UV-C surface disinfection: minimal physics considerations, dynamic vs static light sources, and simulations insights

Desinfecção de superfícies UV-C: considerações físicas mínimas, fontes de luz dinâmicas versus estáticas e insights de simulações

Desinfección de superficies UV-C: consideraciones físicas mínimas, fuentes de luz dinámicas frente a estáticas e información sobre simulaciones

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ABSTRACT

Ultraviolet-C light (UV-C) has been widely used for disinfecting food, water, air, and environments. The use of robots to perform environment disinfection has been considerably researched in recent years, especially after the COVID-19 pandemic. However, the advantages of dynamic UV-C light sources are not well discussed in the literature. This study aims to demonstrate the advantages of using dynamic UV-C sources instead of stationary sources and discuss the appropriate lamp distances and speeds. Through simulations, comparisons were made between the areas covered by a dynamic and stationary UV-C source in a given time frame. The results demonstrate that a punctual dynamic light source in a simple rectilinear movement can cover an area over 66% greater than the best case of a static source in the same time budget. Additionally, this work highlights the importance of considering the incidence angle, the
calculation of the ideal distance for a static point lamp, and the effects of using inadequate simulation resolution. Properly calculating the speed and distance of the UV-C light source can reduce the application time and, consequently, the energy consumption and associated costs.

**Keywords:** disinfection robot, UV-C robot, UV-C disinfection, mobile UV-C disinfection, incidence angle, UV-C simulation.

**RESUMO**
Luz Ultravioleta-C (UV-C) é largamente utilizada para desinfecção de alimentos, água, ar e ambientes. O uso de robôs para realizar a desinfecção de ambientes tem sido bastante pesquisado nos últimos anos, principalmente após o surgimento da pandemia de COVID-19. No entanto, as vantagens do uso de fontes de luz que podem se mover através do ambiente, em vez de lâmpadas estáticas, tem sido pouco discutidas na literatura. Este estudo almeja demonstrar as vantagens de utilizar luzes UV-C móveis em comparação com lâmpadas estáticas, e discutir as distâncias apropriadas da lâmpada e sua velocidade. Através de simulações, foram realizadas comparações entre a área coberta por lâmpadas estáticas e lâmpadas móveis, dado um intervalo de tempo. Os resultados demonstram que uma lâmpada pontual em um simples movimento retílineo pode cobrir uma área 66% maior do que o melhor caso de uma lâmpada estática, no mesmo intervalo de tempo. Adicionalmente, este trabalho demonstra a importância de considerar devidamente os ângulos de incidência, os cálculos para a distância ideal de uma lâmpada pontual estática, e os efeitos de usar resolução inadequada nas simulações. O cálculo da velocidade e distância apropriada da lâmpada UV-C pode reduzir o tempo de aplicação e, consequentemente, a energia gasta e os custos envolvidos com a desinfecção.

**Palavras-chave:** robô de desinfecção, robô UV-C, desinfecção UV-C, ângulo de incidência, simulação UV-C.

**RESUMEN**
La luz ultravioleta-C (UV-C) se ha utilizado ampliamente para desinfectar alimentos, agua, aire y ambientes. El uso de robots para realizar la desinfección del ambiente ha sido ampliamente investigado en los últimos años, especialmente después de la pandemia de COVID-19. Sin embargo, las ventajas de las fuentes de luz UV-C dinámicas no están bien analizadas en la literatura. Este estudio tiene como objetivodemostrar las ventajas de utilizar fuentes dinámicas de UV-C en lugar de fuentes estacionarias y discutir las distancias y velocidades apropiadas de las lámparas. Mediante simulaciones se realizaron comparaciones entre las áreas cubiertas por una fuente UV-C dinámica y estacionaria en un período de tiempo determinado. Los resultados demuestran que una fuente de luz dinámica puntual en un simple movimiento rectilíneo puede cubrir un área más del 66% mayor que el mejor caso de una fuente estática en el mismo presupuesto de tiempo. Además, este trabajo destaca la importancia de considerar el ángulo de incidencia, el cálculo de la distancia ideal para una lámpara puntual estática y los efectos del uso de una resolución de simulación inadecuada. Calcular correctamente la velocidad y distancia de la fuente de luz UV-C puede reducir el tiempo de aplicación y, en consecuencia, el consumo energético y los costes asociados.

