics in 2018 [11]. The robot consists of a mobile base equipped with LIDAR sensors and a series of UV-C lamps mounted on the stop. To operate the robot, the user steers it around the working area by a computer. The robot will recognize the surrounding environment using LIDAR sensors and create a digital map. Then, the mapping data is used by robots for navigation and movement planning. The user will indicate all the rooms and points where the robot should stop implementing the disinfection tasks. The robot's moving speed reaches 5.4 km/h and it takes between 10 and 15 minutes to disinfect a 15m^2 room, the robot spends 1 or 2 minutes in five or six different locations around the room to maximize the disinfecting surfaces. The robot is battery-powered with a 3-hour charge and can disinfect up to 10 rooms. The UV-C lamp system can emit an energy intensity of about 20J/m^2 per second (at a distance of 1 meter) which will completely kill 99.99% of bacteria in just a few minutes.

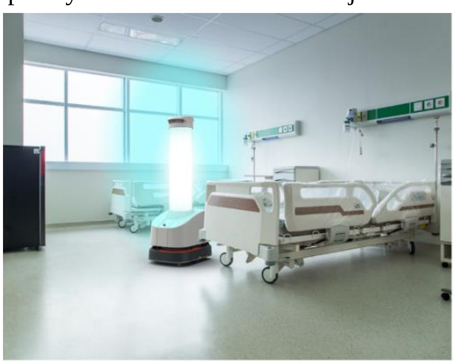

Figure 4. *UVD robot [11]*

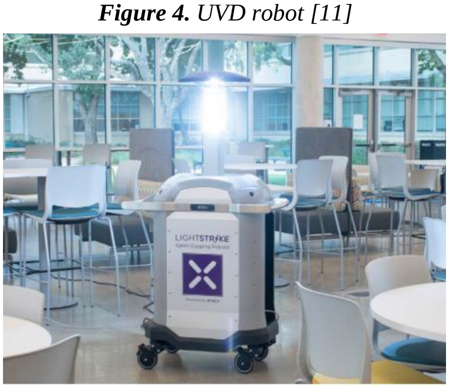

Figure 5. *Robot Xenex LightStrike [12]*

A US company Xenex [12] introduced the UV-C germicidal robot LightStrike patented by Xenon SureStrike technology (Figure5). According to Xenex the UV-C lights generated by LightStrike do not damage the expensive materials available in most hospitals, hotels, and other environments. This robot uses pulsed UV-C rays with a wavelength range of 200–315 nm, the intensity of killing pathogens with these UV rays is 4300 times greater than that of traditional mercury vapor UV-C sources.

Geek+ Robotics, a start-up based in Beijing, China has developed a germicidal robot Smart UVC Disinfection Robot - Lavender using UV-C wavelengths at 253.5 nm which can kill 99.99% of pathogens without the use of chemicals [13]. The UV-C lamps of Lavender are installed in a 360° circle to provide light in all directions. The manufacturer develops 3 different operating modes for this robot: a standard mode that automatically performs full-map disinfection, a user-defined mode that performs disinfection according to a user-defined route, and finally, the static level at which the robot arrives at a specific point to perform the disinfection. To navigate in complex environments, the robot uses Simultaneous Localization and Mapping technology-SLAM.

Figure 6. *Lavender robot [13]*

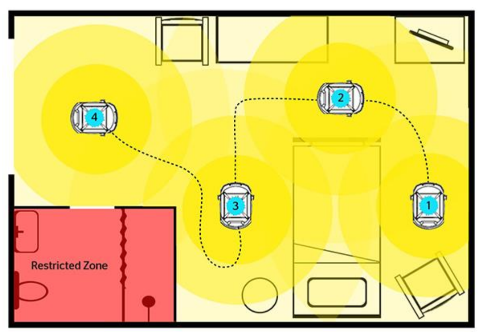

Figure 7. *Movement of the robot in the room [14]*

Omron has introduced the LD-UVC robot to assist in the disinfection of medical facilities [14]. The LD-UVC uses the LIDAR sensor for implementing autonomous navigation and obstacle avoidance tasks. It can automatically move through points according to the route mapped (Figure7). The motion sensors are used to detect people and turn off the UV-C light when a person is detected. The robot has 8 UV-C lamps arranged at 360°, making it capable of destroying 99.9% of pathogens within a germicidal radius.

