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# Control Systems Challenges in Energy Efficient Portable UV Based Water Sterilizer

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*Abstract*— [1] **This paper presents a real world challenge of constructing an energy efficient portable ultra-violet-based water sterilizer. We discuss a novel approach where UV radiation has a dual use, (i) to detect microbial activity through biofluorescence, and (ii) to sterilize the water. This dual use scenario enables us to propose a feedback control based operation scheme. The goal that we want to achieve is to make sure that the bacteria population does not exceed the allowed level, while keeping the energy usage as low as possible.**

**We propose a mathematical model for both the detection and sterilization process, based on experimental data. We then formulate an optimal control problem that minimizes the energy consumption while meeting a probabilistic performance criterion. By using an idea from dynamic programming, we propose a solution where the optimization in the detection and sterilization processes can be decoupled.**

**Keywords: hybrid system, biological systems, UV radiation, sterilization.**

## I. INTRODUCTION

The World Health Organization (WHO) recently estimated that almost one tenth of the global disease burden could be prevented by increasing access to safe drinking water and improving sanitation and hygiene of drinking water. Further, it is estimated that access to safer water can prevent millions of deaths yearly, attributed to malnutrition, diarrhoea, malaria, and other diseases carried by waterborne pathogens [1]. About 1.2 billion people globally lack safe water to consume [2]. UNICEF and the WHO have set Millennium Development Goals to reduce by half the proportion of people without sustainable access to drinking water and basic sanitation by 2015 [3]. From the economical point of view, the global benefits of improving access to safe drinking-water and sanitation is estimated at US$ 84 billions yearly [4]. Several different factors contribute to this amount, such as:

- health care savings from individuals and health agencies,
- gained productive days in the 15- to 59-year age group, and gained school attendance days for children,
- time savings resulting from more convenient and accessible drinking-water,
- values of deaths averted, based on discounted future earnings.

[1]Both authors contribute equally to this paper.

While the WHO analysis is mostly based on research findings in developing and under-developed countries, temporary disruption of clean water supply pose a serious threat virtually anywhere. For example, in the aftermath of Hurricane Katrina in New Orleans, USA, more than half of the surviving victims lacked access to clean water [5]. Similarly, thousands of people were infected by diseases carried by waterborne pathogens when their access to clean water was disrupted by the Asian Tsunami in 2004.

Water sterilization is an important element in providing safe drinking water. In this paper, we discuss the use of ultraviolet (UV) light in water sterilization, and the control systems challenges involved in this effort. UV radiation is not the only method available for water sterilization. There are other methods that are based on the use of mechanical (e.g. filtering, drying and vacuuming), chemical (e.g. chlorination and ozone), electrical (using ultrahigh electric voltage), and thermal (e.g. direct or microwave heating) agents. Generally, these methods are less energy efficient than UV based sterilization [6], [7]. Furthermore, chemical based methods can introduce hazardous side-effect to the environment.

Energy efficiency is a major concern in this project. This is because in the situations where water sterilization is critically needed, the supply of energy is typically slim to none. The novel contribution of this project to the effort of water sterilization using UV radiation can be summarized into three factors:

1. Miniaturization of the UV light source in the form of dual-waveform UV Light Emitting Diode (LED) lamps,
2. The dual use of UV in pathogen detection and sterilization,
3. Incorporation of automatic control strategies to achieve high performance and higher energy efficiency.

Miniaturization of the UV light source will lead to portability of the water sterilization device, and lower the production cost and energy consumption. The use of UV in pathogen detection is based on the phenomenon of biofluoroscense of *nicotinamide adenine dinucleotide* (NADH) molecules under UV radiation. The fluorescence of NADH can be used as a tracer for microbial metabolism, indicating the microbial activity in the water. This is achieved without additional consumables like tagging agents to induce fluorescence. By using the biofluoroscense as sensor measurement, we can develop a control strategy aiming at two objectives:

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(a) minimizing the energy spent for detection and sterilization, and
(b) ensuring high performance sterilization.

