

ASSESSING FIDELITY OF LIDARLITE IN FIRE AND SMOKE ENVIRONMENT

Muhammad Shaheer¹, Muhammad Inaam ur Rehman², Talha Riaz³,
Muhammad Ehsan Siddiqi⁴, Minahil Fatima⁵

^{1,2,3}Hamdard University, Islamabad, Pakistan

⁴Director Research and Development, U Tech Innovative Solutions and Consultancy Limited

⁵FAST National University, Islamabad, Pakistan

³talha.riaz@hamdard.edu.pk

DOI: <https://doi.org/10.5281/zenodo.18321981>

Keywords

Firefighting safety, smoke environment, LIDAR sensor, ultrasonic sensor, range finding, obstacle detection.

Article History

Received: 18 November 2025

Accepted: 05 January 2026

Published: 20 January 2026

Copyright @Author

Corresponding Author: *

Talha Riaz

Abstract

Firefighting is a dangerous job that causes many injuries and deaths. Firefighters' safety is crucial for efficient rescue efforts. Heavy smoke environment causes lack of clearance which makes the operation more difficult which leads to death or injuries. To combat these issues, different sensors are used such as range finding sensors can detect the obstacles which can make the operation easier and successful. These sensors can also put on firefighting assisting robots and sometimes on firefighters. Ultrasonic sensor or LIDAR is such sensor, widely used for range finding and obstacle detection. Research shows that sensors like LIDAR are not fully effective in fire and smoke environment. In this paper, the goal is to check the ability of ultrasonic distance sensors and how they accomplish relevant operations in the blurry environment of fire and smoke.

INTRODUCTION

To help firemen or firefighting robots navigate through buildings and detect walls or other obstacles, a variety of rangefinder technologies are there in the market. These devices help for separations between different objects in their field of vision. Such as a single distance measurement, a plane of distance data, or even a whole distance map could be returned, it depends on specific equipment's. By detecting obvious routes for movement, range finders can provide efficient

navigation when we use right algorithms. Under normal temperature and visibility circumstances, many range finding sensors and cameras function well. However, but nothing is known about how well rangefinders work in situations involving intense heat or smoke which are normal and usually happens in fire situations. It is very important to assess how perfect these technologies work in hot smoke-filled conditions in order to enhance both

human and robotic navigation during such circumstances.

Rangefinder systems work by radiation or energy use from the electro- magnetic or acoustic spectrum. Figure 1 shows the specific common devices that determine the corresponding working waves. For example, Lidar, radar, sonar and more among the most used flight times. These devices send signals by calculating required time then return a reflected signal that corresponds directly to the distance from the target. Because the light moves very fast, Lidar generates many detection points. This gives detailed explanations of two dimensions and three-dimension multimedia cards [7]. Other options are visible light, night vision that detects and captures light in the right spectrum, and thermal creation devices. To calculate distance, these sensors are expanded in stereoscopic order using two or more rooms, and use non-compliance measurements between images to get the location of objects within the representation. Through this method we can also create a 3D model of the scene [8], but it is less speed and accuracy compared to LIDAR. A third type of sensor, like Kinect, projects a model of structured light onto the surface, as usually used in games. Another sensor then records a transformation of this model and the system deals with these differences and evaluates the location of objects within the observed space.

This type of technology is often difficult to interpret the law of light in the presence of sunlight [9], meaning that the radiation emitted by a fire can interfere with its performance during fire extinction. Studies have shown that electromagnetic radiation of various wavelengths can enter smoke to varying degrees [10]. For hydrocarbon smoke, the results generally show that the extinction coefficient decreases as the wavelength increases, passing from the spectrum

seen in the infrared region of light. This trend assumes that sensors operating at longer wavelengths, such as radars operating in the millimeter range, are reflected to exceed those operating at shorter waves on micrometer beaches. However, only a limited number of studies have specifically confirmed these trends for determining the scope. Under dense smoke conditions, one of the most commonly used navigation tools for navigation is LIDAR, which calculates the distance to an object as a function of the time required to return a laser pulse. Previous studies have studied the effects of fog on the Lynares system [11] and the potential use of LIDAR for use as a transmit misometer [3] or for the detection and placement of forest fires [4]. Small number of studies also concern how smoke affects rider productivity [5]. Subsequent studies validated the ability of one leaf and determined the distance of the corridor filled with fire smoke [12]. With a significantly broken visibility [6], multieucnea riders designed for difficult environments such as dusty storms fog and heavy precipitation, can obtain some yields of the released impulses, allowing object distances to be determined even in difficult scenarios. Although this technique demonstrates reliable results in a variety of visual environments, there is a little research into its use in fiery smoke, and no complete research is particularly relevant to multitatting under such conditions.

