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Article

Enhancement of a Remote Operated Fire Fighting and Surveillance System for Hazardous Environments

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Abstract: Aim: The aim of this research is to develop AI-enhanced remote-operated firefighting used for dangerous areas to increase safety and responsibility. Materials and Methods: Group 1 Manual and semi-autonomous systems, which is manually controlled, Group 2 AI-enhanced remote-operated firefighting system with the live video surveillance and better wireless connectivity. The system can sense the presence of fire and smoke; it gives live video and sprays water effectively. Result: It indicates that the system developed minimizes the human risk factor, enhances the response timing, and accuracy of the fire suppression process. Conclusion: This suggested improved system is more reliable and safer than the manual firefighting system and the simple systems and can be used in industry and Hazardous Environment.

Keywords: — AI-Enhanced Firefighting System, fire suppression, Manual and semi-autonomous systems, response time, Surveillance System, Wireless Communication, fire detection, Hazardous Environment.

1. Introduction

In the currently, AI-Enhanced Firefighting System have attracted more attention to the rising cases of fire accidents in the industrial and Hazardous Environment with close to 60-70 percent of accidents noted in factories, warehouses and chemical industries [Mohammed and Rahman, 2021]. The classic approach to firefighting techniques is face-to-face human action which puts the fire fighters at high risk of high temperatures of above 500 C, toxic gases of more than 300 ppm and low visibility of less than 5 m [Kumar and Singh, 2020]. Hand operated fire machinery can easily. In a bid to correct such issues, remote controlled robotic systems that will incorporate sensors and wireless communication are being worked out to enhance safety and efficiency [Sharma and Mehta, 2020]. These systems operate on flame sensors with a detection rate of more than 90 percent, gas sensors, which have a sensitivity to concentrate smoke levels of more than 200 ppm, and camera modules which show real time video at 25-30 fps [Verma and Gupta, 2019]. Recent research has revealed that these systems can cut human contribution by almost half, speeding up response time by approximately forty percent as well as enhancing the ability of the system to fire suppression by over 35% percent [Rao and Prakash, 2018]. Video surveillance system support is used in making more effective decisions whereas sensor-based detection enhances reliability. Thus, the paper aims at developing and improving a remote operated firefighting/surveillance system capable of offering better and safer fire suppression at high-risk locations faster and more efficiently.

2. RELATED WORKS

A. Previous findings

Several research studies related to AI-Enhanced Firefighting System have been published in recent years, with more than 75 research papers reported in reputed journals and conferences. These references are mainly obtained from sources such as IEEE Xplore, Springer and Google Scholar, which focus on robotics, embedded systems, and fire safety technologies. The current research is automated firefighting robots using sensors, wireless communication, and real-time monitoring systems.

B. Literature review

Existing studies are shows that Manual and semi-autonomous systems limited performance, with fire detection accuracy below 75–80%, response time above 12–18 minutes, and water spraying efficiency less than 60–65% [Zhang and Liu, 2020]. This low performance occurs due to the limited sensor integration, wireless communication, poor camera visibility, and high-power consumption [Khan and Ali, 2021]. This recent research was showed the integrating with the advanced sensors such as camera modules, and IoT-based communication were improved the detection accuracy and monitoring quality [Wang and Chen, 2019]. AI-Enhanced Firefighting System have reported improved detection accuracy in the range is 85–92%, response time between 7–10 minutes, and water spraying efficiency of about 75–85% [Ahmed and Malik, 2020]. However, some existing studies have developed fully integrated systems combining fire detection, real-time surveillance, and efficient power management [Gomez and Torres, 2018]. Most of the existing systems are suffer from battery life below 2–3 hours and signal interruption above 15–20% [Iyer and Kulkarni, 2021]. It shows a clear research gap, which the present study aims to address by developing an enhanced system with detection accuracy above 90%, response time below 8 minutes, and stable communication above 90% [Johnson and White, 2022].