The focus of this paper is in developing valid mathematical models for the detection and sterilization processes. We also include both processes in a control loop, with the detection process providing the sensor measurement and the sterilization as the control actuation. We then formulate a control problem aiming at attaining objectives (a) and (b) above.

By nature, both sterilization and detection processes involve randomness. Further, since UV is used both as sensing and sterilization agent, the implementation of the system will involve some kind of switching mechanism. Therefore, effectively, the model that we develop uses the formalism of stochastic hybrid systems. Minimization of energy consumption is formulated as finding an optimal switching strategy between different modes of operation.

## II. UV Detection and Sterilization

### A. Process Description

The detection and sterilization processes have distinct light excitation wavelengths within the ultraviolet range. The detection mechanism is based on fluorescence which has the advantages of greater sensitivity and range in comparison to methods based upon changes in optical density or chemiluminescent emission [8]. Sterilization using UV light causes irreparable damage to the cell's DNA, rendering them inactive. Advantages of UV sterilization over other sterilization methods include the elimination of undesirable by-products and low cost [9]. Each process is described in further detail below.

Bacteria constitute the majority of microorganisms in wastewater using organic compounds for their supply of carbon and energy [10]. Bacteria oxidize organic molecules which engage energy-producing processes that use coenzymes including nicotinamide adenine dinucleotide (NAD). NAD functions as an electron carrier in oxidation-reduction reactions. NAD reduces to $NADH_2$ (NADH) during energy generation from oxidation [8]. Its native fluorescence is excited at 340 nm with emission detected at 440 nm. Detection systems for bacterial metabolic activity, therefore, are based on the native fluorescence of NADH. A narrow-band light emitter at 340 nm with sufficient output power can excite bacterial cells which will induce a fluorescent signal proportional to the number of cells in wastewater. The detector must be tuned to the wavelength of 440 nm. Optimizing the signal-to-noise ratio depends upon the characteristics of the emitter and detector and pulse or modulation techniques.

Ultraviolet disinfection is a cost competitive and time-tested method of sterilization. Not long after the discovery of sunlight's germicidal effects in the 1800's, its practical use began in municipal water facilities using solar UV disinfection in 1910. In the 1950s, UV systems were based on fluorescent tube technology [11]. Today, the UV sources are predominately low-pressure mercury vapor lamps emitting narrowband 254 nm wavelengths and medium pressure mercury vapor lamps with a broad UV spectral range. Recent advances in solid-state UV light emitting diodes afford compact, energy saving sources and enable new opportunities to control light output power.

The mechanism of sterilization begins with the penetration of UV wavelengths from 245-295 nm into the cell wall. It is absorbed by nucleic acids and their damage interferes with normal cell processes such as cell synthesis and cell division. The optimum wavelength for this effect is 265 nm. The efficiency of inactivation of microorganisms is proportional to the UV dose ($W{\cdot}s/cm^2$) which is light source intensity ($W/cm^2$) multiplied by the time of exposure (s) [9]. Most bacteria and virus require low doses for inactivation in the range of 2 to 6 $mW{\cdot}s/cm^2$ for a 90% kill [9].

### B. Light Sources: Enabling Technology

In recent years, there have been significant advances in AlGaN based ultraviolet light emitting diodes. Milliwatt continuous wave output powers have been attained from near to deep ultraviolet wavelengths (254 nm - 340 nm) [12]. SET Inc. commercially produces LED arrays in wavelengths across the UV spectrum including 265 and 340 nm with total UV output power up to 30 mW continuous wave. An individual 265 nm LED in pulsed operation achieves 10 mW output power with 1.2 A of driving current [13]. The superior performance of UV LEDs over traditional light sources for optical stability has been investigated and reported, e.g. in [14], [15], [16], [17]. Multi-wavelength lamps are now available with individual control of each LED within the lamp. Pulsing techniques between the germicidal and detection wavelength can be designed. Research has begun to explore pulsed and modulated UV LEDs for biological detection and sterilization [18], [19]. Spatial, temporal, and spectral alignment response give rise to the need for an effective control strategy.