There is also the appearance of the robot IRIS 3200 m, which is considered the robot with the most powerful UV-C germicidal system in the world [15] (Figure 8). Patented PowerBoost technology allows the UV-C Iris 3200 m robot to disinfect an entire room in one location in much less time than any other device on the market. This robot can automatically measure the size of the room, humidity, temperature to determine the dose, time, and power of the lamp required to completely kill pathogens.

Figure 8. *Robot IRIS 3200m [15]*

The Mini^{TM} UVC robot developed by BLUEBOTICS company (Figure 9) is equipped with 8 UV-C lamps arranged at 360° with a total output of 140W, proven to kill up to 99% of viruses, as well as bacteria and fungi [16]. Mini^{TM} UVC can disinfect surfaces up to one meter away with a travel speed of 4.2m/min. The robot is controlled by ANT® (Autonomous Navigation Technology) developed by Switzerland, which allows to determining the route and sterilization locations with high reliability, now this technology is being used on more than 2,500 self-driving vehicles worldwide. The robot has the ability to avoid obstacles and give voice warnings as well as automatically turn off when it detects people. The robot is capable of operating continuously for 4 hours, charging time is about 3 hours, and can be used in many places such as hospitals, hotel rooms, airports, schools, and commercial centers.

Figure 9. *Mini^{TM} UV-C robot [16]*

In addition, we can list some other types of UV-C germicidal robots capable of operating autonomously from different countries:

- USA: AVD Robot [17], Techi UV Robot [18], Rover Robot [19], UV Disinfection Robot [20].
- Canada: Violet Robot [21], UV Sterilizing Robot [22].
- China: ARIS-K2 Robot [23], ATEAGO Y1 Robot [24], Adibot Robot [25].
- India: UVID Robot [26], Decimator Robot [27], Robo Cop Robot [28].
- Singapore: O-RX Robot [29].
- Turkey: Robocare Robot [30], Seit-uv Robot [31], Covid-Inota Robot [32].

In recent years, there are also germicidal robots that combine the spray method and UV-C light system such as the M2 robot of Keenon company based in Shanghai [33]. The robot is integrated with a bactericidal mist system with a capacity of 15L, superfine particle size under 10µm and 6 UV-C lamp modules that can reach an intensity of 200µW/cm^2 at 1 meter distance. The robot has the ability to avoid obstacles, locate, IoT connectivity, control connection via Wifi, and works for 4 hours after each battery charge. Another product with similar features is Puductor 2 robot, which is also a company based in China [34]. Puductor 2 also has a disinfecting spray system that can hold 15L and a mist particle size of less than 10µm like Keenon's M2 robot. Regarding the germicidal UV-C lamp system, Puductor 2 is equipped with 4 UV-C lamps of 36W that can achieve a luminous intensity of 188µW/cm^2 at a distance of 1m. This robot has the ability to automatically return to the charging dock, the ability to avoid obstacles, and the ability to self-locate SLAM. In addition, we can mention a number of other types of robots that combine both chemical disinfection and UV-C disinfection functions such as Intelligent Disinfection Robot [35] of TmiRob, RoboCop Robot [36] by Milagrow India.

