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Application and Research of Intelligent Multi-source Information Fusion Technology in Firefighting Equipment

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ABSTRACT

As modern firefighting environments become increasingly complex, traditional firefighter equipment and operational methods are no longer adequate to address the high-risk challenges of fire rescue operations. Fire scenes are characterized by complex and hazardous environmental factors, with firefighters facing multiple threats such as extreme temperatures, dense smoke, and toxic gases. Therefore, ensuring the safety and efficiency of firefighters is of paramount importance. This study integrates multiple sensor technologies to enable real-time monitoring of firefighters' physiological status, posture changes, and fire scene conditions. The system incorporates ErgoLAB wireless ECG and PPG sensors, the BWT61CL posture sensor, and the MAG14mini infrared camera, which are capable of simultaneously capturing key physiological data and heat distribution in the fire scene. To ensure data accuracy and real-time performance, the study employs efficient signal preprocessing techniques, including noise reduction, baseline correction, and time synchronization. In addition, wireless transmission technology and multimodal data fusion algorithms are utilized to comprehensively analyze the firefighters' status and fire scene conditions. This approach significantly enhances the precision of firefighter safety monitoring and operational efficiency, demonstrating substantial innovation and practical value.

KEYWORDS

Multi-source Information Fusion; Data Fusion; Intelligent Technology; Firefighting Equipment

1. INTRODUCTION

Existing firefighter safety monitoring systems face multiple limitations in complex fire environments. Firstly, these systems typically monitor only a single data source, making it difficult to comprehensively capture firefighters' physiological load, posture changes, and environmental risks under hazardous conditions such as high temperatures, dense smoke, and unstable structures [1]. Additionally, traditional equipment and data collection systems for individual firefighters suffer from limited monitoring scope, insufficient data accuracy, and a lack of real-time capabilities, hindering the ability of commanders to provide timely and comprehensive decision support [2, 3]. These systems are unable to dynamically assess the overall status of firefighters, thus failing to adequately ensure their safety [4].

To address these issues, this study proposes an integrated firefighter monitoring system that utilizes multiple sensors to provide real-time monitoring of firefighters' physiological status, posture changes, and fire scene conditions, delivering accurate and timely decision support to commanders [5]. The system combines ErgoLAB wireless ECG and pulse sensors, the BWT61CL posture sensor, and the MAG14mini infrared camera to collect and analyze real-time data on firefighters' physiological conditions, posture changes, and heat distribution in the fire scene. Through multimodal data fusion and efficient signal processing algorithms, the system ensures the accuracy and real-time performance of data collection, processing, and transmission, providing comprehensive situational awareness [6]. Commanders can monitor the firefighters' status in real-time, enabling more effective decision-making and improving rescue efficiency and firefighter safety [7].

2. EXPERIMENTAL DESIGN AND PROCEDURE

2.1. Data Collection System Design

This study employs an Internet of Things (IoT)-based distributed sensor network to achieve comprehensive monitoring of firefighters' physiological status and external environmental conditions in fire scenes. The design of the data collection system is shown in Figure 1. By integrating high-precision GPS positioning systems and Inertial Measurement Units (IMUs), firefighters can accurately determine their position and movement within a three-dimensional space. Physiological signal monitoring is conducted in real-time through wearable devices, collecting key biometric indicators such as ECG and pulse data. Additionally, infrared camera sensors are used to sense the external environment, constructing a three-dimensional structural image of the fire scene, and providing real-time feedback to firefighters regarding fire intensity and temperature distribution.