**Palabras clave:** robot de desinfección, robot UV-C, desinfección UV-C, ángulo de incidencia, simulación UV-C.
1 INTRODUCTION

Ultraviolet-C (UV-C) light has been used for many years to disinfect the air, water, and surfaces (Kowalski, 2010). Technology has evolved as much as the forms of its application. The first applications for surface disinfection were carried out from static light sources such as lamps installed on the ceiling or near the ground or in disinfection chambers used to disinfect equipment (Kowalski, 2010).

In an evolution of this disinfection method, a wheeled device equipped with lamps is transported to the environment for disinfection, and a technician activates the lamps for a specified interval to carry out the disinfection. Several commercial solutions are available in the market for this type of application. The effectiveness of such devices has been evaluated in several studies (Nerandzic et al., 2010; Napolitano; Mahapatra; Tang, 2015; Boyce et al., 2016; Kovach et al., 2017; Yang et al., 2019).

A robot capable of navigating the environment and applying light is proposed by (Chanprakon et al., 2019). The robot consists of a base with wheels and motors and a system of lamps fixed on this base. As the robot moves in the environment, it detects and dodges obstacles. Although the author raised the issue of the need to apply an appropriate dose of light, navigation through the environment occurs randomly, merely avoiding the obstacles present. As a justification for using a robot instead of a static light source, the author pointed out that, when moving, the robot minimizes shadow areas.

With the advent of the COVID-19 pandemic, several other mobile robots were proposed and developed to attempt to minimize their impacts. Due to the urgency caused by the pandemic, some studies presented the application of UV-C light as a solution but failed to observe issues such as the necessary dose of light to perform the disinfection (Rai et al., 2020; Ahmed et al., 2020; Nosirov et al., 2020; Ray; Ray, 2020; Saad; Razzak, 2021). Other studies (Guettari; Gharbi; Hamza, 2021; Mikhailovskiy et al., 2021; Mohammed et al., 2021; Chanprakon et al., 2019), commented that it is necessary to deliver the necessary dose to disinfect the environment, but no automated mechanism is used to do this, leaving it up to the operator to guarantee the correct dose.

Disinfection maps are used in (Marques et al., 2021; Conte; Leamy; Furukawa, 2020; Pierson et al., 2021) to show the doses delivered to each of the surfaces in the environments. In
(Conte; Leamy; Furukawa, 2020), the authors used sensors to perform measurements of the amounts of energy reaching a surface and concluded that the UV-C dose must depend on the angle of incidence.

UV-C disinfection of objects moved by a conveyor belt is studied in (Guettari, 2022). As a result, the authors point out that the dynamic disinfection process is more efficient and that the number of lamps can be reduced, compared to the static method, using the same exposure time.

Notably, this research area is relatively recent, and many aspects still need to be studied and matured. As pointed out by (Mehta et al., 2023), dosage modeling, resource management, human safety, and benchmarking are still open problems.

The application of UV-C light for disinfection is most commonly performed in hospital settings. These environments can contain numerous objects, forming a three-dimensional (3D) scenario that is often quite complex, however, it can be described by a set of surfaces. This work aimed to demonstrate, using principles of physics and simulations (dosage modeling), how a mobile source can cover a larger surface area of the environment than a static UV-C light source in the same time budget (resource management).

This paper is organized in the following sections. The next one shows how light is distributed over a surface. Section 3 presents the differences between a mobile UV-C light source and a static source. Section 5, discusses some important points about the results and UV-C light simulations. And lastly, the conclusions.

2 HOW LIGHT IS DISTRIBUTED OVER A SURFACE

The amount of light radiated $I$ from a light source may be expressed by Eq. 1, where $P$ is the UV luminous power of the light source and $A$ is the surface area to which the source emits light (Halliday; Resnick; Walker, 2016). It is worth noting that $P$ is the luminous power, the amount of light that the source effectively generates, not the energy consumed by the lamp.

$$I = \frac{P}{A}$$

(1)

The available UV-C light sources can take the most diverse forms, from small punctual LEDs to long Mercury, Pulsed Xenon, or Excimer Lamps (Mehta et al., 2023). In addition to the
varied shapes of the lamps, reflectors with different shapes can be used, depending on the application. Aiming to observe how light falls on surfaces, in this work, the most simplified format of the light source is assumed, which is the point light source. Mathematical representation for more complex lamp shapes can be obtained from (Sasges; Robinson; Daynouri, 2012) and (Kowalski, 2010).

