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RELIABILITY ANALYSIS OF AN ANTI-DRONE SYSTEM BY CONSIDERING RANDOM ENVIRONMENTAL FACTORS

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Abstract

In today's security landscape, the proliferation of unauthorized drones in restricted airspace has emerged as a significant threat. These drones pose various risks, from potential surveillance and espionage to more sinister possibilities such as physical attacks. Consequently, the development of effective anti-drone laser systems has become increasingly vital. Our study focuses on three main objectives: modeling internal reliability, identifying critical components, and studying the factors affecting the reliability of anti-drone systems. We aim to enhance the overall performance and effectiveness of anti-drone laser systems by analyzing the reliability of critical components and understanding how system parameters influence system reliability. To this end, reliability block diagram (RBD) methodology has been employed to compute the reliability of the laser subsystem in the anti-drone system. Additionally, we conduct a comprehensive review of component-wise reliability to identify vulnerable points within the system, thus enabling targeted improvements and optimizations. To capture the realistic scenario of system failure behavior, different distributions have been used to compute the reliability of the system, ensuring a thorough understanding of its operational reliability in diverse conditions. Finally, the energy values and probability of hitting are obtained for the anti-drone laser system to effectively mitigate environmental challenges.

Keywords: Reliability Block Diagram, Laser Source Subsystem, Weibull Distribution, Mean Time to Failure (MTTF), Rayleigh Distribution, Exponential Distribution, Environmental Factors.

1. INTRODUCTION

Drones have swiftly become an integral part of modern life, finding widespread use across various sectors. While initially linked mainly to military operations, drones now play vital roles in civilian domains. Their applications are diverse, spanning entertainment (aerial photography, videography), geology (mapping, surveying), transportation (traffic monitoring), security (search and rescue, crowd monitoring, disaster relief), shipping (parcel delivery), agriculture (crop monitoring, spraying), and communication (emergency infrastructure). These innovative uses mark a significant shift towards a more autonomous society, with drones poised to revolutionize various aspects of daily life.

In today's security landscape, the threat posed by unauthorized drones operating in restricted airspace is a growing concern. These drones can be utilized for various malicious activities, including surveillance, espionage, and even physical attacks. To address this threat effectively, the development of robust anti-drone laser systems has become imperative. Figure 1 represents the laser implemented anti-drone systems.

An anti-drone laser system serves as a critical security technology designed to detect, track, and neutralize unauthorized drones operating in restricted airspace. By employing advanced detection mechanisms, precise tracking capabilities, and effective neutralization methods, these systems aim to safeguard sensitive areas from the potential risks posed by rogue drones. Laser weapons are emerging as a potent solution for countering the escalating threat posed by drones, leveraging their rapid light-speed engagement, pinpoint accuracy in beam targeting, and cost-effectiveness per shot [19]. In order to analyze the strike capability of laser to drone engine, a comprehensive assessment method for the vulnerability of target to laser is studied in [16]. In [24], Ball suggested that assessing a target's vulnerability to lasers parallels evaluating how non-explosive penetrating objects cause damage when striking a target, although a detailed method was not explicitly outlined.

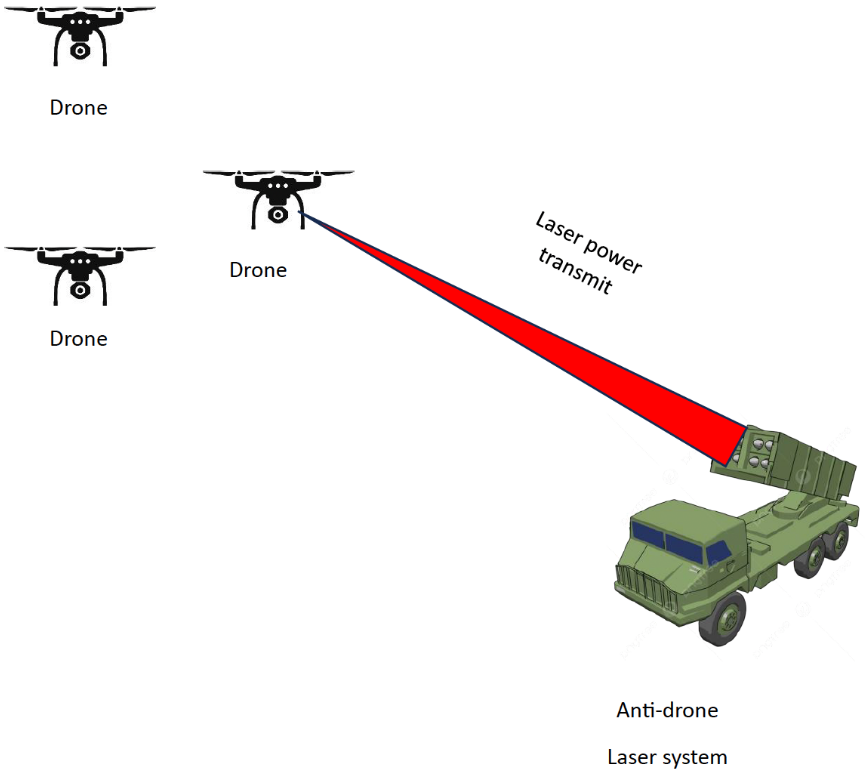

Figure 1: *Anti-Drone Laser System*

1.1. Literature Review

Drones are poised to become a significant factor in future warfare, driven by advancements in artificial intelligence (AI) and information technology. Simultaneously, drones pose a significant challenge to conventional air defense systems. Concerning this practical point of view anti-drone systems are designed and developed. Presently, the majority of anti-drone systems utilize military-grade components to ensure the definitive destruction of hostile drones. Military anti-drone measures commonly employ jamming systems to disrupt the control channel of the target drone [36]. However, in non-military contexts, using RF jamming to thwart fast-moving drones poses the risk of temporarily disabling existing wireless network systems, such as mobile access or wireless sensor networks [1], [2]. Therefore, the majority of national regulations prohibit the non-military deployment of jamming systems, compelling civilian anti-drone systems to explore alternative methods to halt illegal or unauthorized drones. To destroy or neutralize the illegal drone, different destructive technology is studied. Out of all destructive technology, the most useful technologies are laser, killer drone and anti-aircraft weapons.