3.2. UV-C Robot in Academic Research

Besides the growth in the commercial disinfection robots segment, recent studies have reported the current levels of development of UV-C robots in academic research. Chanprakon et al. [37] have designed a UV-C robot that can move around the room and disinfect the entire operating room. The disinfection lamp system is equipped with 3 UV-C lamps of 19.3W mounted in a circle 120° apart and 6 ultrasonic sensors and controlled via remote control. The microcontroller will control the wheels of the robot through the motors to avoid collisions. In [38], Hassan and his colleagues have developed a mobile disinfection device controlled via Bluetooth on the Android platform. The robot can conduct disinfection tasks in a reasonable time without human intervention. With 4 UV-C 30W lamps, this system can disinfect a room of about 11m^2 in just 4.8 minutes without the use of harmful chemicals. The UV-C lamp system can produce a dose of 9,670 mW.s/cm^2 at a distance of 76.2 cm within 14 seconds. A PIR motion body temperature sensor is attached to the robot for stopping the light system when someone approaches the range of UV-C rays. The robot can be easily controlled from a safe distance via the Bluetooth module. The energy to keep the device running is taken from a 12V battery charged by solar panels.

Bentancor and Vidal [39] have proposed a robot controlled remotely via mobile devices using the Android operating system and is equipped with a light-off system when detected human approaching. Using 4 UV-C lamps with a total power of 48W, the robot showed good bactericidal results against E.coli bacteria. In another study, Vyshnavi et al. [40] designed a UV-C Robot that is capable of moving along a pre-defined path, equipped with three 20W UV-C lamps arranged 360°. Since UV-C rays can be harmful to humans, a PIR sensor is used on top of the robot to detect the movement and presence of people.

Moez et al. [41] developed the I-Robot UVC with 8 UV-C lamps around a central column and two lamps on top (Figure 10). The center column is fixed on the mobile platform which integrates the sensors to measure temperature and humidity, detect motion and avoid obstacles. The I-Robot UVC can automatically estimate disinfection time while being monitored using a Wi-Fi connection from a phone or tablet. Using the LIDAR sensor allows creating digital maps and optimizing germicidal travel time. I-Robot UVC can turn off the germicidal light system when there are people around to ensure safety. However, in this study, the authors did not go into the control methods and did not provide the results of testing the robot's operability and bactericidal ability.

Figure 10. *I-Robot UVC [41]*

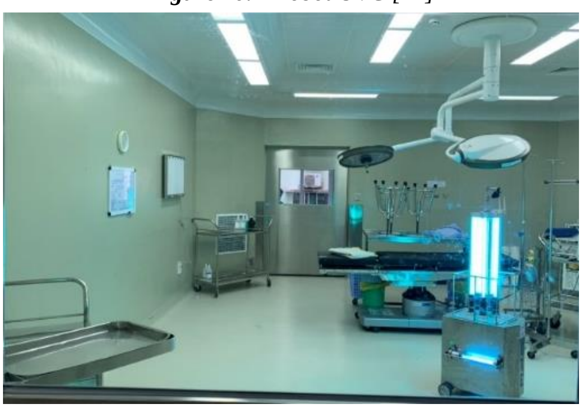

Figure 11. *UV-C robot developed by Phan et al. [42]*

Phan et al. [42] have developed the UV-C germicidal robot which has passed the bactericidal ability at medical facilities, meeting the microbiological criteria of a clean operating room. This robot uses a UV-C ultraviolet lamp system with a wavelength of about 254 nm. The robot has a total weight of 55kg. The robot is equipped with 5 UV-C lamps of 100W mounted in a circular providing the 360° disinfection coverage and 2 UV-C lamps of 30W fixed on the two sides of the robot platform ensuring the UV-C radiation can reach the lower zones near the floor (Figure11). The UV-C lamps are protected by the protective frames to avoid collisions. The robot is controlled remotely via RF, the operator can observe the room space to operate through the camera. The bactericidal test has shown that the harmful microorganisms including Staphylococcus Epidermidis, Gram-positive bacteria, Dermatophytes in the operation room are totally killed after UV-C exposure. The rooms after being disinfected by UV Robot meet the microbiological criteria of the operating room proposed by the hospital.