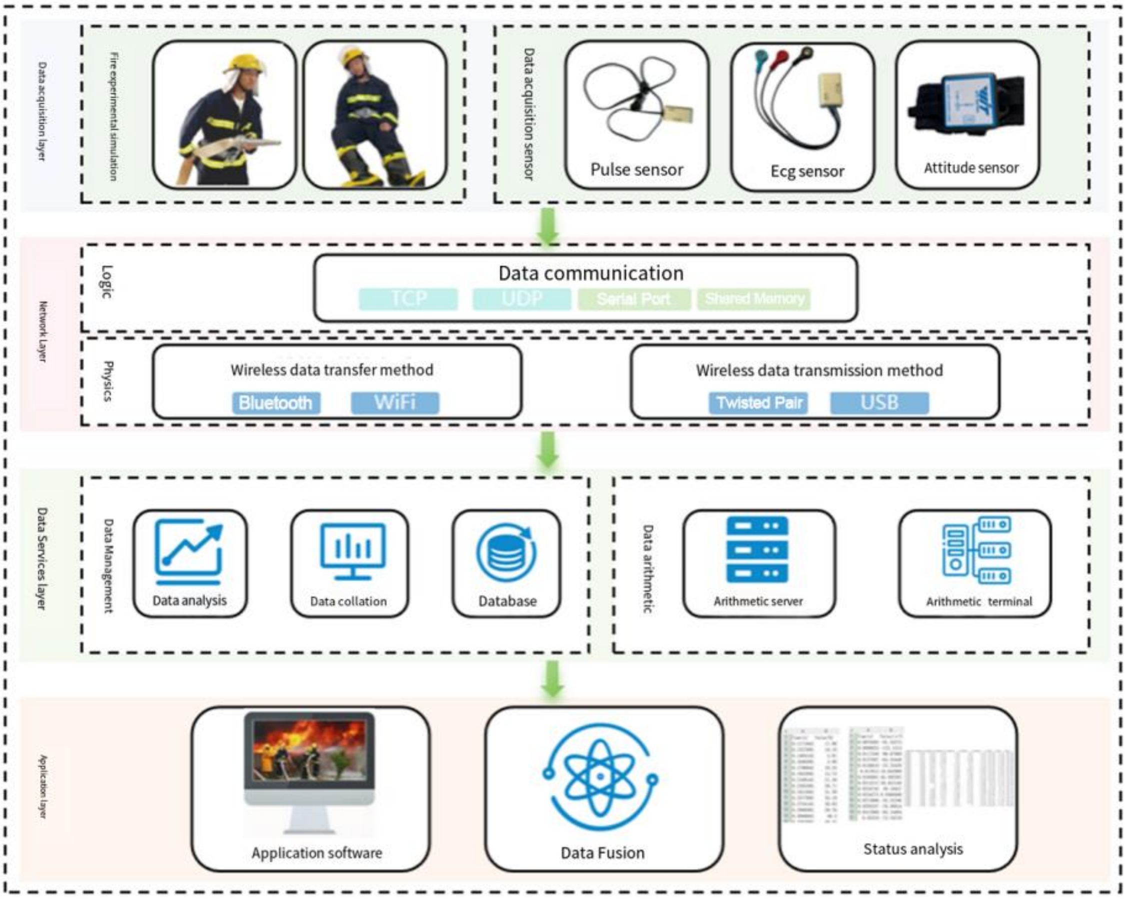

Figure 1. Data Collection System Design

2.2. Data Collection Process

After the initial configuration and calibration of the sensor devices, the system begins collecting key data, including posture, physiological, and visual information [8, 9]. Physiological data is monitored in real-time using ErgoLAB wireless ECG and pulse sensors. ECG data reflects the firefighter's physical exertion and stress levels, while pulse data is used to assess their level of tension and potential signs of fatigue. Posture data is collected by the BWT61CL sensor, which records the firefighter's orientation, angular velocity, and acceleration, providing insights into dynamic posture changes. Visual data is captured by the MAG14mini infrared camera, which helps map the fire scene and identify potential obstacles, assisting in rescue decision-making. Figure 2 depicts the process of data collection and synchronization.