In this study, we first design an elaborate experimental setup to evaluate LIDAR in various scenarios. LIDAR is evaluated against flame without smoke, smoke without flame and flame with smoke. Fire and smoke interference is moved near or far from LIDAR to observe the change in measurement caused by interference. Performance and failure points are shown through

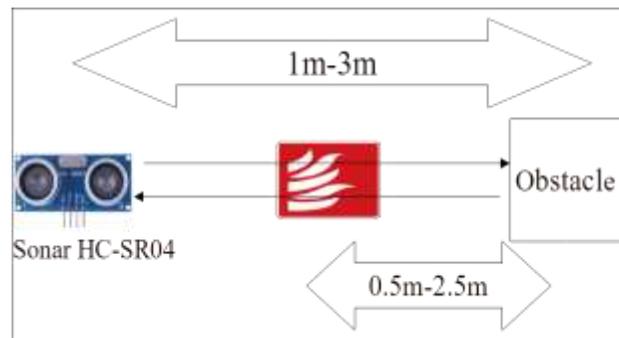


Figure 1: Illustration of experimental setup

experimental results. Empirical data is analyzed and advantages and disadvantages on LIDAR as potential rangefinder technology in fire and smoke environment is discussed.

Experimental Setup

Overview

Experimental setup consists of 3 parts. 1) *LIDAR*: it is a sensor being evaluated. 2) *Interference*: Interference is the disturbance that simulates conditions of structure fire. 3 types of interference are used in this setup; smokeless flame, flameless smoke and fire with smoke. 3) *Obstacle*: it is an immovable structure placed in the line of sight of the LIDAR. LIDAR can easily detect the obstacle under normal conditions. Initially, LIDAR is placed at 1m from the obstacle without any interference. Distance value is measured; we call it nominal value. After that, 3 types of interference are placed at 0.5m from the obstacle and value is recorded.

LIDAR is then moved to 1.5m from the obstacle and nominal value is recorded. Now, interference is placed at 0.5 m from the obstacle and after recording the value it is moved away from the obstacle towards LIDAR to 0.5m and new

LIDAR value is recorded. In every round of experiment LIDAR is moved away from the obstacle 0.5m and interference is placed between obstacle and LIDAR at every 0.5m interval one by one. This process is repeated until LIDAR reaches at 3m from the obstacle and at every step nominal and affected value is recorded. Figure 1 shows the illustration of experimental setup.

Hardware

LIDAR is attached with Arduino Mega2560, a microcontroller board which captures the data. It has 54 digital input/output pins (15 of which can function as PWM outputs) and 16 analog inputs and 4 UARTs (hardware serial ports) in addition to a 16 MHz crystal oscillator, a connection of USB and power jack, an ICSP header and a reset button. Hardware for the experiment is shown in figure 2.

Interference

There are three types of interference used in the experiment. All types are discussed in the following:

Smokeless Flame: 2-Propanol

Propanol is a flammable liquid that can be used to create a smokeless flame in a fire pit. It is a fuel that burns with minimal or almost invisible,



Figure 2: Assembling the Hardware System.

smoke as shown in Figure 3. A smokeless flame from 2-propanol (isopropyl alcohol) typically reaches a temperature around 800°C. This flames spikes the temperature of its surrounding air.

Flameless Smoke: Smoke Pellets

Smoke pellets as shown in figure 4a, can emit smoke without any burning. This interference

mimics the conditions found in hallways after structural fires, as smoke builds up and vision drastically deteriorates. Smoke pellet used in this experiment emits approximately 7m³ in the duration of 30 seconds. One smoke plume has an average diameter of 10 cm as shown in figure



Figure 3: Smokeless burning of 2-Propanol.



Figure 4: (a): Smoke pellet (b): The effect of burning flameless smoke pellet.