Considering a punctual and isotropic light source, light is emitted equally in all directions, in a sphere shape around the light source e (Halliday; Resnick; Walker, 2016). Thus, Eq. 1 may be rewritten as Eq. 2, where \( r \) is the sphere’s radius.

\[
I = \frac{P}{4\pi r^2}
\]

Figure 1 shows how the light emitted by a punctual source reaches a plane surface, where \( h \) is the height of the light source relative to the surface, \( x \) the distance between the light source and the point of interest \( p \) on the surface. Considering that a robot is holding the light source, \( d \) is the distance between the base of the robot and point \( p \).

The amount of light that reaches an area \( A \) of a surface \( S \) depends on the angle of incidence \( \alpha \) (Hecht, 2017), with the incidence angle \( \alpha \) being the angle formed between the light beam and the surface normal. Figure 2 illustrates a small beam of light from a distant light source (distance much greater than the radius of area \( A \)) falling on a surface \( S \). The area on surface \( S \), which is reached by the light beam, is greater than the sectional area \( A \) of the light beam if the light source is not positioned exactly over the surface. By trigonometry, it is possible to infer the ratio between
the sectional area of the light beam $A$ and the surface area illuminated by the beam, that is $A/cos \alpha$.

Figure 2. The amount of light that reaches a surface depends on the angle of incidence.

![Figure 2](source: Prepared by the authors)

The amount of light radiated $I_p$ on point $p$ may be described by Eq. 3, considering $\alpha$ as the angle between the light beam and the surface normal.

$$I = \frac{P}{4\pi x^2} cos(\alpha) = \frac{P}{4\pi x^2} \frac{h}{x}$$  \hspace{1cm} (3)

In turn, the dose of energy that a point $p$ receives is proportional to the interval $t$ during which the light radiates on $p$ (Kowalski, 2010). Thus, the dose $D_p$ that point $p$ receives may be written as Eq. 4.

$$D_p = tl_p = t \frac{P}{4\pi x^2} \frac{h}{x}$$  \hspace{1cm} (4)

The appropriate dose for surface disinfection is tabulated for most viruses, fungi, and bacteria (Kowalski, 2010). Therefore, the interval, power, and distance to the surface must be adjusted to achieve the appropriate dose to exterminate the desired microorganism. For the SARS-CoV-2 virus, for example, the dose is 3.7 mJ/cm$^2$ (or 37 J/m$^2$) for an inactivation greater than 3-log (Biasin et al., 2021).

As presented in Sec. 1, various works do not care about the dose of energy delivered to the surfaces (Rai et al., 2020; Ahmed et al., 2020; Nosirov et al., 2020; Ray; Ray, 2020; Saad; Razzak, 2021). Disinfection will not be appropriate without the proper dose of energy on the surfaces. In other cases, the responsibility for delivering the proper dose rests with the operator (Guettari; Gharbi; Hamza, 2021; Mikhailovskiy et al., 2021; Mohammed et al., 2021;
Even if the operator has a lot of experience, ensuring the dose delivered to each surface is a task that may go beyond human capacity, even more so in environments with complex surfaces full of details.

2.1 EFFECTS OF THE INCIDENCE ANGLE

Figure 2 illustrates how the amount of light coming from a light source (emitted light) is distributed over a surface (incident light). The bigger the angle of incidence is, the bigger the area over which the light is distributed. In other words, the same amount of light is distributed over a much larger area.

A simple simulation was made to show the importance of correctly using the light incidence proprieties, considering a flat surface of $10 \text{ m} \times 10 \text{ m}$, represented in Fig. 3. This surface is discretized in small squares with $0.1 \text{ m} \times 0.1 \text{ m}$, and a punctual light source with $40 \text{ W}$ of luminous power is positioned at the center, with the distance from the surface $h$ equal $0.1 \text{ m}$ during an interval of $1000 \text{ s}$. The region that received little or no energy is shown in red. The area that actually received the minimum energy dose or more (target dose of $255 \text{ J/m}^2$) is shown in blue. The surface that received some energy dose but not the desired amount is shown in shades of cyan.

The white line, in Fig. 3, represent the area that would have received sufficient energy if
α were not considered. Since the source is very close to the surface, the incidence angle is so small that the dose of energy that actually reaches the surface is negligible.