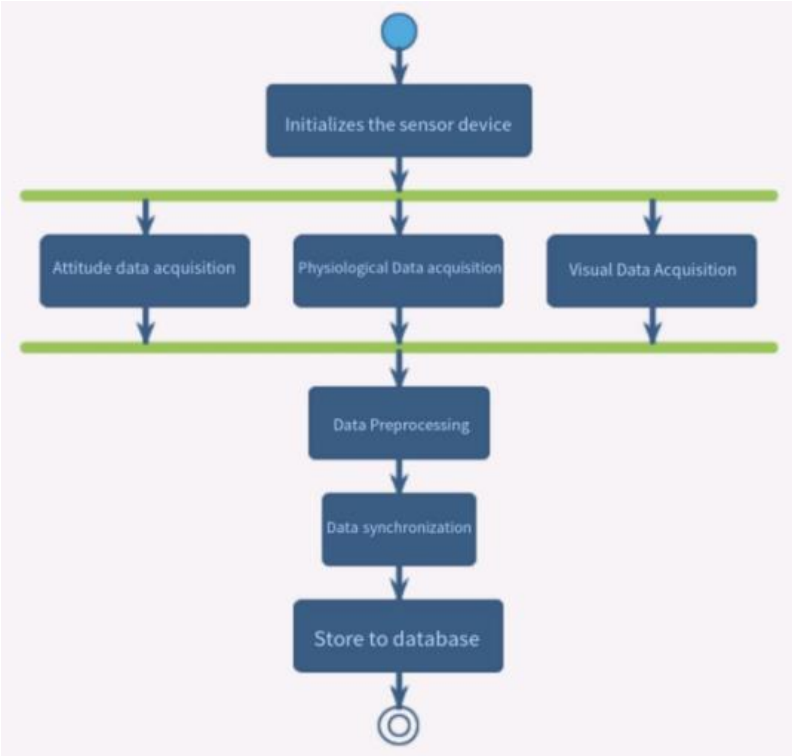

Figure 2. Data Collection and Synchronization Process Diagram

Once collected, the three types of data—posture, physiological, and visual—are initially filtered and denoised before entering the data preprocessing phase. Through timestamp synchronization, data from different sources is accurately aligned to the same time points, ensuring the coordination of physiological, posture, and visual information[10]. This synchronization is critical for analyzing firefighter behavior patterns, physiological responses, and interactions with the environment[11]. After preprocessing, all data is stored in a unified database, supporting efficient querying and analysis, while also ensuring data privacy and security.

3. METHODOLOGY

3.1. Data Collection

3.1.1. The physiological data collection

The physiological data collection devices consist of the ErgoLAB pulse PPG sensor and the ErgoLAB pulse ECG sensor. The PPG sensor is attached to the earlobe using a black ear clip, with a strap fastened around the arm. The ECG sensor is applied by positioning three electrode pads on the designated electrodes and securing the strap around the subject's body.The process of physiological data collection is illustrated in the figure. Figure 3 shows the data curve from the upper computer during the pulse experiment, while Figure 4 presents the data curve from the upper computer during the ECG experiment.