4b. 3 densities (low, medium and high) of smoke is used as interference. The temperature of the smoke at the detection level is 40°.

Flame with Smoke

Two different kinds of flame with smoke interference are used in this experiment. 1) For high

temperature flame and black smoke we use kerosene as fuel as shown in figure 5a. Black smoke is produced when kerosene burns at a high temperature of roughly degrees 700°. 2) For flame with white smoke, we burn smoke pellets with 2-Propanol illustrated in figure 5b.



Figure 5: (a): The black smoke of burning kerosene (Dark fumes) (b): Burning 2-Propanol and smoke.

smoke density measurement setup

Smoke can be quantified by measuring its transmittance [19].The sale of smoke (τ) is described as the share of the intensity of light detected after the smoke intensity (i) has measured to the intensity of light, and is condition of transparency (τ). This got affected by three main variables. First is the density of the smoke mass (DM), the length of the light path (L), and the photoextinction coefficient (S). Equation (1) illustrates this relationship, which is described by the Bouguer-Lambert-Beer law. (1).

$$\tau = \frac{I}{I_0} = e^{-\sigma sml}$$

As shown in Figure 6 we designed a smoke measuring setup for this experiment that includes

a photodiode, a 3.5mW laser and an 850nm wavelength. This smoke measuring setup works simply: the photodiode’s value is first measured with smoke blockage I and then without it I₀. The transmittance of the smoke plume is determined by the ratio of these two variables. Smoke of low, medium, and high intensity has a measured transmittance of 0. This indicates that a smoke plume, regardless of its density, is so dense that it is impossible to see through it.

Results and Discussion

In this section, results discussed use raw LIDAR values. This is done to show the actual performance of LIDAR without the use of any filter. In practice,

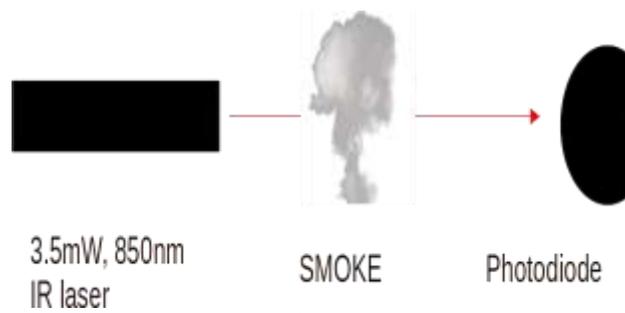


Figure 6: Setup for measuring smoke.

however, LIDAR values are filtered to remove any outliers which can further improve the performance of LIDAR in smoke filled environment. LIDAR is a noisy sensor by nature. Due to noise or stray reflections, LIDAR will nevertheless generate some outliers even under almost perfect circumstances. Simple filtering techniques can be used to combat this issue. To demonstrate the true performance of the LIDAR, we first display the findings without filtering. Next, we present the same results after applying basic filtering to the LIDAR readings. The time of flight (ToF) of the sound wave that the sensor emits at a specific frequency is the basis for LIDAR’s operation. The wave strikes the obstruction and bounces back to the sensor after passing through a medium, which in this case is air. The ToF of the sound wave is used to measure the distance from the obstruction.

LIDAR in the presence of Flameless Smoke

Flameless smoke is produced using a smoke pellet. This smoke does not significantly elevate the air temperature since there is no flame present. The temperature of the smoke along the line of sight (LoS) of LIDAR ranges from approximately 40° to 50°. LIDAR values are captured through the smoke at a location where the thickness of the smoke plume is greatest. Results indicate that flame-free smoke has a minimal impact on LIDAR values. Figure 7 illustrates how LIDAR is influenced when varying densities of smoke

are present. In this experiment, LIDAR is situated 1m from the obstacle, with smoke

interference introduced at a distance of 50cm between the LIDAR and the obstacle. In the first set of readings, one smoke pellet (light smoke) is utilized as interference. In the second set of readings, two smoke pellets (medium smoke) are employed. For the third reading, three smoke pellets (heavy smoke) are used. It is evident in Figure 7 that there is minimal difference between the nominal value and the values obtained with interference near the LIDAR. The smoke has very little effect on the readings.