Killer drones are referred to as legally operated drone designed to track and neutralize target drones by inflicting damage upon them [18]. Killer drones are remotely operated aircraft equipped with weaponry designed to engage and neutralize targets. These drones have gained significant attention due to their role in modern warfare, intelligence gathering, and targeted strikes. The development of killer drones represents a paradigm shift in military tactics, providing armed forces with unprecedented capabilities in surveillance, reconnaissance, and precision strikes. The legal and ethical considerations surrounding the use of killer drones, also known as armed drones, are complex and multifaceted [23].

Another useful destructive neutralization technology for an anti-drone system is a laser power transmitter. Laser power in anti-drone systems plays a pivotal role in countering the proliferation of drones and protecting critical infrastructure, military installations, and public events from potential threats posed by unauthorized drones. Laser based anti-drone systems utilize directed energy technology to disable or destroy hostile drones through the focused emission of high-energy laser beams. In [15], Huang et al. designed and developed laser integrated anti-drone system. Laser integrated anti-drone system combines cutting-edge laser technology with advanced sensors, tracking systems, and command-and-control interfaces to provide a comprehensive and effective defense against hostile drones.

The key components and capabilities of a laser integrated anti-drone system are:

High-Energy Laser Weapons: Compared to traditional projectile weapons, high-energy laser weapons are particularly well-suited for countering such threats due to their precise and scalable effects, with minimal collateral damage [38]. In [17], Lyu and Zhan made a comprehensive overview of the current state of high-energy laser weapons on a global scale. High energy laser weapons nowadays are most useful in military application to protect the country from the evil. The overview of different technologies in high-energy laser systems encompasses both strategic and tactical roles for high-energy laser weapons on the modern battlefield. It delves into the current performance limitations of weapon system components, including various types of laser devices, beam control systems, atmospheric propagation, and issues related to targetting the killing power [21].

Detection system: Laser integrated anti-drone system incorporates a sophisticated sensor system comprising radar systems, electro-optical/infrared cameras, and radio frequency (RF) detectors. These detectors provide comprehensive situational awareness, enabling operators to detect, track, and classify incoming drones with precision. By integrating data from multiple sensors, laser integrated anti-drone system enhances its ability to identify threats and mitigate false alarms. In [3], Abunada et al. discussed a drone detection mechanism utilizing the RF control signal exchanged between the drone and its remote controller. Wang et al. [37] studied the problems and difficulties of existing radar detection technology for small drone detection and provided better outlook on the development of detection technology. The laser can serve as a supplementary sensor, complementing others such as radar to detect, recognize, and track the drone. Additionally it can dazzle and destroy the drone’s optical sensors, enhancing its defensive capabilities. In [32], Steinvall examined diverse laser functionalities and their significance in detecting, identifying, tracking, and countering a drone.

Tracking System: A robust tracking and targeting system forms an integral part of laser integrated anti-drone system, allowing operators to accurately track the movement of hostile drones and maintain a precise lock on the target throughout engagement. This system utilizes advanced algorithms and predictive modeling to compensate for factors such as target motion, atmospheric conditions, and platform dynamics, ensuring optimal laser beam placement for effective engagement. In [33], Steinvall explored the impact of atmospheric conditions and beam jitter resulting from tracking and platform pointing errors on the effectiveness of the laser, whether employed as a sensor, countermeasure, or weapon.

Control Unit: Laser integrated anti-drone system features a user-friendly control unit that enables operators to monitor system status, analyze threat data, and execute engagement protocols with ease. The unit provides real-time feedback on target tracking, laser engagement, and system performance, allowing operators to make informed decisions and adjust tactics as necessary. In [8], Chen et al. presented the design, simulation, control scheme, and implementation of a capture mechanism. A high-power laser is chosen to control the motor motion, ensuring synchronous operation of the surrounding six launch mechanisms. Abunada et al. [3] have proposed a study aimed at devising a systematic design for a drone detection mechanism utilizing the RF control signal exchanged between the drone and its remote controller. The proposed system entails the generation of a high-power jamming signal transmitted over the identical carrier frequency and band of the detected drone. This jamming signal is then directed toward the drone's location with the intent of disconnecting it from its controller, thereby facilitating a safe landing or activating a mechanism to prompt its return to home. However To destroy the illegal drones, Shi et al. [29] conducted a comprehensive review of the technologies employed in drone surveillance as well as the current anti-drone systems.

Communication system: The communication system facilitates real-time data exchange and coordination between different subsystems of the laser integrated anti-drone system, including sensors, tracking systems, laser emitters, command centers, and operator interfaces. This enables synchronized operation and response to detected threats. Laser beam steering plays a critical role in a wide array of applications, including military targeting and surveillance, space communication, optical data storage, and diverse medical procedures. In [6], Chaudhay et al. provided an extensive literature review on the multifaceted aspects of laser beam pointing and stabilization through the utilization of a fast steering mirror.

In the previous research work, very few authors developed the mathematical model of an anti-drone system. Among them, Garcia et al. [12] studied a simulation model for visual based anti-drone system to detect a UAV. The network's accuracy is 93.40% and it has successfully detected the UAVs. In [39], Zheng et al. developed a simulation model to find the accuracy of visual detection anti-drone system. Chen et al. [9] studied a dynamical modelling and simulation for a capture technology based anti-drone system. To get a brief idea about the comparison of our work with some existing works, Table 1 is provided.

In the literature, no work has been recorded for the reliability analysis of an anti-drone laser system. This motivates us to study the reliability analysis of an anti-drone laser system. The proposed work is the first one to analyse the reliability of an anti-drone laser system. To assess the reliability of an anti-drone laser system, a stochastic model has been constructed. For the model analysis, the reliability block diagram (RBD) is proposed. In [11], Fesenko et al. presented an RBD model to find the reliability of drone systems. The analytical results of reliability are verified using the simulation approach.

Significant research has been dedicated to assessing the reliability of diverse communication systems, including drones and high-altitude platforms. Vishnevsky et al. [35] provided a comprehensive overview of recent advancements in k-out-of-n system theory, particularly applicable to reliability evaluations of high-altitude unmanned platforms. Similarly, Selvamuthu et al. ([27] developed a Markov model to analyze tether reliability in high-altitude platforms. Chen et al. [7] focused on reliability modeling of the NASA Remote Exploration and Experimentation system, employing fault trees and stochastic reward nets. Vishnevsky et al. [34] examined the reliability of tethered high-altitude telecommunication platform modules using k-out-of-n:F models. Gautam and Dharmaraja [13] proposed hierarchical models for LTE-A networks, while the studies [26, 28] explored reliability in UMTS and VANET, respectively. However Feng et al. [10] discussed the optimization model to maximize the mission reliability by changing anti-drone number.