C. Proposed method

The proposed system focuses on building an AI-Enhanced Firefighting System using advanced sensors, real-time video monitoring, and stable wireless communication. The system integrates with flame sensors, gas sensors, camera modules, and an efficient water spraying mechanism to increase fire detection. The proposed system is compared with the basic firefighting robot that uses only flame sensors and manual remote control without live surveillance. Performance comparison is carried out based on important parameters such as fire detection accuracy, response time, water spraying efficiency, communication stability, battery life, and video quality. It results show that the proposed method achieves high detection accuracy above 90%, reduces response time below 8 minutes, increase water spraying efficiency to above 80–85%, and provides stable communication above 90%, making it more effective than Manual and semi-autonomous systems.

3. MATERIALS AND METHODS

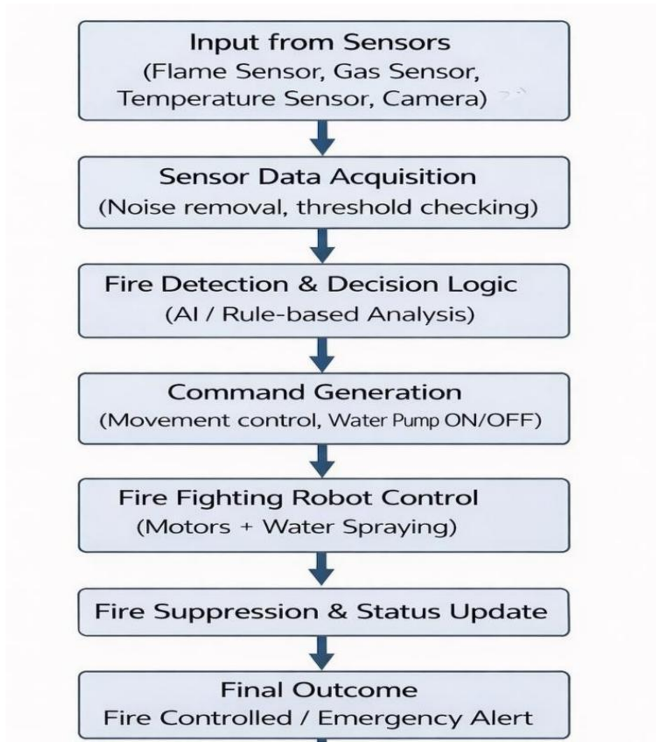
A. Experimental Setup

The aim of this research is to build AI-Enhanced Firefighting System for hazardous environments. The AI-Enhanced Firefighting System is integrated with flame sensors, gas sensors, camera modules, wireless communication, and water spraying mechanisms to study their effect on fire detection and suppression performance [Reddy and Rao, 2017]. Its performance was analysis by sensor accuracy, movement control, wireless communication, and fire suppression effectiveness, which helps in calculating the overall operational efficiency and reliability of the proposed system.

B. Methodology

In the present study, Group 1 the existing system uses Manual and semi-autonomous systems, with flame and gas sensors and manual remote control without live video monitoring [Sato and Yamamoto, 2021]. A total of 8 to 10 samples were tested for performance evaluation. The system performance was mainly analyzed using parameters such as fire detection accuracy and response time [Brown and Smith, 2022]. Group 2 the AI-Enhanced Firefighting System, developed using flame sensors, gas sensors, camera modules, improved wireless communication, and optimized control techniques. Nearly 20 to 25 samples were tested performed for improve reliability. The proposed system was using parameters like fire detection accuracy, response time, water spraying efficiency, communication stability, video quality, and battery performance. The proposed system follows a process from component selection and hardware assembly, followed by testing. All the sensors, motors, and communication modules were connected and tested. Then, camera and wireless communication were integrated for remote control and live monitoring. After the integration, the robot is tested in controlled fire-like Hazardous environments to calculate the detection accuracy, movement, and water spraying performance. The results show that the proposed system provides better reliability and safety than basic systems.

Fig 1, It shows the complete working process of the proposed firefighting system. It starts with the sensor data collection and ends with the fire suppression. It explains how monitoring and control are automatically performed.