The standard deviation can be calculated in order to see how much an

increasing density of smoke has on LIDAR. Figure 7 shows the standard deviation. It can be seen that even in the presence of heavy smoke there is

little deviation in the LIDAR value. The standard deviation is calculated as such

$$N \sigma = \sqrt{\sum (x_i - \mu)^2}$$

Here, σ is a standard deviation, N denotes the total number of readings, x_i indicates the i th value of LIDAR and μ signifies the average of all values. It is important to note that this reflects the standard deviation of unfiltered LIDAR values. The minor rise in standard deviation seen as smoke density grows, influenced by various factors, such as the minor increase in air temperature resulting from the combustion of the smoke pellet or the transition of medium from air to air plus soot. These elements require investigation in future research. Nonetheless, this minor rise in standard deviation is trivial and can be disregarded since, in practice, LIDAR values are

filtered and averaged, which further reduces the standard deviation.

As LIDAR is frequently utilized on various mobility platforms like UAVs, it is essential to thoroughly assess its performance in smoke-filled environments by examining how LIDAR values fluctuate with the distance from smoke interference. To achieve this, LIDAR is positioned 3m away from the obstacle, while high-density smoke is placed 2.5m from the obstacle 3 smoke pellets are used. This procedure is conducted to determine how LIDAR values will change when the obstacle, which is the target to be detected, is obscured by smoke or when a UAV equipped with LIDAR operates within the smoke plume. The findings of this experiment are presented in Figure

8. It is evident that LIDAR encounters minimal challenges in detecting the obstacle, regardless of the placement of smoke interference. The number of outliers increases as smoke approaches the LIDAR, but it remains

operational. To effectively illustrate this occurrence, the standard deviation is calculated and depicted in Figure 8. It is observable that there is a slight increase in the standard deviation as smoke interference shifts closer to the LIDAR. A similar effect is observed when the LIDAR is positioned 3m from the obstacle and the smoke interference is situated at 50cm and 2.5m from the obstacle, as indicated in Figure 9. The standard deviation for the LIDAR values located at 3 m exhibits the same pattern, revealing that the LIDAR values display a slightly greater deviation as smoke interference approaches the LIDAR.

LIDAR is an effective sensor in smoke filled environment. Simple filtering techniques can improve the results further as discussed in. Improved results after filtering can be seen in Figure. Standard deviation after filtering is also improved as shown in Figure 10.

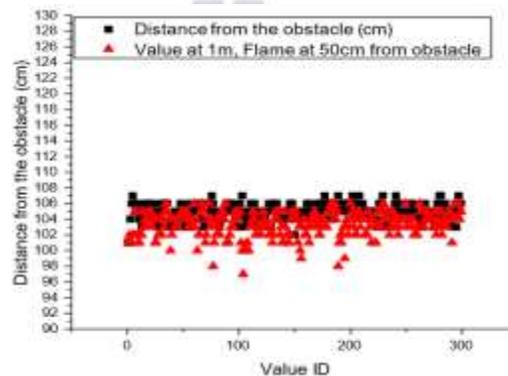


Figure 7: LIDAR Value at 1m, Flame at 50cm from obstacle

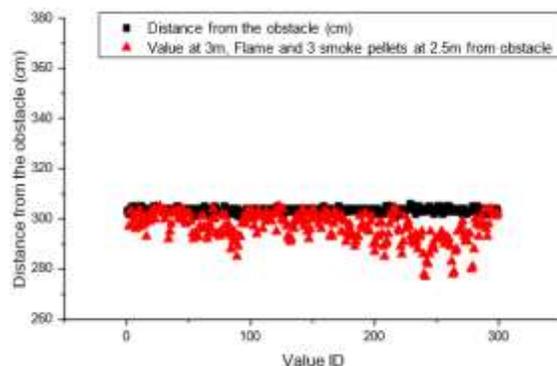


Figure 8: LIDAR Response at 3m with Smoke Interference at 2.5m from the Obstacle.