Another way to view these data is with the graph in Fig. 4, which shows the area that received the desired dose. The dotted line (Without Incidence Angle) represents the area that would have received the dose if the angle of incidence is ignored. The blue line (Received Desired Dose) represents the effectively sterilized area. While the dotted line (Without Incidence Angle) grows linearly, the blue line, which represents the real scenario, reduces its growth over time. In this simulated example, ignoring α, an area with 19.41 m² would have received the desired dose after the 1000 s of application, but only 3.49 m² actually received it (5.5 × difference).

Figura 4 – Comparison of the area effectively sterilized area [blue] to the area that would be sterilized (without considering the angle of incidence α) [dotted] as a function of time. 20 W Point Source. Distance h from the surface of 0.2 m.

Source: Prepared by the authors

In the various cases mentioned in the literature (Marques et al., 2021; Conte; Leamy; Furukawa, 2020; Pierson et al., 2021; Bačík et al., 2020), although the authors were concerned with the dose delivered to surfaces, the angle of incidence of the light on the surface was not considered. As demonstrated, ignoring the angle of incidence may bring a false sense that the surfaces have been disinfected and, consequently, put the people who will occupy the environment at risk.

3 STATIONARY UV-C LIGHT SOURCE VS DYNAMIC

To compare a static UV-C light source and a light source that can move through a
scenario, it is necessary to analyze how the energy is distributed throughout the environment. The Fig. 5 shows the area that reaches the desired dose ($A_D$) (in blue) for three different $h$. The area $A_D$ depends on $h$.

Figura 5. Dose simulation of an area receiving UV-C light from a static source for 1000 s with 40 W UV-C power at different distances from the surface.

The amount of energy the surface receives, in each case from Fig. 5, is represented in Fig. 6. If the light source is too close to the surface, much energy hits the surface but is concentrated in a small area. If the source is farther from the surface, less energy reaches the surface and is distributed over a bigger area. If the light source is too far away, almost no light reaches the surface. So, it is expected that exists an ideal distance $h_i$ which maximizes the area that receives the desired dose $D$ in a time interval $t$.

3.1 IDEAL DISTANCE BETWEEN A STATIONARY LAMP AND A SURFACE – SIMULATIONS

To analyze the ideal distance $h_i$, some experiments were conducted to determine the distance the disinfected area $A_D$ is maximized for static lamps. The surface sections were considered disinfected after receiving a minimum dose of 255 J/m².
Figure 6. Energy simulation of an area receiving UV-C light from a static source for 1000 s with 40 W UV-C power, at different distances from the surface.

(a) $h = 0.2$ m  
(b) $h = 0.8$ m  
(c) $h = 1.5$ m

Source: Prepared by the authors

Figure 7a shows the area disinfected by punctual UV-C lamps of different luminous powers throughout 1000 s. For each lamp, power exists an ideal distance $h_i$ where the $A_D$ is maximized. The weaker the light source is, the closer the lamp must be to the surface. Similarly, considering a variable interval of time $t$ and a lamp with fixed power, an ideal distance $h_t$ exists.

Fig. 7b shows the relationship between the distance of the lamp and the disinfected area for a 40 W lamp, for $t$ ranging from 50 s to 4000 s. The shorter $t$ is, the closer the lamp must be to the surface.

Three aspects can be inferred from Fig. 7: No matter what the power or application time, the disinfected area converges to zero when the distance between the lamp and the surface tends...
to zero; no matter what the power and application time, if the light source is too far from the surface, disinfection will also not occur; there is an ideal distance where the disinfected area is maximized, given a disinfection time and a lamp output power.

An interesting result appears when plotting the best cases (stars) that appear in Fig. 7a and Fig. 7b versus the power and disinfection time, respectively. Can be observed that the best case disinfected area increases linearly with the power, as showed in Fig. 8a, and increases linearly with the disinfection time, as showed in Fig. 8b.

![Figure 8. Best case disinfected area vs lamp power (a) and disinfection time (b).](image)

Source: Prepared by the authors

### 3.2 Ideal Distance Between a Stationary Lamp and a Surface – Mathematical Solution

The area $A$ disinfected by a punctual lamp may be described as the area of a circle, the outermost point of which reached the desired dose $D$. Fig. 9 illustrates this circle, with point $p$ receiving precisely the desired dose of energy considering a distance $h$ between the lamp and the surface.

Using the Pythagorean theorem, Eq. 4 may be rewritten in the form of Eq. 5, where $d$ is the distance between point $p$ and the base of the robot.
Figure 9. Disinfected area ($A_D$).