Table 1: *Comparisons with the related works*

Related works	Anti-Drone	Detection technology	Neutralization technology	Purpose	Mathematical Models
Korsoveczki et al. [14]	$\surd$	Radar	-	Detection in hovering and maneuvering circumstances	Simulation
Multerer et al. [20]	$\surd$	Radar	Jamming	Detect and jamming the signal	-
[15]	$\surd$	-	Laser	In long rang confirmatory destruction	-
Pisa et al. [22]	$\surd$	Radar	-	Evaluation of mono-static Radar cross section	Simulation
Shin et al. [30]	$\surd$	Position tracking	-	To detect and track drones	Simulation
Zhou et al. [40]	$\surd$	Fast steering mirror	Laser	To detect and track drones	Simulation
Mohamed and Somaya[5]	$\surd$	optical focusing system	Laser	To detect and destroy the rogue drones	Simulation
Steinvall [31]	$\surd$	Video Sensor	Laser	To detect and destroy drones	-

1.2. Contribution

Our study encompasses three primary objectives.

1. Firstly, we aim to delve into the internal reliability of anti-drone Laser systems through a comprehensive component-wise analysis. This involves a meticulous examination of each component to identify and assess its reliability. By doing so, we strive to enhance the overall performance and effectiveness of the anti-drone laser system.

2. Secondly, we endeavor to identify the critical components within the anti-drone Laser system. This will be achieved by utilizing statistical distributions for reliability analysis. Understanding the reliability of these critical components is paramount as it enables us to prioritize maintenance efforts and ensure uninterrupted operation of the system.

3. Lastly, we seek to determine the optimal number of lasers required in the anti-drone Laser system and analyze the contributing factors influencing this decision. By leveraging statistical analysis and considering various operational scenarios, we aim to optimize the system configuration to achieve maximum efficiency and effectiveness in neutralizing unauthorized drones.

This work is arranged into five sections. In Section 2, a model for the calculation of reliability has been introduced. Section 3 describes the reliability analysis of the laser source subsystem with the numerical illustration. Further, by considering environmental factors, the energy values and probability of hitting of the laser anti-drone system are obtained in Section 4. Finally, the underlying model is concluded with insight for future works in Section 5.

2. RELIABILITY BLOCK DIAGRAMS

RBDs depict system reliability by illustrating the interconnection of components and their potential failure modes. In constructing RBDs, three fundamental patterns of component connections are employed: (i) Series connection, where components are arranged linearly, rendering the system susceptible to failure if any component fails; (ii) Active Redundancy, involving the simultaneous activation of identical components to ensure system functionality despite failures; and (iii) Standby Redundancy, exemplified by the k-out-of-n configuration, where only a subset of components is active, with others serving as backups, ready to be deployed if necessary. These methods offer diverse approaches to enhancing system reliability and resilience within the framework of RBD analysis.

2.1. Components of an Anti-Drone Laser System

1. **Power Supply:** Provides electrical power to the entire anti-drone system, ensuring continuous and stable power for all the components.
2. **Detection System:** Utilizes sensors technology and triggering mechanism to detect the presence of drones.
3. **Tracking System:** Tracks the movements of detected drones and provides precise targeting information to the laser anti-drone system.
4. **Laser System:** Emits a laser beam to disable and neutralize the targeted drone. Combination of laser diode, focusing lenses, adjustable lenses and, water cooling system.
5. **Control Unit:** Manages and coordinates the overall operation of the anti-drone laser system. Controls the activation and deactivation of the anti-drone laser system based on tracking information.
6. **Communication System:** Facilitates communication between the anti-drone laser system and external command/control centers. Enables the system to receive commands and transmit status updates.
7. **Environment:** Environmental factors significantly impact the performance and reliability of the anti-drone laser system. Variables such as temperature, humidity, wind, and visibility can influence the effectiveness of the laser beam in neutralizing drones.

In Figure 2, all seven components are arranged in series, implying that if one component fails, the failure will cascade throughout the entire mission, ultimately leading to mission failure. Our focus will be on addressing the two most critical components: the laser system and the environment. For simplicity, we assume a reliability value of 1 for all other components, emphasizing the critical importance of addressing issues related to the laser system and environmental factors.

2.2. Components of a Laser System

1. **DC-DC Step Down Converter Voltage Regulator:** Regulates the voltage supplied to the laser diode for optimal performance. This device converts one DC voltage level to another. In the case of a step-down converter, it reduces the input DC voltage level to a lower output DC voltage level. This conversion process is achieved through electronic components such as transistors, diodes, and capacitors.
2. **Laser Diode:** Emits the laser beam for targeting and disabling drones.
3. **Focusing Lenses and Adjustable Lenses:** Focusing Lenses concentrate the laser beam for precise targeting. Adjustable Lenses fine-tune the focus and direction of the laser beam.
4. **Water Cooling System:** Prevents overheating of the laser diode during prolonged use.

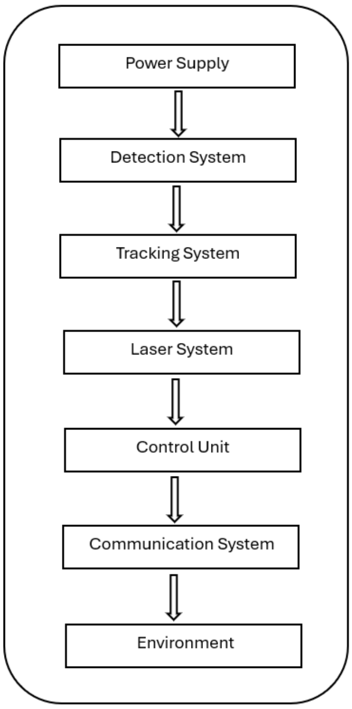

Figure 2: *Block Diagram of Anti-Drone Laser System*

In Figure 3, all components are indeed interconnected in series, with the exception of both lenses, as they constitute integral parts of a single component to adjust and focus the laser beam.

3. RELIABILITY ANALYSIS OF LASER SOURCE SUBSYSTEM

3.1. Assumption

1. We assume the reliability of power supply, detection system, tracking, control unit, communication unit to be 1 that is, they are completely reliable.
2. Under the laser system inside the anti drone system, we specifically consider the most critical subsystem which is the laser source subsystem.
3. The other subsystems- focusing lenses, cooling system and voltage regulator are expected to withstand for longer intervals.

3.2. Reliability Analysis

In this section, the reliability analysis of the laser source subsystem will be performed using different distributions.