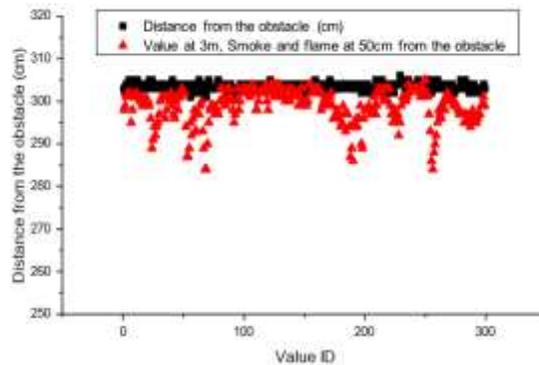


Figure 9: Standard Deviation of LIDAR Readings with Smoke Interference at 50cm and 2.5m from the Obstacle

LIDAR in the presence of Smokeless Flame

LIDAR acts in a markedly distinct manner when faced with flame. This occurs due to elevated air temperatures that interfere with the standard medium for which LIDAR is constructed. We conduct a series of tests to assess the efficacy of LIDAR. The testing arrangement remains consistent with that employed for LIDAR in non-flame smoke research. In this sequence of experiments, smoke interference is substituted with flame interference, utilizing 2-Propanol as the fuel source. It produces no smoke, and its flame ignites at approximately 2000°.

LIDAR is positioned at 1m from the obstacle, while flame interference is set at 50cm from the obstacle. The result can be found in figure 10. The standard deviation is illustrated in figure 14. At a cursory look, it appears that LIDAR exhibited erratic performance with a deviation of roughly 25 points from the base value. Nevertheless, when the results are plotted as depicted in Figure 10 a distinct pattern emerges. In this scenario, LIDAR returned two groups of

values; one group gives the distance measurement to the obstacle, the target to be identified, while the other group reflects the distance from the flame. The reason that one set of values pertains to the distance from the flame is that the flame alters the medium due to elevated air temperature, causing sound waves to scatter, and instead of identifying the obstacle, these sound waves are deflected by the flame container.

This occurrence of acquiring two separate sets of values when flame is present is beneficial as it can be utilized. One can easily sort the set of values by the size of the values. For instance, in Figure 14, we can establish a threshold of 10cm and separate the values into two distinct sets, then select the set with values of greater magnitude. It is also important to mention that conducting standard deviation analysis on raw values will not provide any

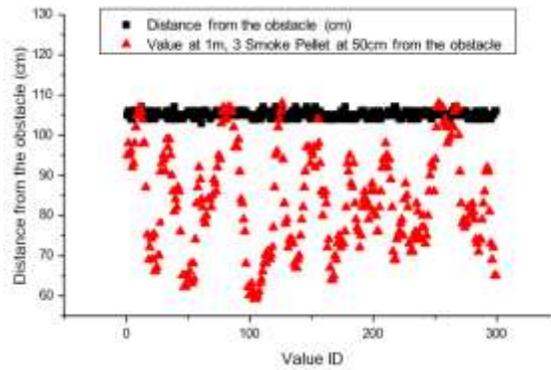


Figure 10: LIDAR Response in the Presence of Smokeless Flame Interference

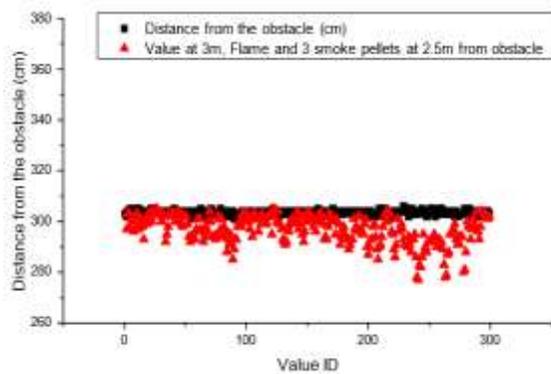


Figure 11: LIDAR Response with Flame Interference Moving Between the Obstacle and LIDAR

meaningful results.

The next step is to examine how LIDAR reacts when flame interference is shifted between the obstacle and LIDAR. This is performed to understand how LIDAR will function on a mobile platform such as UAV. In this session, LIDAR is positioned 3m away and flame interference is situated at 2.5m from the obstacle before being moved towards LIDAR. The results are illustrated

in Figure 11. It is noticeable that LIDAR returns two sets of values regardless of where the flame interference is located. The same effect is seen when LIDAR is set at a distance of 1m from the obstacle, as depicted in Figure 15. It can be observed that as the flame interference approaches LIDAR in increments of 0.5cm, LIDAR records some extraneous values at each movement. LIDAR in the presence of flame does not lose its effectiveness.