From Eq. 5, one may infer the distance $d$ (or the radius of the circumference) that will be disinfected according to Eq. 6 and, consequently, the area $A$, according to Eq. 7.

$$D = t \frac{P}{4\pi (d^2+h^2)} \frac{h}{\sqrt{(d^2+h^2)}} = \frac{thP}{4\pi (d^2+h^2)^{3/2}}$$  \hspace{1cm} (5)$$

One may observe in Fig. 7a and Fig. 7b that the maximum area $A_m$ is reached when the derivative of the area $A$ relative to $h$ is zero. By taking the derivative of Eq. 7 and equating it to zero, the optimal distance $h_i$ between the surface and the lamp is obtained, according to Eq. 8. By applying $h_i$ back in Eq. 7, the maximum area $A_m$, is obtained, according to Eq. 9.

$$d = \sqrt{\left(\frac{thP}{4\pi D}\right)^{2/3} - h^2}$$  \hspace{1cm} (6)$$

$$A = \pi \left(\frac{thP}{4\pi D}\right)^{2/3} - h^2$$  \hspace{1cm} (7)$$

$$h_i = \frac{1}{2(3)^{3/4}} \sqrt{\frac{P t}{\pi D}} \approx 0.219 \sqrt{\frac{P t}{\pi D}}$$  \hspace{1cm} (8)$$

$$A_m = \frac{\sqrt{3} P t}{18 D} \approx 0.096 \frac{P t}{d}$$  \hspace{1cm} (9)$$

Equation 9 shows that $A_m$ increases linearly with power $P$ and the exposure time $t$, which is consistent with the results of the simulations, as shown in Fig. 8a and Fig. 8b. Similarly, $A_m$
increases inversely proportional to the desired dose $D$.

3.3 DYNAMIC UV-C LIGHT SOURCES

A lamp that can be moved can be discretized as a lamp in minimally different positions over time. In each position, it radiates a certain amount of UV-C light. Fig. 10 illustrates a lamp moving in a linear trajectory and its various positions over time ($t_0$, $t_1$, $t_2$, ...). The regions where the lamp delivers UV-C light at each moment overlap, forming a disinfection trail.

![Figure 10. Mobile source in a linear trajectory.](source)

From Fig. 10, it can be observed that the faster the source is, the smaller the areas where the light overlaps. Therefore, in addition to the lamp’s power and the light’s application time, another relevant factor is the speed of the light source.

Likewise, if the robot makes parallel trajectories, the amount of energy delivered in the first pass will also be added to the energy delivered in the following passes. Fig. 11 illustrates this situation.

![Figure 11. Parallel trajectories.](source)
Considering that nearby trajectories can overlap the amount of energy delivered to the surface, a linear trajectory can be assumed as the worst-case move for a large surface disinfection.

3.4 DYNAMIC LIGHT SOURCE – WORST CASE

In a real-world application, there will hardly be a situation where the worst case (a linear trajectory with no other trajectories in the neighborhood) is applicable. However, comparing the worst-case motion with the best-case stationary lamp gives an overview of the problem. For a linear trajectory, some simulations were performed to determine the area that may be disinfected in a given period.

Fig. 12 shows the disinfected area for a 20 W lamp and 1000 s of simulation for different distances from the surface, varying the speed of the UV-C lamp. For each distance from the surface, there is an ideal speed that maximizes the disinfected area. Excessive speed may lead to none of the points on the surface being disinfected. The diamond represents the best case of the static lamp disinfection, presented in Sec. 3.1. Various combinations of lamp distance and speed may result in a more disinfected area than the best case for the stationary lamp.

Fig. 12 shows that even when using the ideal distance for a static source (1.10 m), adding a little movement makes it possible to increase the disinfected area (gain up to 22% in relation to...
the static one). By decreasing the distance between the lamp and the surface and increasing the speed, this increase in area is even more significant (gain of up to 66% in relation to the static one).

To maximize the disinfected area, as the source moves closer to the surface, the width of the disinfected trail decreases while the ideal speed and, consequently, the traveled distance increases. The graph in Fig. 12 indicates a plateau, with no significant gains in coverage area as the speed increases and the distance $h$ decreases.