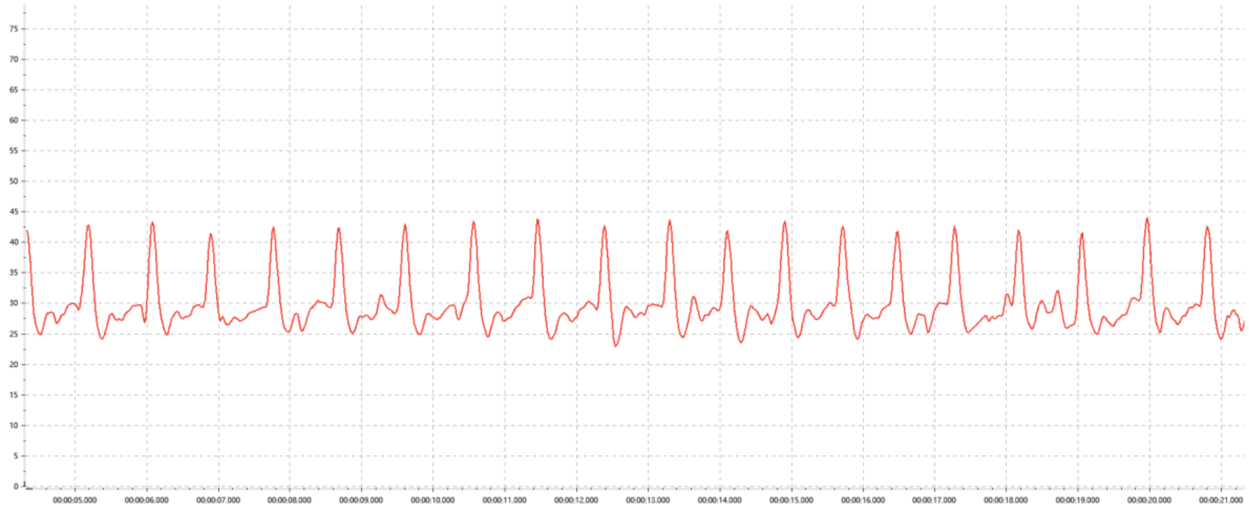

Figure 3. PPG Sensor Data Collection Diagram

Figure 4. ECG Sensor Data Collection Diagram

3.1.2. The posture data collection

The posture data collection device used is the WT61CL posture sensor, which is fixed at the center of the subject's lower back. Through multiple experimental validations, it was determined that the ideal placement for the device is at the waist. Posture data is collected in four forms: standing, free movement, sitting, and lying down. For each subject, the data collection time for each group is 15 seconds, with four sets for standing and free movement, and eight sets for the falling state. Standing and free movement are classified under the upright state category. As shown in Figure 5, the data collection process for posture is illustrated, with three sets of curves representing angles, acceleration, each sample from the posture sensor includes nine data points: angles in the x, y, and z directions (in degrees), acceleration in the x, y, and z axes (in g), and angular velocity in the x, y, and z directions. (in degrees per second).

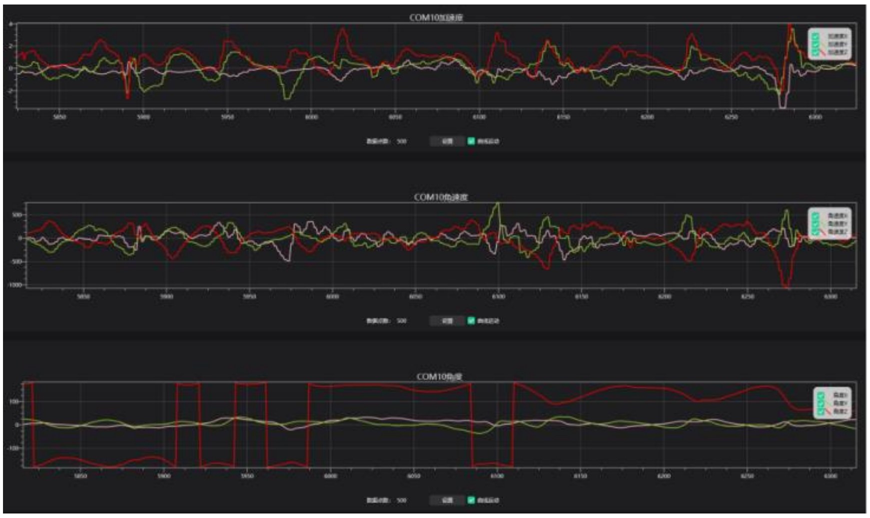

Figure 5. Posture Sensor Data Collection Diagram

3.1.3. The visual data collection

The visual data collection device used is the MAG14mini infrared camera, which is mounted on the firefighter's head. During experiments, when the flame temperature is high and the infrared image displays concentrated high-gray areas, the threshold segmentation algorithm is considered an ideal choice. To enhance the system's real-time performance and accuracy, this study employed both global threshold and local adaptive threshold algorithms for simulation experiments and compared their segmentation results. The experimental results are shown in Figure 6. A comparison of the two algorithms demonstrates that the local adaptive threshold segmentation method is more precise and complete in extracting the flame foreground from infrared images. In contrast, the global threshold segmentation algorithm tends to misclassify background noise as part of the flame, especially in cases where flame edges are blurred or the background is complex. This misclassification directly affects the subsequent feature extraction process, thereby reducing the precision and dependability of flame detection. Thus, to maintain the accuracy and stability of the fire detection system, this study selects the local adaptive threshold segmentation algorithm as the optimal method for foreground extraction in infrared images.