Perminov et al. [43] have developed an autonomous UV-C robot for disinfecting the indoor environments in the presence of humans. The design of the robot is composed of two isolated sides of UV-C lamps in order that it could be driven separately. The robot is operated by 3 operational modes: manual control mode (robot movement controlled by joystick), the autonomous mode in an unknown environment (using the SLAM), and autonomous mode in a known environment. The disinfection distance recommended is less than 2.8 m for a long disinfection time.

Figure 12. *Ultrabot robot [43]*

For inactivating SARS-CoV-2, Zaman et al. [44] developed a semi-autonomous robotic system named UVC-PURGE (Figure 13). The robot has six UV-C lamps of 35W mounted vertically in a circle. The navigation mode is implemented through the Robot Operating System (ROS). The battery can help the robot work in 1.5 hours and needs 4 hours for full charging. The lifetime of the UV-C lamp is about 8,000 to 10,000 hours.

Figure 13. *UVC-PURGE robot [44]*

4. Discussion

It is worth noting that the efficacy of UVGI disinfection is dependent on the types of UV-C. Through the review of literature, there were three main types of UV-C light used for disinfection robots: UV-C mercury lamps, UV-C Xenon lamps, and the UVC-LEDs (Table 1). Most of the reviewed robots have the ability to achieve a disinfection rate of more than 99% of bacteria, viruses, and other harmful microorganisms. The UV-C mercury lamp is the most commonly used in UV-C disinfecting products due to its better optical power and low cost. However, they have several critical limitations such as low energy efficiency, risk of mercury exposure, and a long warm-up time [45]. The UV-C xenon lamp, on the other hand, generates ultra-high peak power UV pulses at low temperatures but requires high energy [46]. The UV-C LEDS is also emerging as a promising alternative to mercury lamps and xenon lamps. The advantages of UV-C LEDs are energy saving and more environmentally friendly than mercury and xenon lamps [47]. However, the safety guidelines available at the present are mostly based on mercury lamps, the safety standards of UVC LEDs have yet to be defined with effective verification, therefore the use of UV-C LEDs in robots is still not popular compared to UV-C mercury lamps. Recently, the use of far-UV-C for disinfection is underway as an alternative to UV-C. The wavelength of far UV-C is about 207-222 nm and has been proven as efficient in killing pathogens as conventional UV-C light and is safe to use around people [48]. The limited range in biological materials of far UV-C cannot harm human skin and eyes while still killing the microorganisms such as viruses and bacteria [49]. Therefore, the far UV-C lamps may be used as a standard light in many public places [50].

Table 1. *Classification of UV-C lamp*

Ref	Type of UV-C lamp			Disinfection rate
	Mercury	***Xenon***	***LED***	
[8], [10]–[22], [24],[25], [27]–[32], [34]–[41]	X			Over 99%
[12], [30]		X		Over 99%
[29], [51]			X	Over 99%

Table 2. *Summary of prevailing UV-C robots*

Name	Price	Autonomous
UVD Robot [11]	$81,000	Yes
Xenex LightStrike Robot [15]	$125,000	No
SEIT-UV Robot [31]	$80,000	Yes
Adibot [25]	$40,000	Yes
Keenon Robot M2 [33]	$41,000	Yes
ARIS-K2 Robot [23]	$40,000	Yes

Table 2 presents some prevailing UV-C robots on the market in terms of price and the ability for autonomous navigation. The average market price of the prevailing robots is about 67,833 USD ranging from 40,000 USD to 125,000 USD. Obviously, cost-inefficiency is one of the biggest barriers for using UV-C robots in healthcare facilities in middle-income and low-income countries. Thus, developing the UV-C robots with human safe, time-efficient and cost-effective disinfection becomes a research problem for researchers [44].

The major robots mentioned in the literature have the feasibility of autonomous navigation with common functions such as obstacle avoidance, moving autonomously through a map obtained by LIDAR, as well as motion sensors for human detection. The use of these autonomous robots would not only increase disinfecting efficiency but would also reduce human intervention and disinfection times. The robots reviewed in this article may not represent the complete list, but it can describe a representative sample of the current development in the UVGI robot sector.