3.2.1 Weibull Distribution

To create a mathematical model for reliability analysis of the laser source, we'll consider the failure behavior of the laser source over time. Since failure rates may vary over time and the failure behavior of electronic components often follows the bathtub curve (initial high failure rate, followed by a period of low failure rate, and then an increase in failure rate over time), the Weibull distribution is used for reliability modeling.

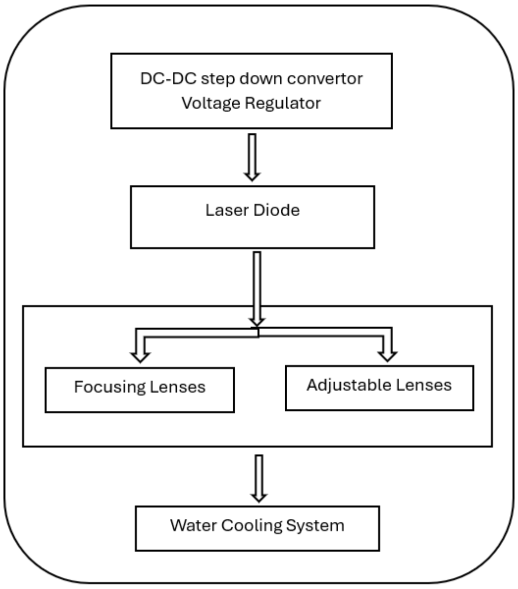

Figure 3: *Block Diagram of Laser System*

1. **Mathematical model**

   The Weibull distribution has the probability density function (PDF) given by:

   $$f(t) = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} e^{-(t/\lambda)^k},\ t \geq 0$$

   where:

   - t is the time variable.
   - k is the shape parameter (reflects the failure behavior: $k < 1$ for decreasing failure rate, $k = 1$ for constant failure rate, $k > 1$ for increasing failure rate).
   - λ is the scale parameter (reflects the characteristic life or scale of the distribution).

   The reliability function $R(t)$, which represents the probability that the laser source will function without failure up to time t, is the complement of the cumulative distribution function (CDF) of the Weibull distribution:

   $$R(t) = 1 - F(t)$$

   where the CDF $F(t)$ is given by:

   $$F(t) = 1 - e^{-(t/\lambda)^k}.$$

   The reliability function $R(t)$ for the Weibull distribution is given by [4]:

   $$R(t) = e^{-\left(\frac{t}{\lambda}\right)^k}.$$

2. **Analysis:**

   (a) **Scale Parameter (λ) Estimation:** The estimated scale parameter λ represents the characteristic life of the laser source. The range of mean time to failure (MTTF) [25]values have been taken and corresponding lambda values as listed in table 1 have been calculated using the stated equation

   $$MTTF = \lambda\Gamma\left(1 + \frac{1}{k}\right). \tag{1}$$

Table 2: *MTTF for Different Values of λ and k*

MTTF	λ $(k = 0.8)$	λ $(k = 1)$	λ $(k = 1.2)$
500	442	500	532
1500	1327	1500	1595
2500	2212	2500	2658
3500	3097	3500	3721
4500	3982	4500	4784

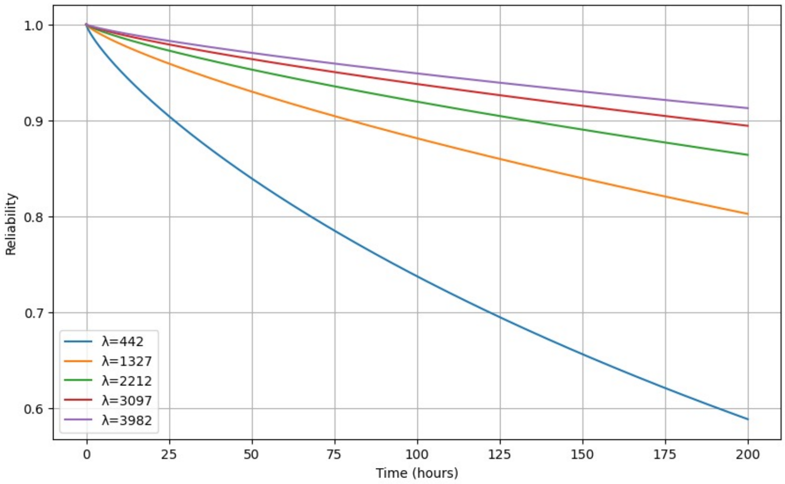

Figure 4: *Reliability of laser subsystem for Weibull distribution* $(k = 0.8)$

(b) **Shape Parameter (k) Estimation:** The estimated shape parameter k reflects the failure behavior of the laser source.

- A shape parameter $k < 1$ suggests that the laser source is prone to early-life failures. This means the failure rate decreases over time, indicating a "burn-in" period where defective units fail early.
- If $k = 1$, it indicates that the failure rate is constant over time, implying a constant hazard rate or "random failures" occurring independent of time.
- When $k > 1$, it suggests that the laser source experiences wear-out failures, where the failure rate increases over time due to aging or degradation of components. This is the most relevant case for the laser source subsystem as more failures are observed in later stages.

In Table 2 values of λ have been calculated for listed MTTF values and assumed k values. The corresponding λ values for $k = 0.8$ have been then used to plot the reliability time graph (Figure 4) for the first 200 working hours of laser subsystem assumed to follow a Weibull distribution. Figure 5 represents the reliability time plots for $k = 1$ that is constant failure rates and λ values as calculated in Table 2 for $k = 1$. Figure 6 shows the reliability time plots for $k = 1.2$ and corresponding λ values as obtained from Table 2. The $k = 1.2$ that is the increasing failure rate case is the relevant case for laser subsystem. For the laser subsystem with MTTF values above 2500 hours the reliability is greater than 0.95 for the observed period of 200 hours.