## III. Experimental Data and Mathematical Models

### A. Sterilization

Research findings indicate that when given UV radiation at the right wavelength range ($\sim$265 nm), the population size of bacteria decrease exponentially with the UV radiation energy that they receive (see e.g. [20], [21]). This can be written as a differential equation:

$$\frac{dN(t)}{dt} = -\frac{W(t)N(t)}{\kappa}, \tag{1}$$

where $N(t)$ is the number of bacteria in the population, $W(t)$ is the UV radiation power (in W), and $\kappa$ (J) is the species specific constant that defines the amount of energy needed for sterilization. If we express $N(t)$ in log scale, Equation (1) becomes

$$\frac{d}{dt}(\ln N) = -\frac{W(t)}{\kappa} \Rightarrow \ln N(t) = \ln N(0) - \frac{1}{\kappa}\int_0^t W(s)\, ds.$$

This relation agrees with the experimental data reported in [20], [21], as shown in Figure 1.

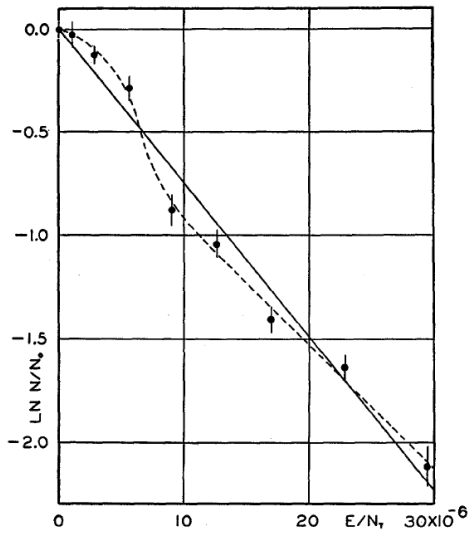


Fig. 1. (taken from [20]). The vertical axis is the the number of bacteria cells (in normalized logarithmic scale), while the horizontal axis is the amount of radiated energy (in linear scale). The experimental data are plotted as dots, while the solid line denotes the best linear fit for the data.

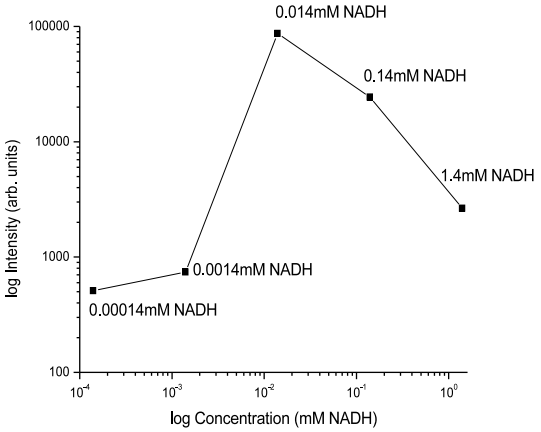


Fig. 2. Fluorescence intensity vs. NADH fluorosphore concentration (mM) for excitation wavelength of 340nm and emission peak maximum wavelength at 454 nm.

If the time horizon of interest is much shorter than the bacterial doubling time, we can ignore the bacterial growth factor in this population model. For example, the data shown in Figure 1 is based on a 2 to 5 minute observation. For longer time horizon, we need to include the bacterial growth factor in the model. For that purpose, we modify the standard Verhulst population dynamics model [22] as follows:

$$\frac{dN(t)}{dt} = -\frac{W(t)N(t)}{\kappa} + \frac{N(t)}{\tau} - \lambda N^2(t). \qquad (2)$$

The second and third terms on the right hand side of (2) represent the population dynamics in the absence of UV radiation. The constant $\tau$ denotes the characteristic growth time while $\lambda$ represent the competition effect among the bacteria when the environmental support is finite. In the absence of UV radiation, the largest population size supported by the environment is given by $N_{\max} := \frac{1}{\tau\lambda}$. One interesting consequence of (2) is the existence of a minimum UV intensity for total sterilization. Indeed, by manipulating (2), one can see that in the presence of a constant UV radiation, $W(t) \equiv W$, the population dynamics still converges to a positive quantity as long as

$$W < W_{\min} := \frac{\kappa}{\tau}. \qquad (3)$$

For a constant radiation intensity $W(t) \equiv W$, (2) can be solved analytically to obtain

$$N(t) = \frac{\gamma}{\left(\frac{\gamma}{N_0} + \lambda\right) e^{\gamma t} - \lambda}, \qquad (4)$$

where $\gamma := \frac{W}{\kappa} - \frac{1}{\tau}$ and $N_0 := N(0)$.

