Radiation Plan Optimization for UV-C Disinfection Robots

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Abstract. The proper disinfection of indoor places shared by a group of people on a daily basis has become a fundamental task recently which is usually tackled by using UV-C light. The number of mobile robots equipped with UV-C tubes has increased in the past few years due to their ability to effectively disinfect large buildings without supervision. In order to successfully meet all related expectations several challenges need to be faced including environment reconstruction, irradiance computation, and the visualization of the estimated disinfection level. In this work, in addition to fulfilling the previously mentioned tasks, we propose a novel genetic algorithm based optimization method to compute appropriate radiation positions for the mobile robot. A patent application regarding the whole system has been submitted under the number PCT/HU2022/050048.

1 Introduction

Mobile robots are often used to autonomously perform various cleaning activities in apartments or offices, for instance mopping or vacuum cleaning. Recently, physical disinfection using UV-C lamps has become increasingly popular because it is a reliable alternative to chemical methods, as UV-C light is able to significantly reduce the number of bacteria and viruses by causing irreversible damage to their molecular structure [1]. By mounting UV-C tubes on a moving platform, high quality surface and air disinfection can be achieved without having to supervise the process [2].

In order to correctly estimate the irradiance on the surfaces of various objects in the environment of the robot, several factors have to be considered. First, the characteristics of the lamp has to be determined, i.e., how irradiance varies on a sphere around the light source. Then a detailed 3D model of the environment is required which is important for both the computation and the visualization. By creating a 3D map, the whole irradiation process can be simulated before the disinfection begins. The model also allows for considering the structure of the environment. In many cases the UV-C lamps are placed in the center of the room and does not move during the disinfection process. However, it can be advantageous to select multiple radiation positions as the structure of the room might be complex. Therefore, the created algorithm has to be able to compute optimized locations where the mobile robot should stop to radiate. Finally, the whole irradiation process need to be visualized.

2 Irradiance Estimation

Most of the considered factors that affect the irradiance estimation depend on the position of the light source relative to the irradiated surfaces. Therefore, the 3D model of the area to be disinfected has to be created. On the one hand, it is important to preserve as many details of the objects as possible to precisely estimate irradiance on their surfaces. On the other hand, as the time required for the calculation highly depends on the size of the 3D map, it must not contain too many elements. We completed the reconstruction task using an RGB-D camera to obtain the 3D occupancy grid representation [3] of the environment which can be seen in Fig. 2.

The radiant exposure (i.e. the irradiance of a surface integrated over the time of irradiation) for each voxel was computed based on a lamp characteristics parameter $l(\alpha(\mathbf{x}))$, a visibility factor v, the distance $r(\mathbf{x})$ between the center of the light source and the radiated surface, and also the angle of incidence $\beta(\mathbf{x}, \mathbf{n})$, according to Equation 1.

$$H\left(l, v, \beta, r, t\right) = \frac{l(\alpha(\mathbf{x})) \cdot v \cdot cos(\beta(\mathbf{x}, \mathbf{n})) \cdot t}{r^2(\mathbf{x})} \cdot \Theta_{ref} \tag{1}$$

Θ_{ref} denotes the radiant power transmitted to a perfectly visible voxel, 1 meter from the center of the light source, for which the corresponding beam is parallel to the horizontal plane and perpendicular to the radiated surface. Since the efficiency of disinfection highly depends on the duration of the irradiation process, a time parameter t was also considered. The visualization of $\alpha(\mathbf{x})$ and $\beta(\mathbf{x}, \mathbf{n})$ can be seen in Fig. 1.

3 Optimization of the Radiation Positions

While disinfection is being performed, the mobile robot that carries the UV-C lamps might move constantly or stop in certain positions to radiate. Although, for smaller 3D environment models the created algorithm is able to estimate irradiance in real time, the movement of the robot would make calculations much more difficult, as the position of the light source relative to the voxels would change constantly. Instead, in this work we assumed that the robot moves to several target positions and stops at each of them to radiate for a given period. However, on the one hand, the random selection of these radiation positions can easily lead to inferior performance, while on the other hand, manual selection would require human interaction thus the disinfection task could not be accomplished autonomously. To solve these problems a novel genetic algorithm based optimization method was implemented.