Fig. 13 compares the disinfected area over disinfection time for the same 20 W point source, both stationary and mobile. The red line represents the static source at 0.2 m from the surface. It quickly disinfected the nearby region because it is close to the surface. However, due to being too close to the surface, it cannot disinfect a vast area. The blue line represents the same static source but in its ideal position, at 1.10 m from the surface. The source is farther from the surface, it takes longer (193 s) for the first portions of the area to reach the desired dose. But because it is a little farther from the surface, it can cover a larger area at the end of the period. Both the red and blue lines follow Eq. 7 and have a growth of the disinfected area proportional to the cubic root of the squared interval, changing only the parameter $h$. The green line represents the mobile source, also at 0.2 m from the surface. It is also very close to the surface and quickly delivers the energy dose to the first region. As the source moves, in the following moments, it will again be close to the other region that has not yet received the appropriate dose, which will quickly receive its dose. Hence, the disinfected area increases linearly, considering a uniform rectilinear movement.
When comparing the shape of the curves in Fig. 13, the area disinfected by the mobile source \( [a \text{ linear function } f(t) = a_1t + b_1] \) will always be more greater than that by a static source \( [f(t) = a_2t^{2/3} + b_2] \), considering a sufficiently large time.

3.5 DYNAMIC LIGHT SOURCE – SWEEPING NAVIGATION

As mentioned, a real situation will hardly be limited to a worst-case solution. Fig. 14 shows a lamp movement composed of parallel trajectories. In this case, a 40 W lamp is used, with a speed of 0.08 m/s, to disinfect a surface with 10 m × 10 m. The total area that reached the desired dose was 47.2 m², 3.17 × more than the best-case static lamp.

Fig. 14 also shows that performing the coverage of a surface and/or defining an ideal trajectory is a challenge in itself. In some places, at the beginning and end of the path, the desired dose was not reached. This demonstrates that the path must be carefully calculated so that disinfection occurs as expected. An in-depth analysis of the sweeping algorithm is covered in (Pfleger; Röning; Plentz, 2023).
Analyzing the energy distribution over the surface, presented in Fig. 15, it can be observed that the energy peaks were reduced when compared to the energy graphs presented in Fig. 6. This shows that a mobile light source can make a better distribution of over the surface than a static one.

The surface coverage strategy is linked to the shape and dimensions of the surfaces themselves and should be explored according to each need.
4 SIMULATION INSIGHTS

Simulators such as Gazebo (Robotics, a) are widely used to simulate robots with ROS (Robotic Operating System) (Robotics, b). However, how light is projected onto the Gazebo is quite limited, making simulations where it is necessary to calculate the dose of energy deposited on the surfaces difficult. Other engines can better render the projection of light onto surfaces. Still, dosimetry on surfaces is not a common application, and a way to perform dosimetry would have to be implemented. In any case, for other researchers to have access to the simulation, it would be necessary to install and configure several packages. Efficient dosage modeling is still an open problem (Mehta et al., 2023), especially for complex lamp and reflector assemblies. But for simpler modeling, like the one used in this work, it is possible to carry out quick simulations. So, to provide easy access to basic concepts and basic simulations, to perform the simulations presented in this work, a simple simulator was implemented, using HTML and JS, that can be run in any browser¹.

Some important aspects of dosage modeling could be observed from these simulations in addition to the issues presented in the previous sections. Since the lamp is in motion and the simulations are discretized representations of this motion, adopting an inappropriate spatial or temporal resolution may bring inappropriate results. Fig. 16 exemplifies this issue. All sub-figures are for a 20 W lamp at a distance of 0.3 m from the surface and a speed of 0.02 m/s, considering the dose of 255 J/m². As can be seen, different spatial or temporal resolutions of simulations can generate different results that may be distant from the reality intended to be represented.

Figure 16. Different simulation resolutions for the same lamp, speed, and distance between the lamp and the surface.

(a) Appropriate resolution.  
(b) Inappropriate temporal resolution.  
(c) Inappropriate spatial resolution.  
(d) Inappropriate spatial resolution.  
Source: Prepared by the authors

¹ Available at https://github.com/sergiogenilson/simple-uvc-simulator
Fig. 16a shows the area disinfected by a lamp with a resolution that can be considered appropriate for this speed and distance from the surface, using area segments of 5 cm × 5 cm and one iteration every second. As a result, the total area disinfected in this simulation was 12.68 m².

Fig. 16b shows the area disinfected by the same lamp with the same spatial resolution of 5 cm × 5 cm but using an inappropriate temporal resolution of one iteration every 100 s. Even with the speed of only 0.02 m/s, the lamp will have traveled a distance of 2 m in the interval between iterations, and the space between positions will not be interpolated. As a result, the total area disinfected in this simulation was only 8.65 m².