### *B. Detection*

The detection experimental data reported in this subsection were obtained by the Sawyer's group at RPI. Two types of experiments were conducted. The biofluoroscense of NADH standard solution and *Escherichia coli* cells were measured in separate experiments to determine relative fluorescence intensity levels with respect to concentration. For proof-of-concept, both were measured using a Fluorimeter-Spectrometer with a Halogen Lamp UV light source with a spectral range from 200-900 nm. Excitation and emission monochromators within the setup select both the excitation in a fixed wavelength and detection in a range of wavelengths. The fluorescence signal was detected with a cooled Photomultiplier Tube (PMT) module with voltage-varied gain.

The NADH fluorosphores were measured first to determine the fluorescence without any potential interference from the cell. To determine the upper and lower limits of detection, a series of standards (1000 – 0.1 mg/L or 1,4 – 0.00014 mM, respectively), were prepared from $\beta$-NADH (Sigma-Aldrich, Germany) in 0.01M Tris Base (molecular biology grade, Fisher BioReagents, USA) with pH 8.5. Figure 2 shows the measured fluorescence intensity of NADH with increasing concentration. There is a nonlinear response including a decrease of intensity with increasing concentration of NADH due to self-quenching [10]. Self-quenching in our experiment is consistent with data found in [12] regarding the measurement of intracellular and extracellular NADH. Intracellular NADH refers to NADH on the inside of each cell that reflects cell count directly. Reliable quantification will depend on identifying where the NADH concentration lies on the non-linear curve and whether the measurements reflect intracellular or extracellular concentrations.

Fortunately, direct *E. coli* cell concentration measurement does not exhibit self-quenching behavior. A second experiment with native *E. coli* cells was created to determine whether whole cell concentrations have the same quenching effect. *E. coli* K-12 MG 1655 strain was grown in M9 Minimal Media (Maniatis formulation) at 37°C in a shaker incubator at the rate of 225 rpm. After 24 hour growth the concentration of bacterial cells were enumerated using the standard plate count method. The concentration in the

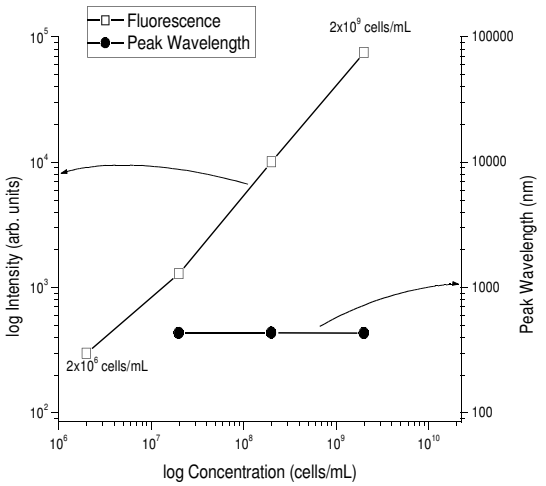


Fig. 3. Fluorescence intensity vs. *E. coli* cell concentration (cells/mL) for excitation wavelength of 340 nm. Peak emission wavelength varied from 435 +/- 2 nm.

culture of *E. coli* K-12 MG 1655 was $2.0 \times 10^9$ cells/mL. This culture was serially diluted 1 to 10 with sterile Minimal Media (Maniatis formulation).