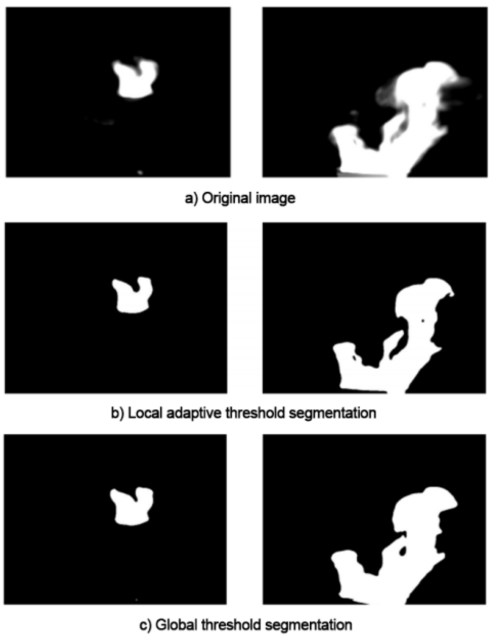

Figure 6. Algorithm Results Comparison

3.2. Data Preprocessing

In the preprocessing of ECG signals, a moving average filter is applied with the aim of removing high-frequency noise while preserving the essential waveform of the ECG signal. The filtering formula for the ECG signal is given by:

$$H_{\text{filtered}}[\mathrm{n}] = \frac{1}{N}\sum_{i=0}^{N-1} H[\mathrm{n}-i] \tag{1}$$

Where $H_{\text{filtered}}[\mathrm{n}]$ represents the n-th filtered ECG value, N is the window length of the filter, and $H[\mathrm{n}-i]$ is the $n-i$ -th value of the raw ECG signal sequence.By selecting an appropriate window length N, a balance can be achieved between signal smoothness and latency, resulting in a more stable and realistic ECG waveform.In addition to noise removal, detecting and handling outliers is equally important. During the experiments, a custom code was developed to detect abnormal ECG values, aiming to identify and flag outliers that may result from sensor errors, vigorous firefighter movements, or other incidental factors. The preprocessed ECG data is used for subsequent time series analysis, and when combined with posture and visual signals, it simulates the physiological status changes of firefighters during fire rescue operations.Timely detection of abnormal conditions and the establishment of related warning mechanisms could play a critical role in reducing safety risks for firefighters during real operations. Through accurate data analysis, the command center can make more informed decisions based on changes in firefighters' physiological signals, thereby improving both the efficiency and safety of fire rescue operations.

In processing the posture signals, the first step is to perform time synchronization on the collected raw triaxial gyroscope signals, ensuring data coherence and consistency. The synchronization operation is based on the timestamps of the sensor output data, where any potential time lags or leads are eliminated by comparing and correcting the timestamp errors. Next, the raw gyroscope data θ_{raw} is corrected using the gyroscope calibration formula:

$$\theta_{calib} = \theta_{raw} - \theta_{offset} \tag{2}$$

Where θ_{offset} represents the error caused by the sensor bias, which is obtained through static calibration in the experimental environment. To implement this calibration process and further optimize signal quality, a gyroscope posture correction algorithm was developed. This code features efficient computational logic while maintaining readability. After completing the preprocessing of the posture signals, the calibrated and filtered data must be validated. Standard motion patterns are established, and the corresponding gyroscope outputs are collected and compared against predefined ideal models to evaluate the efficiency and effectiveness of the preprocessing workflow. Once the preprocessing steps are finalized, the filtered posture data will be used to construct a firefighter's motion trajectory and posture estimation model, providing real-time monitoring and decision-making support.