Fig. 16c and 16d show the area disinfected when using 1 m × 1 m area segments and one iteration every second. As a result, in the first case, in which the trajectory of the lamp was between the segments, the area receiving the desired dose was zero. In turn, in the second case, in which the trajectory of the lamp was exactly in the middle of the area segments, the area that reached the desired dose was 21 m².

The examples presented as inappropriate in Fig. 16 are purposely extrapolated to illustrate how an inadequate choice of resolution can interfere with the results and are, therefore, easily identifiable. However, even in Fig. 16a, there is an inaccuracy in the simulation, albeit more challenging to notice. As Fig. 16c and 16d show, the positioning of the lamp relative to the surface segments may also generate inaccuracy in the simulations, even when using a higher resolution.

The ideal spatial and temporal resolutions can probably be equated and will be explored in future work.

5 DISCUSSIONS ON THE RESULTS FOUND

Based on the results presented in Sec. 3 it was possible to observe that mobile lamps can cover significantly more area than static lamps in the same time interval. Based on the worst-case scenario, which would be a linear trajectory, it is possible to cover an area up to 66% larger than that of the best case of the static lamp in the same interval. The area covered maybe even more extensive when using other navigation strategies. In the example presented, it was possible to cover an area 217% larger in the same period by making parallel trajectories. However, the best case was not explored, as it depends on the application and the surface. Still, there may be
situations where the area covered in the same interval is even more significant.

It is also important to note that the ideal distance from the surface to a static source may not be the optimal distance to a dynamic source. The simulations indicate that shorter distances can be more efficient. However, the shorter the distance is, the greater the ideal speed, which may lead to difficulties controlling the position and speed of the lamp when taken to the extreme.

The ideal distance to the mobile source depends on the speed and navigation strategy. When making parallel trajectories for full surface coverage, the ideal distance also depends on the distance between the trajectories. Since the ideal distance of the mobile source depends on the navigation strategy, it must be explored according to the application.

Considering that static lamps form energy peaks over the position where they are installed, that the higher the peak, the greater the waste, and that simple trajectories form disinfection trails, distributing the energy peak over a much larger area and consequently optimizing the distribution of energy, it is possible that there are ways to distribute the energy over the surface in a way that further minimizes waste. However, this is not the scope of this work and will be explored in future work.

The simulations and calculations were carried out using a punctual UV-C source and demonstrated, in a more simplified and understandable manner, that using a mobile source can cover a larger area with the appropriate dose than a static source in the same interval. A real-world application must consider the shape, the set of reflectors used, and other lamp characteristics.

6 CONCLUSION

Through simulations, it was demonstrated how much the angle of incidence of light on a surface can interfere with the results. Not considering the angle of incidence may lead to the feeling that an area has been disinfected that is much more extensive than that actually disinfected, which may put people’s lives at risk depending on the environment in which the light is being applied.

The simulations demonstrated that using dynamic UV-C light sources instead of static sources brings advantages beyond reducing shadow areas (areas where light cannot reach due to some covering object). The simulation showed that in its worst-case scenario, a mobile UV-C
light source can cover an area up to 66% larger than a static source in its best case, considering a point source of 20 W of luminous power and an interval of 1000 s. The simulations also demonstrated that, depending on the trajectory adopted, the same source could cover 217% more area than the static source’s best case in the same interval. These results can be even better by exploring other navigation strategies.

The experiments also showed that exists an ideal distance between the surfaces and the lamps. Moreover, the ideal distance is different for the mobile and static sources. In addition to the ideal distance, there is also an optimal speed for the mobile source. The ideal distance and optimal speed depend on the surface coverage strategy adopted.

It has been demonstrated that the ideal distance for a static lamp depends on the luminous power of the lamp, the application time and the desired dose and can be calculated. Furthermore, it has been shown that ignoring the angle of incidence of UV-C light on the surface can give the impression of a disinfected area much larger than the area that was actually disinfected. The importance of using adequate temporal and spatial resolution to perform accurate disinfection was also demonstrated.

Using mobile UV-C light sources to disinfect environments may reduce shadow areas, provide a better energy distribution over the surface, and carry out disinfection in less time, reducing the energy consumed in the disinfection process. Moreover, a shorter application time leads to less time spent in the disinfection process, increasing the performance of the cleaning staff and reducing the time with the room closed for cleaning.

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REFERENCES