In the proposed algorithm, the size of an individual (i.e. radiation plan candidate) depends on the required number of radiation positions which can be set as

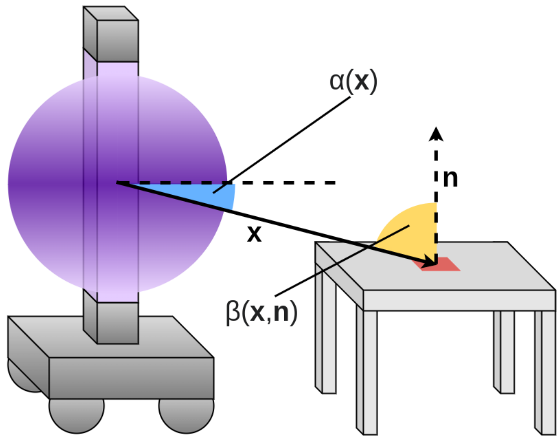

Fig. 1: The visualization of $\alpha(\mathbf{x})$ and $\beta(\mathbf{x}, \mathbf{n})$. The vector pointing from the center of the light source to the radiated surface and the local surface normal vector are denoted by **x** and **n** respectively.

an input parameter. Each individual in the initial population encodes the x and y coordinates of the positions and the corresponding radiation times. The recombination and individual modification can be performed by uniform or two-point crossover and normal or uniform distribution based mutation respectively.

Radiation plan candidates are evaluated according to the ratio of properly disinfected surface elements. More precisely, the score of an individual is equal to the number of voxels for which the radiant exposure is higher than a predefined value H_{limit} divided by the total number of voxels. The P_{i} score of an individual is described by Equation 2, where m and H_{j} denote the total number of voxels and the radiant exposure value of the jth cell respectively.

$$P_i = \frac{\sum_{j=1}^{m} \delta_j}{m} \qquad \delta_j = \begin{cases} 1, \; if \;\; H_j > H_{limit} \\ 0, \; if \;\; H_j \leq H_{limit} \end{cases} \tag{2}$$

The results of the evaluation can be used to select parents for crossover, individuals to mutate or in general to find the best radiation plan candidate. In addition, we also implemented the bacterial evolutionary algorithm based version of the optimization which can be used as an alternative.

The created system was tested in several synthetic environments that were created in Gazebo [4] during the development process. The result of the optimization for four radiation positions in one of these test environments can be seen in Fig. 2. Note that although the disinfection is not perfect, most of the surfaces were highly affected by the UV-C light. The imperfect result follows from the fact that currently the number of radiation positions is fixed, however, to overcome this limitation we plan to implement an adaptive method in the future.

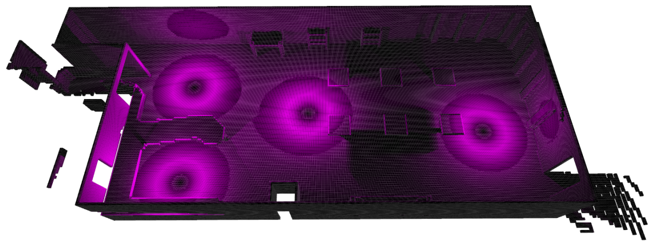

Fig. 2: Optimized disinfection plan for four radiation positions in a synthetic test environment.

4 Conclusion

The presented system can estimate irradiance on nearby surfaces around a UV-C disinfection robot, and also simulate the irradiation process. Irradiance values are computed based on the characteristics of the light source, the visibility of the target surface, the distance between the center of the light source and the radiated surface, and the angle of incidence. Leveraging these estimated values the presented genetic algorithm based method is able to produce an optimized disinfection plan for an autonomous robot equipped with UV-C light source. During the conference we plan to demonstrate how the presented system works in synthetic environment.

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