CDF $F(t)$ when we have n number of lasers in the system is given by:

$$F(t) = \left(1 - e^{-(t/\lambda)^k}\right)^n.$$

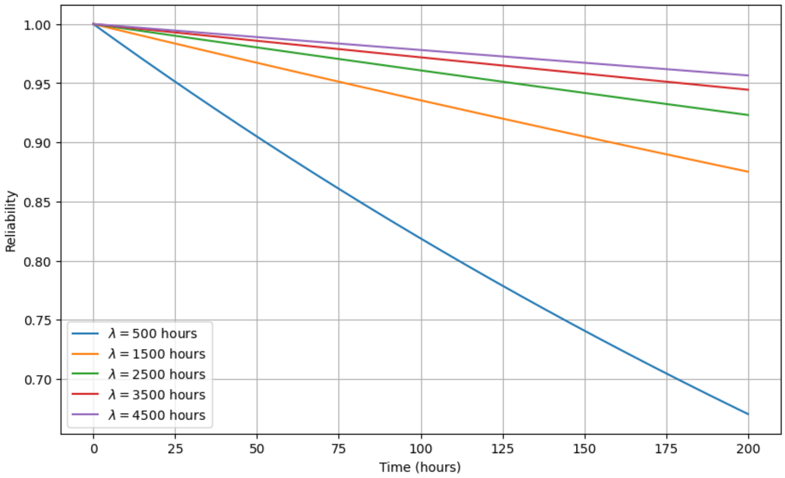

Figure 5: *Reliability of laser subsystem for Weibull distribution ($k = 1$)*

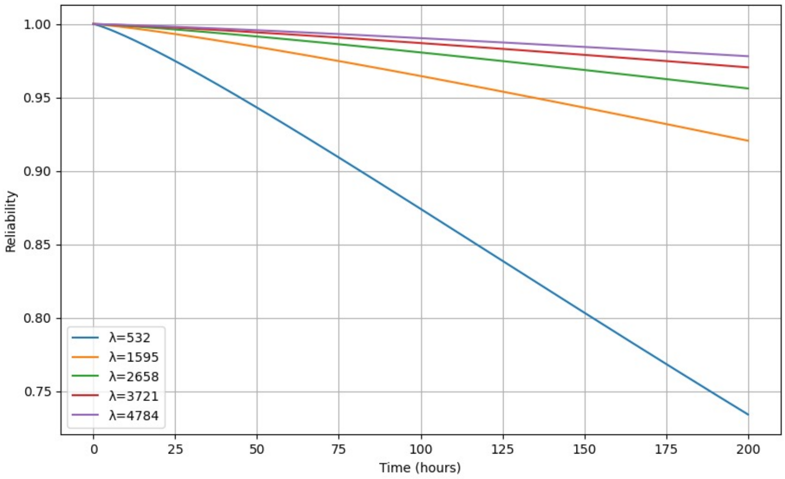

Figure 6: *Reliability of laser subsystem for Weibull distribution ($k = 1.2$)*

The reliability function $R(t)$ for the Weibull distribution is given by:

$$R(t) = 1 - \left(1 - e^{-(t/\lambda)^k}\right)^n .$$

Figure 7 represents the reliability time plots for system with number of lasers $= 2, 4, 6$ and 8. The failure rate of each of these lasers is assumed to follow the Weibull distribution ($k = 1.2$) with mean time to failure taken as 4000 hours.

3.2.2 Rayleigh Distribution

The Rayleigh distribution is often used to model the time-to-failure of systems where failure events are influenced by the accumulation of random factors. It can model a wide range of failure patterns, from early-life failures to wear-out failures.

1. **Mathematical Model**
   Notations:
   - T: Time-to-failure of the laser source subsystem, which follows a Rayleigh distribution.
   - σ: Scale parameter of the Rayleigh distribution, representing the characteristic life of the laser source subsystem.

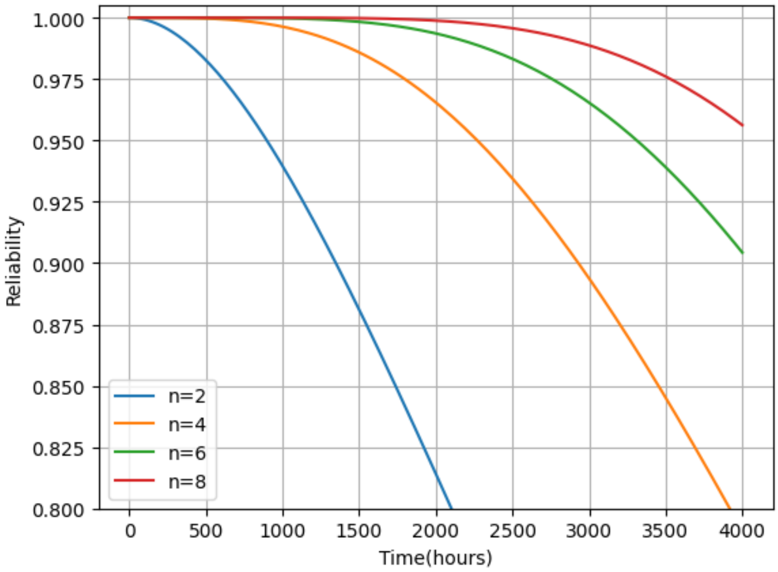

Figure 7: *Reliability of laser subsystem (Weibull distribution) for different number of lasers*

PDF

$$f(t;\sigma) = \frac{t}{\sigma^2} e^{-\frac{t^2}{2\sigma^2}}, \; t \geq 0.$$

Reliability Function

$$R(t;\sigma) = 1 - F(t;\sigma)$$

where CDF $F(t;\sigma)$ is given by:

$$F(t;\sigma) = 1 - e^{-\frac{t^2}{2\sigma^2}}.$$

2. **Analysis**

A larger value of σ indicates a longer characteristic life of the laser source subsystem, while a smaller value suggests a shorter characteristic life. In Table 3 corresponding σ values are calculated for the MTTF values. Figure 8 represents reliability time plots for these σ values obtained.

Table 3: *MTTF vs σ*

MTTF	σ
500	399
1500	1197
2500	1995
3500	2793
4500	3591

CDF $F(t)$ when we have n number of lasers in the system is given by:

$$F(t;\sigma) = \left(1 - e^{-\frac{t^2}{2\sigma^2}}\right)^n.$$

The reliability function $R(t)$ for the rayleigh distribution is given by:

$$R(t) = 1 - \left(1 - e^{-\frac{t^2}{2\sigma^2}}\right)^n.$$

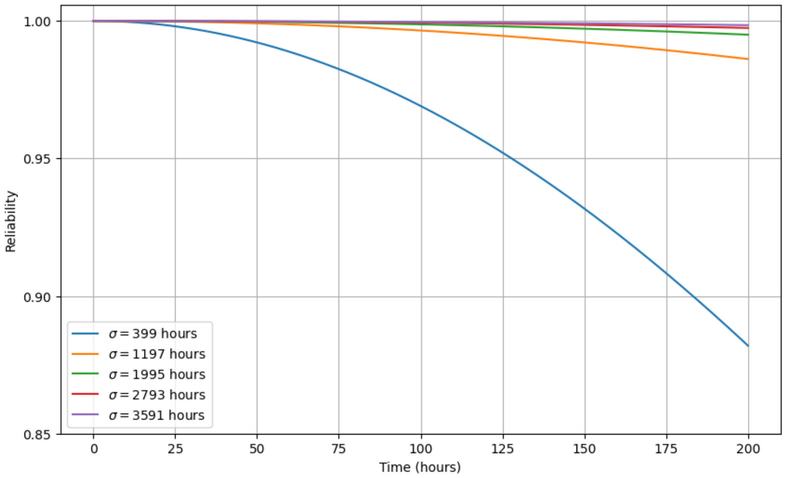

Figure 8: *Reliability of laser subsystem for Rayleigh distribution*

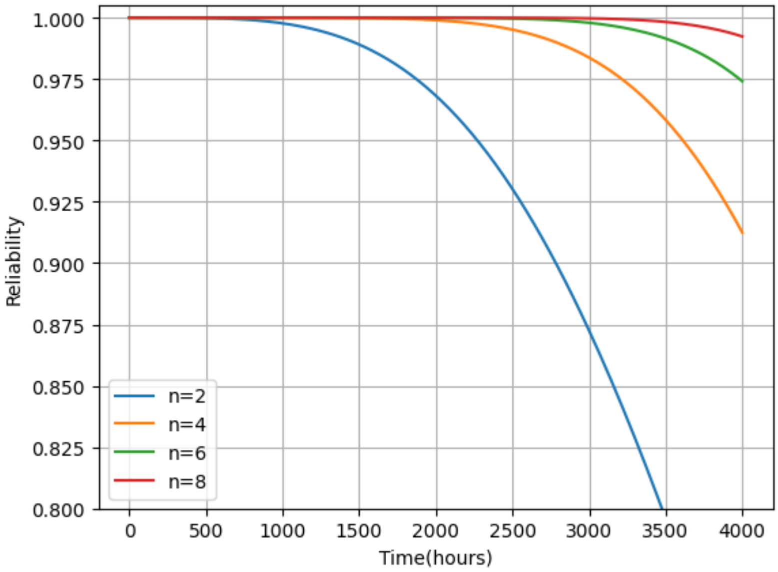

Figure 9: *Reliability of laser subsystem (Rayleigh distribution) for different number of lasers*

Figure 9 represents the reliability time plots for system with number of lasers= 2,4,6 and 8. The failure rate of each of these lasers is assumed to follow rayleigh distribution with mean time to failure taken as 4000 hours.

3.2.3 Exponential Distribution

The exponential distribution is commonly used to model the time between events in a Poisson process, where events occur continuously and independently at a constant average rate [4]. It is characterized by a single parameter, the failure rate λ.

1. **Mathematical Model**
   Notations:
   - T: Time-to-failure of the laser source subsystem, which follows an exponential distribution.
   - λ: Failure rate of the exponential distribution, representing the average number of failures per unit time.

The PDF is given as follows

$$f(t;\lambda) = \lambda e^{-\lambda t},\ t \geq 0.$$

The Reliability function is given as follows.

$$R(t;\lambda) = e^{-\lambda t}.$$

2. **Analysis**

The MTTF for an exponential distribution is the reciprocal of the failure rate λ, given by:

$$\text{MTTF} = \frac{1}{\lambda}.$$

Table 4: *MTTF for Different Values of λ*

MTTF	λ
500	0.00200
1500	0.00067
2500	0.00040
3500	0.00029
4500	0.00022

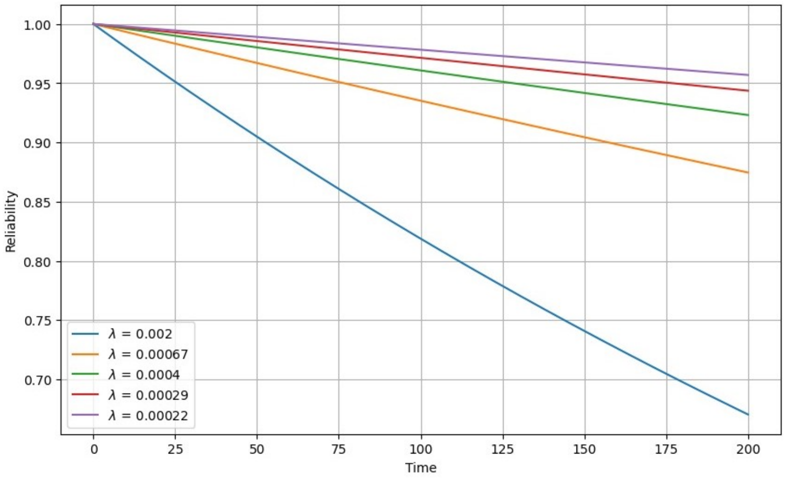

Figure 10: *Reliability of laser subsystem for Exponential distribution*

Once λ is estimated, it can be interpreted in the context of the laser source subsystem's reliability. A larger value of λ indicates a higher failure rate, meaning shorter time-to-failure, while a smaller value suggests a lower failure rate and longer time-to-failure. The Table 4 maps the corresponding λ values according to the MTTF values obtained using the MTTF formula. Figure 10 represents the plots of laser subsystems with obtained λ values assumed to follow exponential distribution.

CDF $F(t)$ when we have n number of lasers in the system is given by:

$$F(t) = (1 - e^{-\lambda t})^n.$$

The reliability function $R(t)$ for the exponential distribution is given by:

$$R(t) = 1 - (1 - e^{-\lambda t})^n.$$

Figure 11 represents the reliability time plots for system with number of lasers= 2,4,6 and 8. The failure rate of each of these lasers is assumed to follow exponential distribution with mean time to failure taken as 4000 hours.