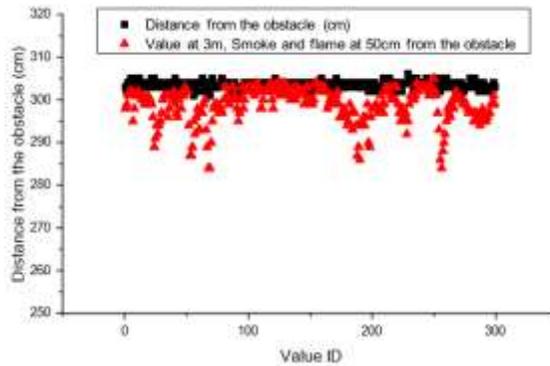


Figure 12: LIDAR Value at 3m, Smoke and flame at 50cm from the obstacle

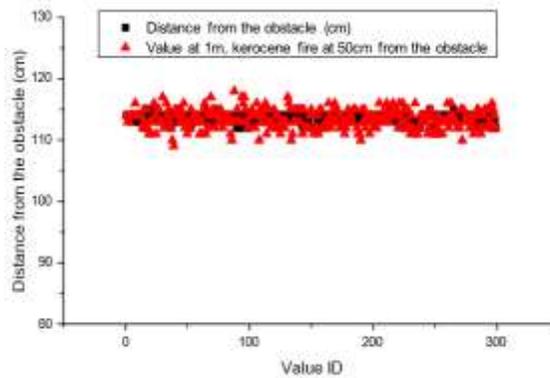


Figure 13: Filtered LIDAR value at 1m, smokeless flame at 0.5m from obstacle

LIDAR in the presence of fuel with smoke and fire

Structure fires can exhibit various types of flames due to different materials present in buildings. To replicate this, we employ two kinds of interference. 1) Kerosene is utilized because it burns quite intensely at 2000°C and generates black smoke as demonstrated in Figure 5. 2) 2-Propanol combined with smoke pellets is utilized to replicate a fire that produces heavy smoke, as illustrated in Figure 13.

As anticipated, kerosene and 2-Propanol with smoke produce the same impact on LIDAR as liberating flame, as depicted in Figure 12 and Figure 13 respectively. This is because, as previously mentioned, smoke does not render LIDAR ineffective, and due to elevated air temperature, smoke generated by both fuels disperses rapidly, leading to a minimal effect of smoke on LIDAR in this scenario. Nonetheless, the flame aspect of these fuels has an effect similar to that of smokeless flame.

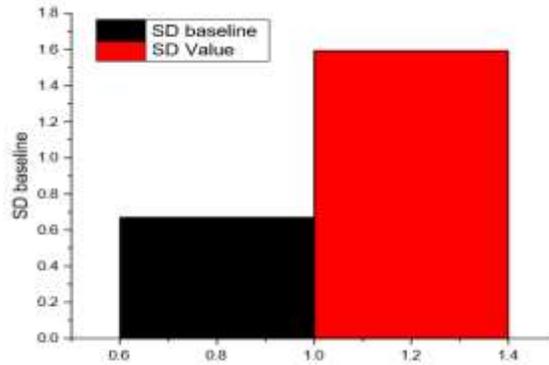


Figure 14: Threshold-Based Separation of LIDAR Readings in the Presence of Flame Interference