In the preprocessing of visual signals, this study designed a multi-signal synchronization and analysis workflow tailored to real-world emergency scenarios, providing real-time monitoring support for firefighter operational efficiency and safety. For capturing firefighter posture in video, the raw video stream is first preprocessed to filter out background noise and non-target moving objects. A local adaptive threshold segmentation algorithm is applied to extract the foreground from infrared images, effectively capturing the dynamic contours of firefighters while maintaining low computational complexity. Next, to enhance the visibility of firefighters in the video, especially when they are far from the surveillance camera, a super-resolution convolutional neural network (SRCNN) based on deep learning is introduced. This allows for clear recognition of the firefighters even at greater distances. Furthermore, edge detection plays a critical role in extracting key posture features. By integrating feature extraction algorithm codes, edge detection techniques such as the Sobel operator and Canny algorithm are used to fully extract and highlight the contours of firefighters' actions in complex scenes. When applying the Sobel algorithm, this study adjusts the kernel size (ksize) in the x and y directions to obtain edge responses at different resolutions, enabling more precise localization of firefighter posture structures. In the Canny algorithm, thresholds are set to adapt to changes in ambient lighting and target movement speed, producing more stable and coherent edge contours. In the post-processing of visual signals, morphological transformations, such as dilation and erosion, are utilized to further enhance visual features. Additionally, closing and opening operations are employed to remove small noise and repair broken edges, ensuring the completeness and accuracy of the final extracted firefighter contours. The visual signal preprocessing stage integrates various advanced image processing techniques, constructing an efficient video image processing workflow. From frame processing to feature extraction and edge optimization, each step is designed to improve the accuracy of firefighter action recognition and analysis in emergency tasks. This comprehensive preprocessing process not only ensures data quality but also enhances the reliability of subsequent posture and behavior analysis, providing a solid data foundation for in-depth situation assessment and decision-making support.

4. RESULTS AND DISCUSSION

4.1. Physiological Signal Analysis

The physiological signals obtained from the ErgoLAB pulse PPG and ECG sensors underwent analysis following preprocessing to eliminate noise and detect outliers.Figure 7 presents a comparison of the heart rate signal before and after applying a moving average filter to remove noise. The filtered signal exhibits a smoother waveform, accurately reflecting the physiological state of the firefighter during the rescue operation.

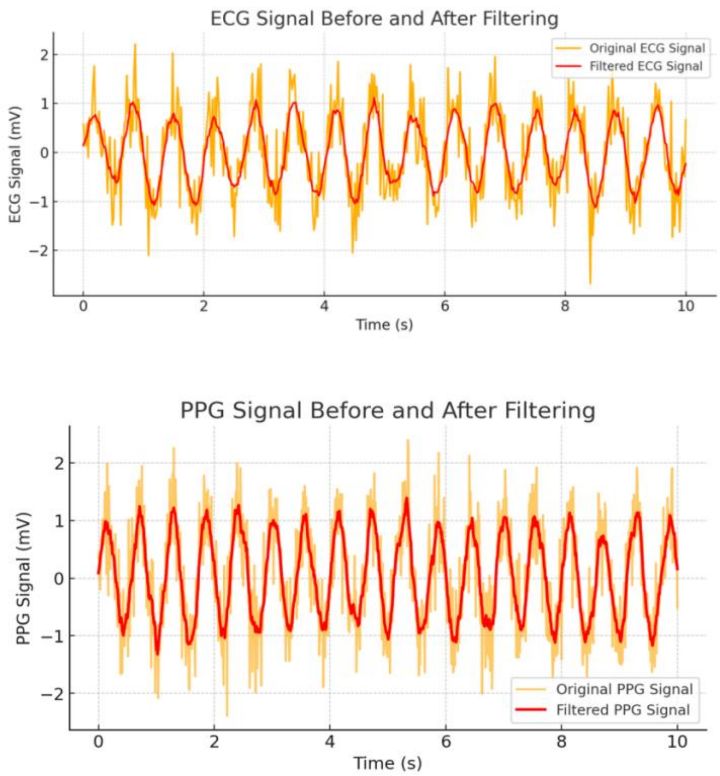

Figure 7. ECG and PPG Signal Before and After Filtering

4.2. Posture Signal Analysis

The posture signals collected using the BWT61CL sensor were analyzed to detect key movements and posture changes of the firefighter during the rescue operation. Figure 8 illustrates the posture angles obtained through the gyroscope sensor, identifying key movements that allow for the assessment of the firefighter's stability and safety. The smoothing and calibration of the gyroscope data significantly improved the accuracy of posture monitoring.