As opposed to the NADH fluorescence experiment, the whole cell experiment does not exhibit any saturation in detection. Figure 3 shows the measured fluorescence intensity of *E. coli* cells for different concentrations. In this case, we observe a linear response with an increase of intensity with increasing concentration. The four highest concentrations were the only of the serial dilutions that produced a detectable response. The first three concentrations were the only samples to demonstrate a significant peak (435 +/- 2nm) as shown in Figure 3.

Based on the experimental data, we assume that we can compile a look-up table that relates the amount of biofluoroscense with the number of bacteria in the measured volume. However, because of measurement noise, the reading will generally be a random variable. Furthermore, the distribution of this random variable is related to the accuracy of the reading, which will generally depend on the amount of radiation during the detection procedure for bacterial cells. We assume that the probability density function of the actual bacteria population size, $N_0$, can be written as $\varphi(\cdot;\rho)$, where $\rho$ denote the parameters of the distribution (mean, standard deviation, higher order moments, etc.). Further, the fact the distribution depends on the radiation can be captured by assuming that the parameter $\rho$ is time-varying, and that its dynamics is given by

$$\frac{d\rho(t)}{dt} = F(\rho, W, t), \tag{5}$$

where $W$ is the radiation intensity. We do not yet have the distribution $\varphi(\cdot;\rho)$ and the function $F$.

## IV. Control Problem Formulation

### A. Hybrid Automaton Formulation

The main idea that we want to pursue in this project is to incorporate UV radiation in both detection and sterilization processes. The main concern is the minimization of energy usage during the operation while keeping the bacterial concentration low.

One of the main facts that we gather from the experimental data is that the optimal UV wavelength range for sterilization and detection are different. Sterilization is most effectively achieved at $\sim$265 nm wavelength, while detection is peaked at $\sim$340nm wavelength. Based on this observation, we propose the incorporation of both processes in its most basic form as follows.

1) A batch of drinking water is put into the system. The system begins the detection mode with 340 nm LEDs within the lamp pulsing at an optimized frequency.
2) Detectors sensitive to emission at 440 nm receive microorganism fluorescence only at the corresponding frequency.
3) A threshold, determined by the intensity of the fluorescence signal over noise from the system, initiates the switch to sterilization mode or idle mode for an allotted time.
4) If sterilization is required, the 265 nm LEDs within the lamp emit light with the radiation intensity and time of exposure varied by the outcome of the detection process.
5) System operation is completed when the microbial content in the water is driven below a predetermined threshold.

The system dynamics during this operation can be naturally modeled as a hybrid automaton [23], [24], as shown in Figure 4. The three modes of operation, detection, sterilization, and idle can be expressed as a hybrid automaton with four locations/modes of dynamics.

During the detection mode, the evolution of the probabilistic distribution of bacterial content is given by (5). During this period, we assume that the UV radiation is set at wavelength 340 nm with constant intensity. Since the 340 nm radiation has been found to be largely ineffective for sterilization [21], we ignore the dynamics of the population size in this mode. The power consumed during this mode is represented by the radiation intensity $W_1$. Consequently, this contributes to the cost function $J$, which is formulated as the total energy consumption as

$$\frac{dJ}{dt} = W_1.$$

The transition to sterilization mode occurs when the distribution parameters $\rho$ enter a set $R$. The set $R$ is a design parameter that needs to be chosen so as to minimize energy consumption during operation. During the sterilization mode, we irradiate the bacteria with 265 nm UV radiation with intensity $W_2$. The population dynamics in this case follows