5. Conclusions

UVGI has been used in many disinfecting applications for decades and its application in disinfection robots has grown rapidly during recent years, promoted greatly by new science and better technology in robotics. In this paper, we have presented shortly the scientific background for UV-C disinfection and summarized the deployment of UVGI in disinfection robots as a means of surface and air disinfection. UV-C robots cannot replace humans in all activities of the cleaning procedure since dirt on the surface can capture microorganisms that may be hard to kill by UV-C light but using UV-C robots for disinfection should be considered as an add-on to manual cleaning procedures. UV-C mercury light source was the most commonly used technology for disinfection robots in the literature. The integration of autonomous robots with UV-C LEDS and far-UV as the UVGI source has become a high potential technology, but more research is needed to further evaluate their efficiency. Using UV-C sources presents a variety of potential health hazards to humans as well, including eye damage, and skin burns. Therefore, the UV-C robot should be operated without the human presence or some robots should be equipped with sensors that automatically turn off UV-C lamps when a person is detected.

The majority of robots reviewed are able to clear and disinfect environments from the risk of bacteria and viral transmission with semi-autonomous or fully autonomous modes. However, the price of germicidal robots is quite high, which is one of the major challenges for medical facilities in many developing countries. Therefore, research on germicidal robots should be investigated more with the aim of reducing costs and ensuring effective disinfection and safe for humans.

Acknowledgment: This research is funded by the People's Committee of Danang City, under contract number 22/HĐ-SKHCN (2021).

REFERENCES

[1] Schwalm, Reinhold. *UV Coatings: Basics, Recent Developments and New Applications*. Elsevier, 2006.

[2] Bolton, James R., and Christine Anne Cotton. *The Ultraviolet Disinfection Handbook.* American Water Works Association, 2011.

[3] Schahawi, Diab-El, et al. "Ultraviolet Disinfection Robots to Improve Hospital Cleaning: Real Promise or Just a Gimmick?" *Antimicrobial Resistance & Infection Control*, vol. 10, no. 1, 2021, pp. 1–3.

[4] Oguma, Kumiko, et al. "Photoreactivation of Escherichia Coli after Low-or Medium-Pressure UV Disinfection Determined by an

Endonuclease Sensitive Site Assay". *Applied and Environmental Microbiology*, vol. 68, no. 12, 2002, pp. 6029–35.

[5] Schmid, Julian, et al. "UV-C Inactivation of Legionella Rubrilucens". GMS Hygiene and Infection Control, vol. 12, 2017.

[6] Modest, Michael F. *Radiative Heat Transfer*. Academic press, 2013.

[7] Kowalski, Wladyslaw. *"Mathematical Modeling of UV Disinfection"*. Ultraviolet Germicidal Irradiation Handbook, Springer, 2009, pp. 51–72.

[8] Phan, Nguyen Duy Minh, Ngo Quoc Huy Tran, Le Anh Doan, Quang Truong Vo, et al. *"Numerical Study of Ultraviolet Germicidal Effect Against Virus"*. Regional Conference in Mechanical Manufacturing Engineering, Springer, 2022, pp. 913–24.E.

[9] Mitscherlich, Eilhard, and Elmer H. Marth. *Microbial Survival in the Environment: Bacteria and Rickettsiae Important in Human and Animal Health*. Springer Science & Business Media, 2012.

[10] Kowalski, Wladyslaw. *Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection*. Springer science & business media, 2010.

[11] UVD Robotics. Available online: https://uvd.blue-ocean-robotics.com/ (accessed on June 25, 2022).

[12] XENEX Disinfection Services, "Xenex LightStrike UV Robots Deactivate SARS-CoV-2 on Surfaces in 2 Minutes in New Peer Reviewed Study", 2020. Available online: https://www.newswise.com/coronavirus/xenex-lightstrike-uv-robots-deactivate-sars-cov-2-on-surfaces-in-2-minutes-in-new-peer-reviewed-study (accessed on June 25, 2022).