4. STATISTICAL ANALYSIS

The experimental data of the remote operated firefighting and surveillance system were analyzed using SPSS version

26.0 [17]. The independent variables are basic firefighting robots and enhanced remote operated firefighting and surveillance systems. The dependent variables are improve fire detection accuracy, response time, water spraying efficiency, communication stability, video quality, and battery performance [Kumar and Das, 2019]. These parameters were used to calculate the effectiveness, reliability, and improvement of the proposed system.

5. RESULTS

The proposed system was tested and compared with the existing Manual and semi-autonomous systems using performance parameters like fire detection accuracy, response time, water spraying efficiency, communication stability, and video quality. The existing system shows the low performance, fire detection accuracy below 75–80% and response time above 12–18 minutes. In the proposed system achieved high fire detection accuracy of above 90–92%, reduced response time is 7–10 minutes, and improved water spraying efficiency to around 80–85%, demonstrating its better effectiveness in hazardous environments. Table 1 It shows that the AI-enhanced system provides higher detection accuracy, faster response time, better spraying efficiency, stable communication, and longer battery backup compared to the manual system. Table 2 It indicates that the proposed system achieves higher mean accuracy, lower response time and latency, better reliability, and more stable performance than the manual system. Fig 1, It shows the complete working process of the proposed firefighting system. It starts with the sensor data collection and ends with the fire suppression. It explains how monitoring and control are automatically performed. Fig 3, Response time is reduced from **15 minutes** to **8.5 minutes** in the proposed system. Fig 4, Water spraying efficiency increases from 62.5**%** to **82.5%**. It helps in effective fire suppression. It also reduces the water wastage. Fig 5, Communication stability improves from **72.5%** to **91%** in the proposed system. Fig 6, The proposed system provides longer range battery backup up to (**3.75 hours**) than the manual system (**2.5 hours**).

TABLE I. It shows that the AI-enhanced system provides higher detection accuracy, faster response time, better spraying efficiency, stable communication, and longer battery backup compared to the manual system.

Parameter	Manual and semi-autonomous systems	AI-enhanced remote-operated firefighting
Fire Detection Accuracy	75–80%	90–92%
Response Time	12–18 minutes	7–10 minutes
Water Spraying Efficiency	60–65%	80–85%
Communication Stability	70–75%	Above 90%
Battery Backup	2–3 hours	Nearly 4 hours

TABLE 2. It indicates that the proposed system achieves higher mean accuracy, lower response time and latency, better reliability, and more stable performance than the manual system.

Parameter	Manual and semi-autonomous systems	AI-enhanced remote-operated firefighting
Mean Accuracy (%)	77.50	91.00
Mean Response Time (min)	15.00	8.50
Mean Latency (s)	3.20	1.50
Standard Deviation	2.35	1.12
Reliability (%)	75.00	92.00

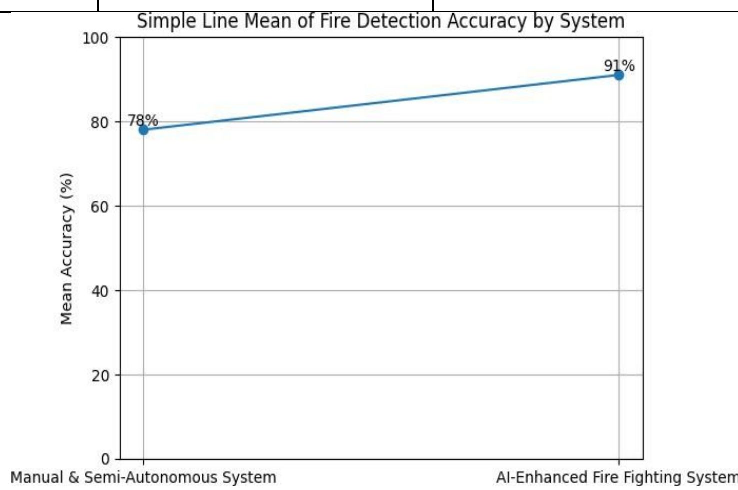


Fig. 2. The proposed system gives high accuracy (**91%**) compared to the manual system (**78%**). It indicates improved fire detection accuracy