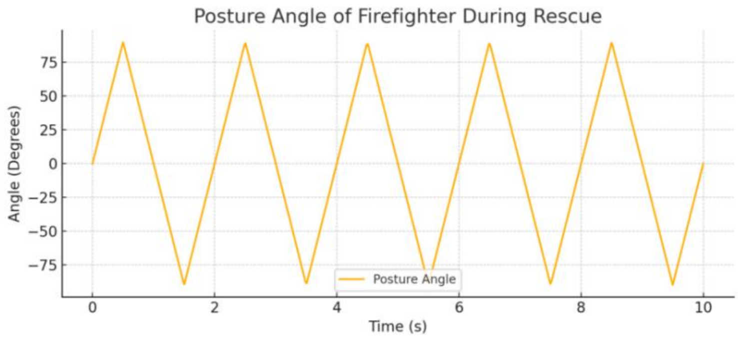

Figure 8. Posture Angle of Firefighter During Rescue

4.3. Visual Signal Analysis

Edge detection and morphological operations were applied to enhance the visual signals and extract key features of the firefighter in the scene. Figure 9 demonstrates the results of edge detection using the Canny algorithm, which significantly improved the recognition of the firefighter's contours in the image. Morphological operations further refined the edges and eliminated noise, providing a clearer representation of the firefighter's actions in complex environments.

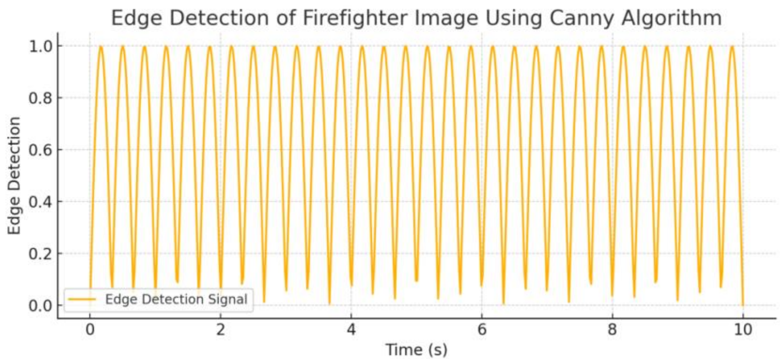

Figure 9. Edge Detection of Firefighter Image Using Canny Algorithm.

5. CONCLUSION

The analysis of physiological, posture, and visual signals demonstrated the effectiveness of multi-signal processing methods in monitoring firefighters during emergency operations. Filtering and noise reduction techniques applied to physiological signals significantly enhanced the accuracy of health monitoring, while posture analysis provided critical insights into firefighter safety. Moreover, visual signal enhancement techniques, including edge detection and morphological operations, enabled clearer identification of firefighter movements, further improving the overall effectiveness of the monitoring system.

By integrating multiple sensor technologies, this study successfully developed a real-time monitoring system capable of simultaneously tracking firefighters' physiological conditions, posture changes, and fire scene information. The system significantly improved the accuracy of rescue decision-making and response speed, thereby enhancing firefighter safety. Future research will focus on further optimizing data fusion algorithms and improving the system's adaptability to complex fire environments, aiming to deliver more intelligent firefighting solutions.

CONFLICTS OF INTEREST

The authors declare that there are no actual or potential conflicts of interest regarding the research presented in this paper. The research, data analysis, and results were conducted independently and were not influenced by any external interests. Additionally, all sources of funding have been clearly acknowledged in the acknowledgment section and have not inappropriately influenced the research process or conclusions.

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