[13] The Robot Report Staff, "Jasmin and Lavender disinfection robots launched by Geek+ worldwide in response to pandemic", 2020. Available online: https://www.therobotreport.com/jasmin-lavender-geekplus-launches-two-disinfection-robots-worldwide/ (accessed on June 25, 2022).

[14] The Robot Report Staff, "Omron Asia Pacific and Techmetics Robotics launch LD UVC disinfection robot", 2020. Available online:https://www.therobotreport.com/omron-asia-pacific-techmetics-robotics-launch-disinfection-robot/ (accessed on June 25, 2022).

[15] Infection Prevention Technologies LLC, "UV-C disinfection robots more effective than pulsed xenon models, study finds", 2015. Available online: https://www.cleanroomtechnology.com/news/article_page/UVC_disinfection_robots_more_effective_than_pulsed_xenon_models_study_finds/107372/ (accessed on June 25, 2022).

[16] Bluebotics, "Robot scales up the fight against viruses", 2022. Available online: https://bluebotics.com/uvc-disinfection-robot-fights-viruses/ (accessed on June 25, 2022).

[17] Sterilray, "Real disinfection robots". Available online: https://sterilray.com/sterilray-com/products/sterilray-autonomous-disinfection-vehicle-adv/ (accessed on July 15, 2022).

[18] Techmetics robotics. Available online: https://www.techmetics-group.com/products/techi-uv-disinfection/ (accessed on July 15, 2022).

[19] Safe space technologies. Available online: https://www.safe-space.us/roveruv-mobile-disinfection-robot (accessed on July 15, 2022).

[20] Ava robotics. Available online: https://www.avarobotics.com/disinfectionrobots (accessed on July 15, 2022).

[21] Prescientx. Available online: https://prescientx.com/uv-robots (accessed on June 15, 2022).

[22] Vtrac robotics. Available online: https://www.vtracrobotics.com/product/uv-sterilizing-robot/ (accessed on July 15, 2022).

[23] Shenzhen Youibot Robotics, "YOUIBOT ARIS-K2 UV Disinfection Robot". Available online: https://www.lotsofbots.com/en/shenzhen-youibot-robotics-coltd/youibot-aris-k2-uv-disinfection-robot/ (accessed on June 15, 2022).

[24] Ateago, Available online: http://www.ateago.com/productinfo/638477.html (accessed on June 15, 2022).

[25] Ubtech. Available online: https://www.ubtrobot.com/AdibotA/index.aspx (accessed on June 15, 2022).

[26] Jetbrain ASOLARIS. Available online: https://jetbrain.ai/#/robots/lytbot (accessed on June 15, 2022).

[27] Addverb Technologies. Available online: https://addverb.com/product/decimator-uv-disinfection-robot/ (accessed on July 15, 2022).

[28] Y V PHANI RAJ, "Hyderbad-based H-Bots building new humanoid robot", 2020. Available online: https://telanganatoday.com/h-bots-building-new-humanoid-robot (accessed on July 15, 2022).

[29] OTSAW, "The world's first UV-C LED disinfection robot". Available online: https://otsaw.com/o-rx-disinfection-robot/ (accessed on July 15, 2022).

[30] Dof robotics, "DOF Robotics presents healthcare solutions to combat COVID-19", 2021. Available online: https://dofrobotics.com/pr/presents-healthcare-solutions-to-combat-covid-19 (accessed on July 15, 2022).

[31] Milvusrobotics. Available online: https://milvusrobotics.com/products/seit-uv (accessed on July 15, 2022).

[32] Inovasyon Engineering. Available online: https://www.inovasyonmuhendislik.com/en/products/covid-inota (accessed on July 15, 2022).

[33] Keenon. Available online: https://www.keenonrobot.com/EN/Product/pro3.html (accessed on July 15, 2022).