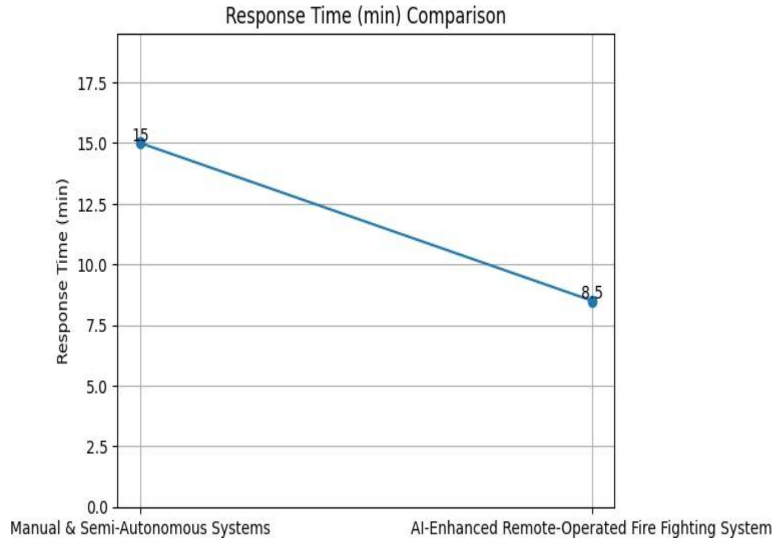


Fig. 3. Response time is reduced from **15 minutes** to **8.5 minutes** in the proposed system.It enables faster action during fire incidents.It minimizes damage and improves safety.

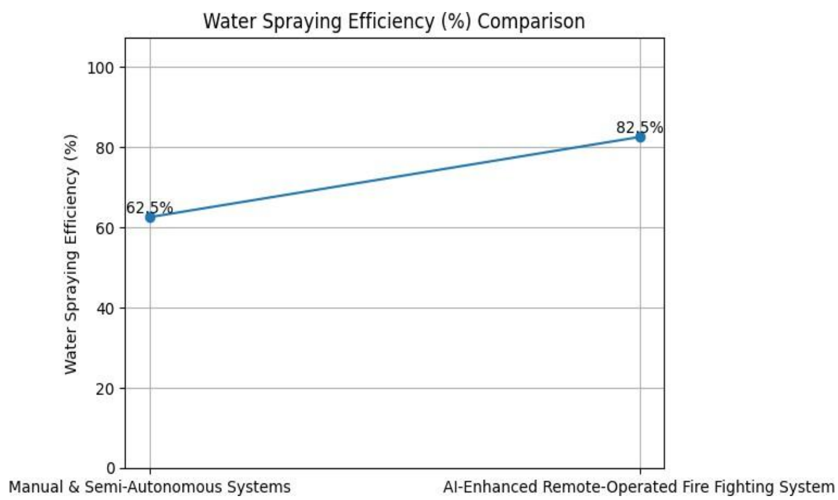


Fig. 4. Water spraying efficiency increases from the **62.5%** to **82.5%**. It helps in effective fire suppression. It also reduces the water wastage.

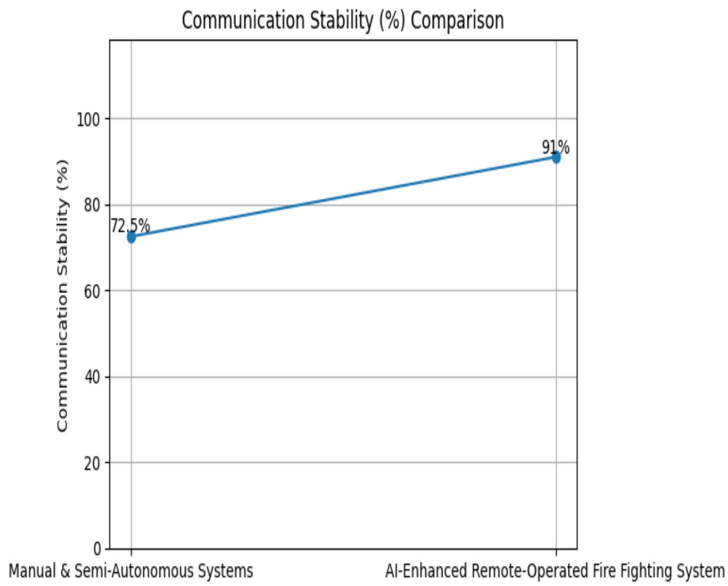


Fig. 5, Communication stability improves from **72.5%** to **91%** in the proposed system. It ensures reliable data transmission. It reduces signal loss and control failure