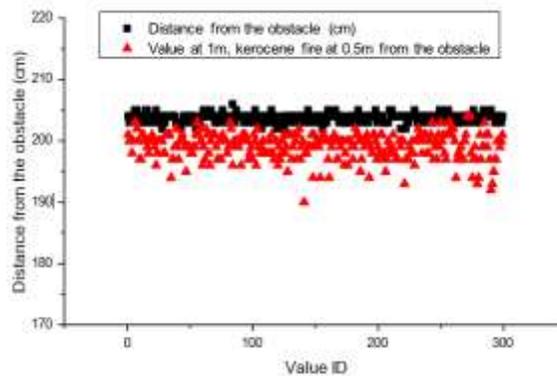


Figure 15: LIDAR Response at 1m with Kerosene Fire at 0.5m from the Obstacle

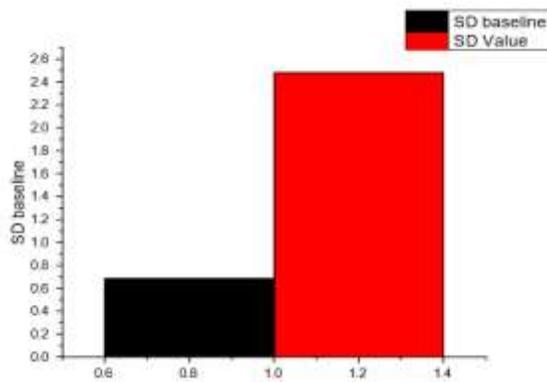


Figure 16: filtered standard deviation

Filtering Algorithm Analysis

A straightforward filtering algorithm analysis has been created to utilize Ladar values influenced by fire and smoke environmental interference. The purpose of this algorithm is to eliminate undesirable readings from Ladar. Algorithm 1

requires distance values from Ladar in groups. One group of values can contain any quantity of values. The size of the group will determine the duration the algorithm takes to produce a filtered value. If Ladar is configured to function at 100Hz and with a group size of 20, Ladar can generate 5

filtered values every second. The proposed algorithm also necessitates an accuracy threshold value; for our needs, we can set the accuracy threshold to 10 cm. Each value in the group is compared with the subsequent value, and the corresponding difference is computed. If the difference is below the threshold, the value is assigned to group 1. Otherwise, it is assigned to group 2. The mean of both groups is determined, and the higher of the mean values is chosen as a filtered value. Results indicate that the proposed filtering algorithm effectively delivers satisfactory output. It is not only effective when applied to Ladar values influenced by flame interference, but it also enhances the results when used on values affected by smoke. We know that Ladar is relatively unaffected even by high-density smoke, but simple filtering enhances it further. The standard deviation is also slightly enhanced. The primary benefit of the proposed algorithm is evident in cases of flame interference. After eliminating unwanted values, relatively precise results can be attained. The standard deviation is also improved compared to the standard deviation. It can be noted that after filtering out unwanted values, Ladar can provide a relatively accurate distance to the obstacle. However, this output relies on the threshold value set in the algorithm. A higher threshold value will increase the number of data points but reduce the accuracy of Ladar output, while a lower threshold will enhance the accuracy of Ladar output but decrease the number of data points, resulting in gaps in the output value. The proposed filtering algorithm minimizes Ladar results when the interference is solely smoke because Ladar is already quite accurate in the presence of flameless smoke.

Conclusion

Low visibility in a fire and smoke environment can lead to numerous challenges, such as reducing firefighters' effectiveness or causing injuries that could result in fatalities. Distance sensors installed on assistant robots or firefighters may aid in navigation, mapping, or identifying obstacles. Nonetheless,

these sensors might become less effective in environments filled with fire and smoke. In this paper, we examine the effectiveness of commonly used LIDAR. The fire and smoke environment is replicated using smoke pellets to create flameless smoke, 2-Propanol to produce smokeless flames, kerosene to imitate high-temperature flames accompanied by black smoke, and 2-Propanol with smoke pellets to generate high-temperature flames with dense smoke. LIDAR is operated amidst these interferences, and empirical data is collected. The operation of LIDAR under conditions of fire and smoke is elaborated on in detail.

Data Availability Statement

Data Sharing is not applicable to this study because no datasets were produced and processed. The results are based only on controlled lab experiments, which have been elaborated in the manuscript. There was no external and publicly archived data utilized.

Funding Statement

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

REFERENCES

- Igor Veselovskii, Mikhail Korenskiy, Nikita Kasianik, Boris Barchunov, Qiaoyun Hu, Philippe Goloub, and Thierry Podvin. Fluorescence properties of long-range-transported smoke: insights from five-channel lidar observations over Moscow during the 2023 wildfire season (ACP, 25, 1603–1615, 2025).
- Haodong Duan, Zhangwei Peng, Xiaoyi Gan, Shaofeilong Wang, Lin Xie, Xiangwei Zeng, Xueye Chen and Yongbiao Ma. Polarization characteristics and power analysis of 532nm laser in smoke environment, 2025.
- Shichao Kuai, Wei Zheng, Ningning Li, Lei Xu, Zibo Qi. Experimental study on the influence of smoke on laser radar and millimeter wave radar mapping, 2024.