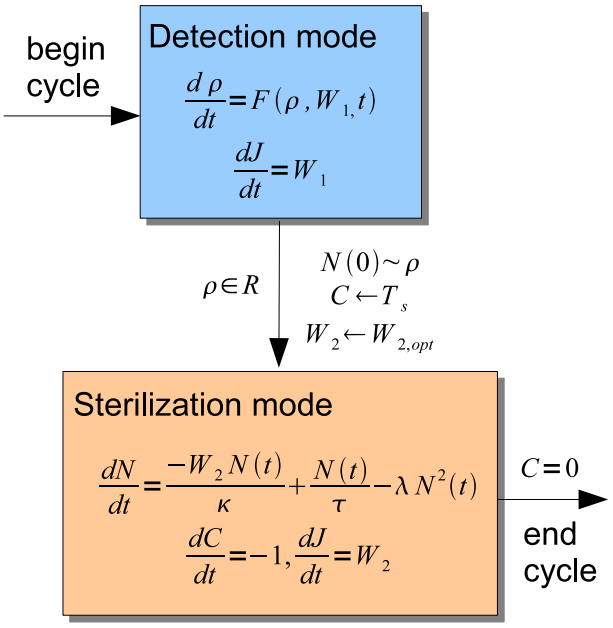


Fig. 4. The system dynamics expressed as a hybrid automaton. Each box represents a mode of dynamics. The arrows represent transition between modes, with their guard conditions and reset maps. The expressions $\rho \in R$ and $C = 0$ represent guard conditions. We assume that a transition occurs as soon as the corresponding guard becomes active. The expressions with arrows represent the reset maps. For example, $C \leftarrow T_s$ means the transition resets the value of the clock $C$ to the constant $T_s$. The expression $N(0) \sim \rho$ represents the fact that $N$ is initialized as a random variable, whose distribution is parametrized by $\rho$.

(2). The dynamics of the cost variable $J$ is given by

$$\frac{dJ}{dt} = W_2.$$

The duration of the sterilization process is determined by a clock variable $C(t)$. When the clock variable $C(t)$ becomes zero, the process is completed. Initially, the clock variable is set at a value $T_s$. The radiation intensity $W_2$ and duration $T_s$ are also design parameters to be chosen (depending on $\rho$) so as to minimize energy consumption.

### B. Control System Challenges

In terms of the formulation above, we can express the control system design challenge as follows.

**Problem:** Design $W_1$, $W_2$, $R$, and $T_s$ to minimize the cost variable $J(T_s)$, where time $T_s$ indicates the end of the cycle and the accumulation of the cost in both modes are shown in Figure 4. This minimization is performed under a probabilistic performance constraint given by

$$\Pr\{N(T_s) \geq N_{\text{allow}}\} \leq \varepsilon, \tag{6}$$

where $N_{\text{allow}}$ is the maximum allowed bacterial content in drinking water and $\varepsilon$ is a small number that indicates the required confidence level.

We can solve this problem using an idea from dynamic programming [25]. First, we compute the optimal "cost to go" at the beginning of the sterilization mode, as a function of $\rho$. With this result, we can decouple the optimization procedure during the detection and sterilization mode.

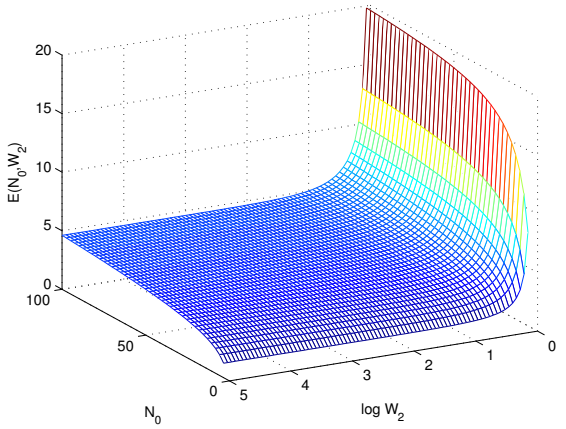


Fig. 5. The plot of energy required for sterilization $E(N_0, W_2)$, as a function of initial population size ($N_0$) and radiation intensity ($W_2$).