[34] Pudu. Available online: https://www.pudurobotics.com/product/detail/puductor (accessed on July 15, 2022).

[35] Tmirob. Available online: http://www.tmirob.com/products?cate=3 (accessed on July 15, 2022).

[36] Milagrow. Available online:. https://www.tradeindia.com/products/milagrow-robocop-indoor-disinfection-robot-6429368.html (accessed on July 15, 2022).

[37] Chanprakon, Chanprakon, Pacharawan, et al. "An Ultra-Violet Sterilization Robot for Disinfection". *2019 5th International Conference on Engineering, Applied Sciences and Technology (ICEAST)*, IEEE, 2019, pp. 1–4.

[38] Hassan, Sana, et al. "Androidbased UV-C Disinfecting Mobile Unit". *Pakistan Journal of Engineering and Technology*, vol. 4, no. 01, 2021, pp. 159–62.

[39] Bentancor, Marcel, and Sabina Vidal. "Programmable and Low-Cost Ultraviolet Room Disinfection Device". *HardwareX*, vol. 4, 2018, p. e00046.

[40] Vyshnavi, A., et al. "UV Disinfection Robot with Automatic Switching on Human Detection". *EAI Endorsed Transactions on Internet of Things*, vol. 6, no. 23, 2020.

[41] Guettari, Moez, et al. "UVC Disinfection Robot". *Environmental Science and Pollution Research*, 2020, pp. 1–6.

[42] Phan, Nguyen Duy Minh, Ngo Quoc Huy Tran, Le Anh Doan, Duy Chung Tran, et al. "An Ultraviolet C Light-Emitting Robot Design for Disinfection in the Operating Room". *Recent Trends in Mechatronics Towards Industry 4.0*, edited by Ahmad Fakhri Ab. Nasir et al., Springer Singapore, 2021, pp. 185–96.

[43] Perminov, Stepan, et al. "Ultrabot: Autonomous Mobile Robot for Indoor Uv-c Disinfection". *2021 IEEE 17th International Conference on Automation Science and Engineering (CASE)*, IEEE, 2021, pp. 2147–52.

[44] Zaman, Akib, et al. "UVC-PURGE: A Novel Cost-Effective Disinfection Robot for Combating COVID-19 Pandemic". *Ieee Access*, vol. 10, 2022, pp. 37613–34.

[45] Kim, Soo-Ji, et al. "Using UVC Light-Emitting Diodes at Wavelengths of 266 to 279 Nanometers to Inactivate Foodborne Pathogens and Pasteurize Sliced Cheese". *Applied and Environmental Microbiology*, vol. 82, no. 1, 2016, pp. 11–17.

[46] Gomez-Lopez, Vicente M., et al. "Pulsed Light for Food Decontamination: A Review". *Trends in Food Science & Technology*, vol. 18, no. 9, 2007, pp. 464–73.

[47] Vilhunen, Sari, and Mika Sillanpää. "Recent Developments in Photochemical and Chemical AOPs in Water Treatment: A Mini-Review". *Reviews in Environmental Science and Bio/Technology*, vol. 9, no. 4, 2010, pp. 323–30.

[48] Buonanno, Manuela, et al. "Far-UVC Light (222 Nm) Efficiently and Safely Inactivates Airborne Human Coronaviruses". *Scientific Reports*, vol. 10, no. 1, 2020, pp. 1–8.

[49] Ponnaiya, Brian, et al. "Far-UVC Light Prevents MRSA Infection of Superficial Wounds in Vivo". *PLoS One*, vol. 13, no. 2, 2018, p. e0192053.

[50] Holland, Jane, et al. "Service Robots in the Healthcare Sector". *Robotics*, vol. 10, no. 1, 2021, p. 47.

[51] Dhikle, Mansi, et al. "Cost-Effective Disinfection Robot Using UVC Radiation". *ITM Web of Conferences*, vol. 40, EDP Sciences, 2021, p. 02003.