- Riccardo Damiano, Salvatore Amoruso, Alessia Sannino, Antonella Boselli. "Lidar Optical and Microphysical Characterization of Tropospheric and Stratospheric Fire Smoke Layers Due to Canadian Wildfires Passing over Naples (Italy)", 2024.
- Xi Zhang, Liming Li, Boning Li, Zhibin Mei. Experimental Study on Early Fire Smoke Characteristics in a High-Volume Space: A Fire Detection Perspective, 2024.
- evin Ohneiser, Albert Ansmann, Jonas Witthuhn, Hartwig Deneke, Alexandra Chudnovsky, Gregor Walter, and Fabian Senf. Self-lifting of wildfire smoke in the troposphere and stratosphere: simulations and space lidar observations, 2023.
- Igor Veselovskii, Nikita Kasianik, Mikhail Korenskii, Qiaoyun Hu, Philippe Goloub, Thierry Podvin, and Dong Liu. Multiwavelength fluorescence lidar observations of smoke plumes, 2023.
- Rodanthi-Elisavet Mamouri, Albert Ansmann, Kevin Ohneiser, Daniel
- A. Knopf, Argyro Nisantzi, Johannes Bühl, Ronny Engelmann, Annett Skupin, Patric Seifert, Holger Baars, Dragos Ene, Ulla Wandinger, and Diofantos Hadjimitsis. Wildfire smoke triggers cirrus formation: lidar observations over the eastern Mediterranean, 2023.
- N. Midzak, J. E. Yorks, J. Zhang, E. P. Nowotnick. An Investigation of Non-Spherical Smoke Particles Using CATS Lidar, 2023.
- Karter, Michael J., and Joseph L. Molis. US Firefighter Injuries-2011. Quincy, MA: National Fire Protection Association, Fire Analysis and Research Division, 2012.
- NFPA (2012) Deadliest fires in the U.S. with 5 or more firefighter deaths at the fire grounds, 1977-2010. Fire Incident Data Organization, Quincy
- Karter, Michael J. Fire loss in the United States during 2010. Quincy, MA: National Fire Protection Association, 2011.
- Karter, M. J. "Selected special analyses of firefighter fatalities." National Fire Protection Association Quincy, MA2005 (2005).
- Fahy, Rita F., Paul R. LeBlanc, and Joseph L. Molis. Firefighter fatalities in the United States-2008. National Fire Protection Association. Fire Analysis and Research Division, 2009.
- Campbell, Richard. "US firefighter injuries on the fireground, 2010-2014." *Fire technology* 54.2 (2018): 461-477.
- Gorbett, Gregory E., Ronald Hopkins, and P. Kennedy. "The current knowledge training regarding backdraft, flashover, and other rapid fire progression phenomena." annual meeting of the National Fire Protection Association, Boston, MA. 2007.
- Zhang, Guowei, et al. "Methods for prediction of temperature distribution in flashover caused by backdraft fire." *Mathematical Problems in Engineering* 2014 (2014).
- Wang, Yong, et al. "Key technologies of tunnel firefighting robots." *IETE Technical Review* 34.1 (2017): 3-10.
- Imdoukh, Abeer, et al. "Semi-autonomous indoor firefighting UAV." 2017 18th International Conference on Advanced Robotics (ICAR). IEEE, 2017.
- Starr, Joseph W., and B. Y. Lattimer. "Evaluation of navigation sensors in fire smoke environments." *Fire Technology* 50.6 (2014): 1459-1481.
- Sales, Jorge, et al. "Multi-sensor person following in low-visibility scenarios." *Sensors* 10.12 (2010): 10953-10966.
- Maxwell, Floyd D. "A portable IR system for observing fire thru smoke." *Fire Technology* 7.4 (1971): 321-331.
- Wegrzyński, Wojciech, Piotr Antosiewicz, and Jadwiga Fangrat. "MultiWavelength Densitometer for Experimental Research on the Optical Characteristics of Smoke Layers." *Fire Technology* (2021): 1-24.
- Bohn, Dennis A. "Environmental effects on the speed of sound." *Journal of the Audio Engineering Society* 36.4 (1988): 223-231.