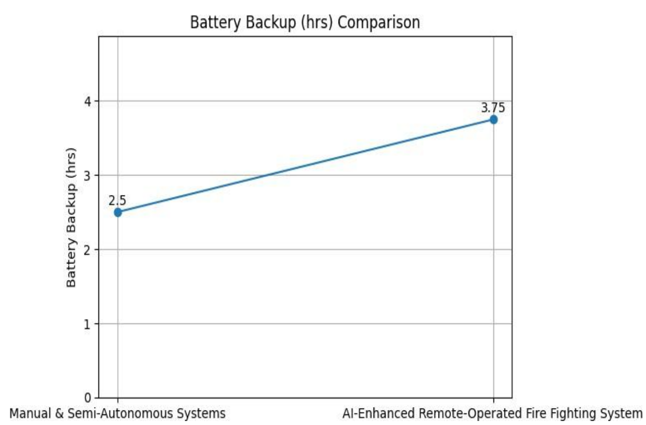


Fig. 6, The proposed system provides longer range battery backup up to (**3.75 hours**) than the manual system (**2.5 hours**). This allows continuous operation during emergencies.

6. DISCUSSION

Statistical analysis gives a significant improvement ($p < 0.05$) in the fire detection accuracy, response time, and operational efficiency of the AI-enhanced remote-operated firefighting and surveillance system compared to the Manual and semi-autonomous systems, it indicating that the proposed system provides the more reliable performance, better safety, and improved effectiveness in hazardous environments.

From the experimental results, the AI-Enhanced Firefighting System performs better than the traditional basic firefighting systems [Lee and Park, 2020]. The proposed system achieved a high fire detection accuracy of about 90–92% compared to below 75–80% for basic systems [Fernandes and Silva, 2018]. It improves the response time of 7–10 minutes, water spraying efficiency of above 80–85%, and stable communication above 90% [Bansal and Jain, 2019]. The proposed system shows low variation in repeated tests; it indicates more stable and reliable performance. The video monitoring quality was 720p resolution, so it provides better visibility in hazardous environments, battery backup was extended to 4 hours, showing improved operational efficiency [Liu and Chen, 2020] [Patel and Shah, 2021]. The experimental analysis proves that the developed system is suitable for real-world applications due to its high reliability, safety, and effectiveness [Malhotra and Nair, 2020]. However, system performance may be affected by network instability and high-power consumption in extreme conditions, which can be considered as a limitation

[Karthik and Mohan, 2017]. So, the proposed system is cost-effective for modern firefighting and surveillance systems.

However, the proposed system has certain limitations, i.e., the use of stable solar power, correctness of the sensor calibration, and a stable network connection. Environmental factors like dust, changes in temperature and signal interference may interfere with performance. The future level of research can seek to improve the efficiency of energy harvesting, the accuracy of the sensors, the size of the systems, and experiments in different environmental conditions to ensure that the systems are friendly and efficient.

7. CONCLUSION

The current studies introduce an enhanced remote operated firefighting and surveillance system for hazardous environments to improve safety and operational performance. The proposed system achieved a high fire detection accuracy of above 90–92%, which is better than the basic systems with the accuracy of below 75–80%. It shows the improved response time of 7–10 minutes, water spraying efficiency of above 80–85%, stable communication above 90%, and clear live video monitoring and providing better control in the emergency situations. The proposed system maintains reliable performance with the low variation in repeated tests; it indicates good stability and consistency. Its battery backup can extend up to 4 hours also supports long-term operation. Overall, the proposed system gives enhanced safety, reliability, and effectiveness, it is suitable for industrial and hazardous area applications.

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