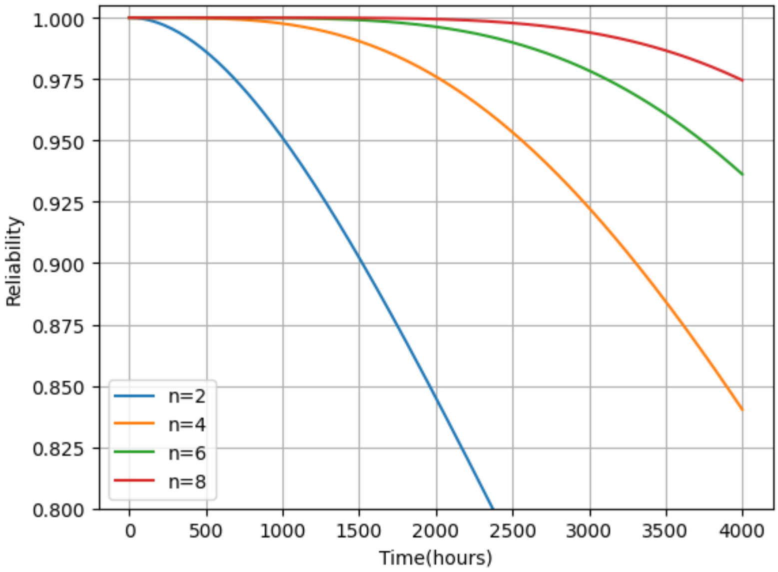

Figure 11: *Reliability of laser subsystem (Exponential distribution) for different number of lasers*

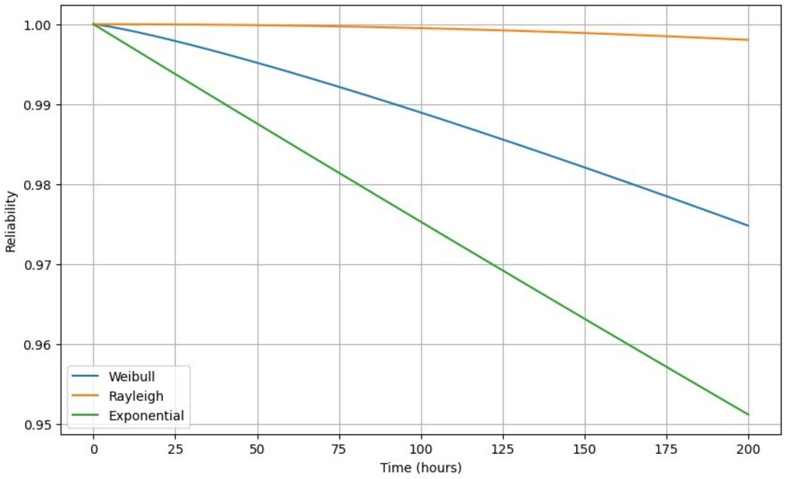

Figure 12: *Reliability comparison for different distributions (MTTF = 4000 hours)*

Figure 12 represents the reliability time curves assuming the laser subsystem follows the three distributions: Weibull ($k = 1.2$), Rayleigh and exponential with MTTF of 4000 hours. This depicts the reliability values comparison over time with Rayleigh distribution depicting the highest reliability.

Figure 13 represents the reliability time curves assuming the laser subsystem follows the three distributions: Weibull ($k = 1.2$), Rayleigh and exponential with MTTF of 4000 hours for six number of lasers. This depicts the reliability values comparison over time with Rayleigh distribution depicting the highest reliability. The reliability is better than 0.995 (the desirable range) for the first 2000 hours of operation for all three distributions for $n = 6$.

4. ENVIRONMENTAL FACTORS

The effectiveness of laser-based anti-drone systems is significantly influenced by environmental conditions encountered during operation. Environmental factors such as wind, fog, snow, and atmospheric turbulence vary spatially and temporally, posing challenges to the performance and

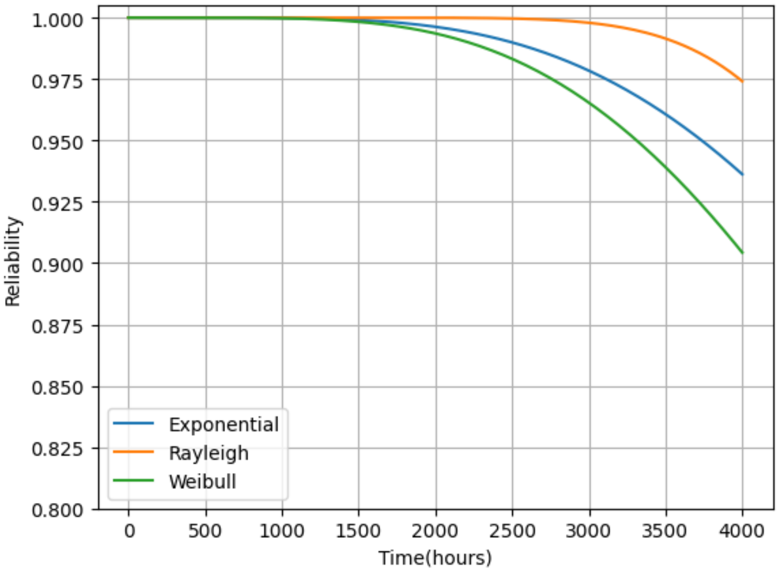

Figure 13: *Reliability comparison for different distributions (MTTF = 4000 hours, n=6)*

accuracy of the system. These conditions directly impact parameters crucial for laser propagation, such as diffraction and turbulence, ultimately affecting the beam quality (effectiveness in damaging drones) and targeting precision of the anti-drone system.

Contributing factors: The propagation of laser beams in the atmosphere is subject to the effects of diffraction and turbulence, which can significantly impact their trajectory and intensity. These effects can be quantified using mathematical formulations that consider various environmental parameters.

The spreading angle of laser beam due to diffraction and beam quality ($\theta_{\text{diff\&qual}}$) are determined by the wavelength of the laser beam (λ), the diameter of its emitting aperture (D), and beam quality factor (M^2):

$$\theta_{\text{diff\&qual}} = M^2 \frac{C\lambda}{D} \tag{2}$$

where, C is a constant, usually set to be 1.22.

The spreading angle resulting from atmospheric turbulence (θ_{turb}) is calculated based on the Fried parameter (r_0), which is influenced by the wavelength (λ), path length of laser beam (target distance, L) and the refractive index structure constant (C_n^2):

$$\theta_{\text{turb}} = \frac{1.6\lambda}{\pi r_0} \tag{3}$$

where,

$$r_0 = 0.184 \left(\frac{\lambda^2}{C_n^2 L} \right)^{3/5}. \tag{4}$$

The dependency of these parameters on environmental conditions such as humidity and temperature is crucial for understanding their impact on laser beam propagation. Specifically, the refractive index structure constant (C_n^2) is essential for characterizing atmospheric turbulence and is influenced by the potential refractive index gradient, denoted by M:

$$C_n^2 = a^2 A L_0^{\frac{4}{3}} M^2 \tag{5}$$

where a^2 is a dimensionless constant, most commonly used at a value of 2.8, equal to unity. L_0 is the outer scale of turbulence, which can be set equal to the resolution of the radiosonde data (e.g., 10 m).

$$M = -\frac{77.6 \times 10^{-6}}{T} \cdot p \cdot \frac{\partial \ln \theta}{\partial z} \cdot \left[1 + \frac{15500 \cdot q}{T} - \frac{15500}{2 \cdot T} \cdot \frac{\left(\frac{dq}{dz}\right)}{\left(\frac{\partial \ln \theta}{\partial z}\right)} \right]$$

where p is average pressure for a layer. ∂z is thickness of layer. T is absolute average temperature. θ is potential temperature. q is specific humidity.

