Smart Fire Fighting Robot with Raspberry Pi 5

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KEYWORDS	ABSTRACT
Raspberry Pi 5, Fire Detection, Fire-Fighting Robot, Flame Sensor, Gas Sensor, Temperature Monitoring, IoT, Telegram Alert System, GSM Communication, Autonomous Robot, Industrial Safety.	*Fire accidents pose a serious threat to human life, infrastructure, and industrial environments, requiring rapid detection and immediate response to minimize damage. This paper presents the design and development of a Smart Fire-Fighting Robot with Raspberry Pi 5 capable of detecting and suppressing fire hazards without direct human intervention. The proposed system integrates multiple environmental sensors including flame, temperature, and gas sensors to continuously monitor surroundings and identify potential fire incidents at an early stage. The Raspberry Pi 5 serves as the central processing unit that analyzes real-time sensor data and determines the intensity of the fire. Based on the detected conditions, the robot automatically activates an appropriate suppression mechanism. A dual fire suppression system is implemented, where a water sprinkler is used for low-intensity fires such as paper or wood fires, while a foam-based system is activated for high-temperature or electrical fires. The foam is generated using a hot water and dry ice interaction that produces dense carbon dioxide fog capable of reducing oxygen concentration and suppressing flames effectively. To enhance monitoring and safety, the system incorporates IoT-based communication that sends real-time alerts through Telegram notifications and GSM-based SMS messages when abnormal temperature, gas leakage, or fire is detected. Additionally, an ESP32-CAM module provides live video streaming of the affected area for remote observation. The robot can operate in both autonomous and manual modes, allowing users to control movement and suppression when necessary. The proposed system provides a reliable, cost-effective, and intelligent fire safety solution suitable for industries, warehouses, laboratories, and residential environments. By combining real-time sensing, autonomous navigation, intelligent decision-making, and IoT communication, the system significantly improves fire detection and response efficiency while reducing risks to*

INTRODUCTION

Fire accidents remain one of the major causes of loss of life, environmental damage, and destruction of industrial and residential infrastructure across the world. Rapid urbanization and the increasing use of electrical and chemical equipment have significantly increased the risk of fire hazards. Therefore, early fire detection and fast response systems are critical for minimizing damage and improving safety. Traditional fire safety methods mainly rely on smoke detectors, alarm systems, or manual firefighting, which often require human intervention and may lead to delayed responses in hazardous environments.

Recent research has focused on intelligent fire detection techniques using image processing, sensor networks, and automated monitoring systems. Vision-based fire detection methods analyze color, motion, and temporal characteristics of flames to identify fire events in real time. Several studies have demonstrated that statistical color models and video-based analysis can effectively detect flames in complex environments [4, 8]. Similarly, machine learning approaches such as support vector machines have been applied to improve detection accuracy using vision sensors [5]. Other works have explored flame recognition and motion analysis in video sequences for reliable fire monitoring [6, 7].

In addition to vision-based systems, researchers have investigated remote sensing technologies for monitoring forest fires and large-scale environmental disasters. Unmanned aerial systems and satellite-based imaging provide valuable information for assessing fire spread and damage [2]. Near-infrared detection techniques have also been proposed to identify fire signatures in outdoor environments [3]. Moreover, advanced video processing and multi-feature fusion approaches have improved early fire detection performance in intelligent surveillance systems [1, 13, 20].

Image segmentation and feature extraction methods have further enhanced fire detection capabilities. Techniques such as histogram analysis, dynamic texture analysis, and spatiotemporal modeling help distinguish flames from other moving objects or lighting variations [16, 19]. These approaches have enabled automated systems to detect fire events with higher accuracy and

reduced false alarms [9, 10, 21]. Despite these advancements, many existing systems are limited to monitoring and alert generation, without providing an active response mechanism to suppress fires.