### C. Optimal Solution

For a given (deterministic) initial condition $N(0) = N_0$, under a constant sterilization radiation with intensity $W_2$, we can compute the minimum time required to reduce the population size to $N_{\text{allow}}$ as follows (see (4)):

$$T(N_0, W_2) = \frac{\kappa\tau}{W_2\tau - \kappa} \ln\left(\frac{\frac{W_2\tau-\kappa}{\kappa\tau N_{\text{allow}}} + \lambda}{\frac{W_2\tau-\kappa}{\kappa\tau N_0} + \lambda}\right). \tag{7}$$

The energy spent during this process is given by

$$\begin{aligned} E(N_0, W_2) &= W_2 T(N_0, W_2), \\ &= \frac{W_2\kappa\tau}{W_2\tau - \kappa} \ln\left(\frac{\frac{W_2\tau-\kappa}{\kappa\tau N_{\text{allow}}} + \lambda}{\frac{W_2\tau-\kappa}{\kappa\tau N_0} + \lambda}\right). \end{aligned} \tag{8}$$

Therefore by minimizing $E(N_0, W_2)$ with respect to $W_2$, we can find the radiation intensity level $W_2$ that optimizes the energy usage. A plot of $E(N_0, W_2)$ for the parameter values $\tau = \kappa = N_{\text{allow}} = 1$ and $\lambda = 10^{-2}$ is shown in Figure 5.

Figure 5 shows that $E(N_0, W_2)$ is monotonically decreasing with $W_2$. This means that $W_2$ should be designed to be **as high as the system would allow**. We denote this value as $W_{2,\max}$. In this case, the optimal energy usage is given by

$$J_{\text{opt}}(N_0) = \frac{W_{2,\max}\kappa\tau}{W_{2,\max}\tau - \kappa} \ln\left(\frac{\frac{W_{2,\max}\tau-\kappa}{\kappa\tau N_{\text{allow}}} + \lambda}{\frac{W_{2,\max}\tau-\kappa}{\kappa\tau N_0} + \lambda}\right). \tag{9}$$

The optimal sterilization strategy for stochastic initial condition $N_0$, which is distributed according to the parameter $\rho$, is as follows. We use the fact that under constant radiation intensity, $N(t)$ is a monotonically increasing function of $N_0$ (see (4)). Let $\hat{N}_0(\rho)$ be the smallest number such that

$$\Pr\{N_0 \geq \hat{N}_0\} \leq \varepsilon,$$

given the distribution parameter $\rho$. We treat $\hat{N}_0(\rho)$ as the worst case initial condition for the confidence level $\varepsilon$. The

optimal sterilization energy given the distribution parameter $\rho$ is then given by

$$J_s^*(\rho) = J_{\text{opt}}(\hat{N}_0(\rho)).$$

If the distribution $\varphi(\cdot, \rho)$ and the dynamics in (5) are known, then the optimal detection policy can found by solving the following optimal control problem with free final time

$$\min J_s^*(\rho(T_d)) + \int_0^{T_d} W_1(t)\ dt,$$

under the constraints

$$\frac{d\rho(t)}{dt} = F(\rho, W_1, t),\ \rho(0) = \rho_0.$$

## V. Discussion and future research agenda

In this paper we present some control system challenges associated to a real world problem, constructing a portable energy efficient UV water sterilizer. One of the novel aspects in our project is the technology that will enable the use of UV both as detection and sterilization agent. To this end, we formulate a mathematical model for both the sterilization and the detection process and propose a basic operation scheme involving both of them. This model takes the form of a hybrid system. Further, we formulate an optimal control problem that minimizes the energy consumption during the system operation, while meeting a probabilistic performance criterion. We propose a solution to this problem that takes an idea from dynamic programming, whereby the optimization for the detection and sterilization modes can be decoupled.

We identify several directions, in which future research will be conducted. First, we need to develop the missing mathematical model for the detection process, and solve the optimal detection problem as outlined in the previous section. Second, we so far assume that the model parameters ($\tau$, $\kappa$, and $\lambda$) are known. In reality, they might not be known or only known up to a certain probabilistic distribution. In this case, we are interested in designing a robust optimal control policy that takes into account this stochasticity. Finally, we would like to explore and exploit the spatial factor in the design of this device. With the proposed technology of UV LED arrays and UV detector arrays, the lumped parameter model might be replaced with a distributed parameter model, where the spatial and geometric aspects of sensor/actuator placement can be addressed. While this approach will result in higher system complexity, we believe that it can further optimize the energy usage during the operation of the system.

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