We can vary the refractive index structure constant (C_n^2) with time (i.e., changing temperature, pressure, and humidity with time). To obtain an overall measure of the spreading angle (θ_{total}) of the laser beam considering both diffraction and turbulence effects, we can compute the root mean square (RMS) of the individual spreading angles:

$$\theta_{\text{total}} = \sqrt{\theta_{\text{diff}}^2 + \theta_{\text{turb}}^2}. \tag{6}$$

In the context of our mission, the success criterion is met when the energy per unit area reaching the target drone surpasses a predefined threshold energy value. This threshold energy level, denoted as e_{th}, represents the minimum energy required to effectively neutralize the drone. Upon meeting this condition, the drone is effectively destroyed.

To quantify this condition, we employ the concept of the brightness (B) of our laser weapon system. This brightness must exceed the ratio of the square of the target distance (L^2) to the threshold energy (e_{th}) multiplied by the dwell time of the laser beam (τ).

Mathematically, this relationship is represented as:

$$B = \frac{P_0 \cdot (1-\alpha)^L}{\pi \theta_{\text{total}}^2} > \frac{L^2 \cdot e_{\text{th}}}{\tau}. \tag{7}$$

Here, P_0 denotes the total output beam power, α represents the atmospheric attenuation ratio of the laser beam, L signifies the target distance measured in kilometers, θ represents the root mean square of both the diffraction and quality of the laser beam, as well as the atmospheric turbulence, and τ denotes the dwell time of the laser beam irradiated on the target.

$$\text{Energy\_on\_target} = \frac{P_0 \cdot \tau \cdot (1 - e^{-\eta \cdot L})^L}{\pi \cdot \theta_{\text{total}}^2 \cdot L^2}. \tag{8}$$

We are utilizing the fixed laser system with the following parameter values and is shown is Table 5.

Table 5: *Parameters Values*

Parameters	Values
Beam quality (M)	1.5
Power Output	150KW
Aperture Diameter	50cm
Wavelength	1.045 micro-meter
Target Range	17km
Alpha	0.2
Threshold energy	50KJ

By assuming the parameter values mentioned in Table 5, we have obtained the energy values and probability of hitting which is mentioned in Table 6.

$$\text{Probability of hitting} = 1 - e^{-\frac{\text{Energy\_on\_target}}{e_{\text{th}}}}. \tag{9}$$

From Figure 14, it is noticed that as the turbulence increases the reliability of the system decreases. This depicts that environmental turbulence can affects the system reliability. This is happen because higher levels of turbulence may introduce more variability or unpredictability into the system, leading to disruptions or failures. For instance, increased turbulence might cause misalignment or disturbances in the laser beam, impacting its effectiveness or stability.

Therefore, the relationship depicted in Figure 14 suggests that environmental turbulence has a significant impact on the reliability of the system. This underscores the importance of considering environmental factors when designing or operating the system to ensure its consistent and dependable performance.

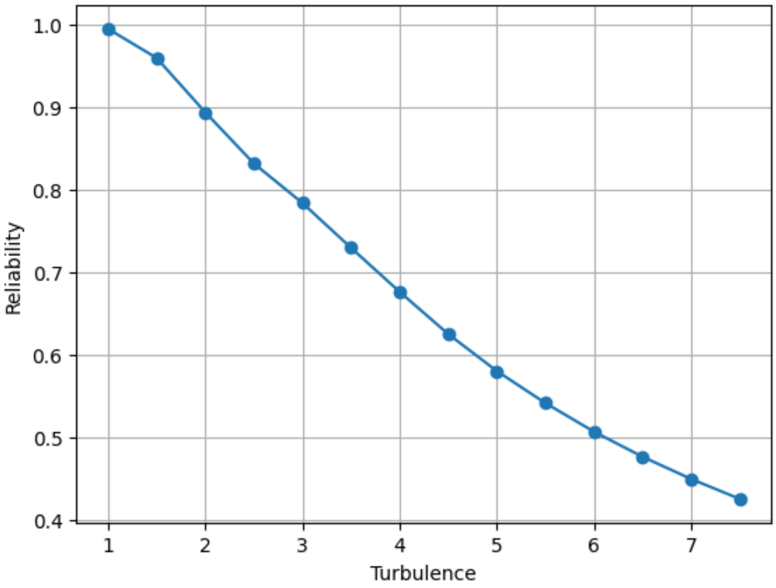

Figure 14: *Reliability values at different turbulence levels*

Table 6: *Energy Values and Probability of Hitting*

Turbulence (in $10^{-14}\,\mathbf{m}^{-\frac{2}{3}}$)	Energy (KJ)	Probability of hitting
1	257.1968	0.9946
1.5	158.66	0.9593
2	112.53	0.8937
2.5	86	0.8317
3	69.28	0.7838
3.5	57	0.7296
4	49.09	0.6763
4.5	42	0.6252
5	37.57	0.5804
5.5	33.51	0.5416
6	30.1995	0.5070
6.5	27.43	0.4766
7	25.1039	0.4497
7.5	23.11	0.4256

5. CONCLUSIONS AND FUTURE DIRECTION

The proposed study present reliability analysis of laser subsystem in anti-drone system using RBD methodology. To represent the failure behaviour of the reliability blocks, Weibull and Rayleigh distribution have been used. Numerical results are presented to demonstrate the behaviour of reliability of the system with respect to several parameters of the system. Further, the study focus on investigating and modeling the environmental factors that impact the reliability of anti-drone laser systems. Factors such as temperature, humidity, wind, and visibility can significantly affect the system's performance. By gaining a comprehensive understanding of these environmental variables, we obtain the energy values and probability of hitting of the anti-drone laser system to effectively mitigate environmental challenges.

The parameters involved in the reliability analysis of the anti-drone system will be estimated in future work. Furthermore, various stochastic models, such as Markov model, semi-Markov model, etc., will be constructed to evaluate the reliability of the anti-drone system. To verify the validity of the obtained results, simulation analysis will be conducted.

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