To address these limitations, the development of autonomous robotic systems for firefighting has gained significant attention. Fire-fighting robots can navigate hazardous environments, detect fire sources, and suppress flames without risking human lives. By integrating sensor technologies, embedded processing platforms, and IoT communication, such systems can provide real-time monitoring and intelligent response capabilities.

This work proposes a Smart Fire-Fighting Robot using Raspberry Pi 5 that integrates multi-sensor fire detection, autonomous navigation, and a dual fire suppression mechanism. The system uses flame, gas, and temperature sensors to detect hazardous conditions and activates either a water sprinkler or foam-based extinguisher depending on the severity of the fire. Additionally, IoT-based communication allows real-time alerts and remote monitoring through Telegram and GSM modules. The overall concept and system workflow of the proposed firefighting robot are illustrated in Fig. 1.
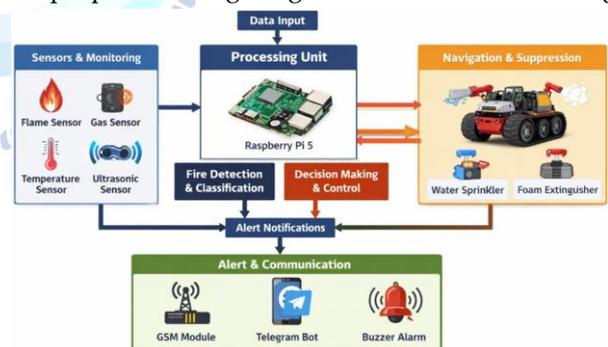

Figure 1: Overview of the proposed Smart Fire-Fighting Robot system architecture.

The proposed system aims to improve fire safety by combining intelligent detection, automated suppression, and remote monitoring into a single integrated platform. Such a system can be effectively deployed in industries, warehouses, laboratories, and residential environments where rapid fire response is essential.

RELATED WORK

Early research on fire detection primarily focused on image processing and video-based analysis techniques. Chen et al. [6] proposed a smoke detection system for

early fire alarming using video processing methods capable of identifying smoke patterns in surveillance footage. Similarly, Liu and Ahuja [17] introduced a vision-based fire detection approach that analyzed motion and color variations in video sequences. To¨reyin et al. [12] further developed a real-time computer vision-based method combining motion and color features for flame detection. Phillips et al. [11] also investigated flame recognition techniques in video sequences.

Several researchers explored statistical color models for flame detection. Celik et al. [9] developed a statistical color model to detect fire in video sequences by analyzing flame color distributions. Later, Celik and Demirel [13] introduced a generic color model to improve detection robustness. Horng et al. [16] proposed an image-based real-time flame detection method using color analysis technique.

Machine learning approaches were applied to improve detection accuracy. Ko et al. [10] presented a fire detection system using vision sensors combined with Support Vector Machines (SVM), demonstrating enhanced classification performance. Dimitropoulos et al. [24] introduced spatio-temporal flame modeling and dynamic texture analysis to improve the reliability of video-based fire detection systems.

Various image processing and segmentation techniques were also proposed. Marbach et al. [14] developed an im- age processing technique for detecting fire in video frames, while Celik [15] proposed a fast and efficient algorithm for flame detection using image analysis. Chen et al. [18] further improved detection performance using multi-feature fusion methods. Zhang and Hu [21] applied a 2D Otsu-based segmentation method to enhance object separation in image analysis tasks. Agarwal and Khandare [22], along with Yadav et al. [23], presented fire detection systems based on optimized image processing techniques.

In addition to camera-based detection, remote sensing technologies were explored for large-scale fire monitoring. Wing et al. [7] discussed the use of remote sensing and unmanned aerial systems for assessing forest fire impacts. Thomas and Nixon [8] proposed a near-infrared fire detection method capable of identifying fire signatures in forest environments. Rossi et al. [20] introduced a stereovision-based system to extract geometric characteristics of fire fronts for improved monitoring. Recent intelligent video analysis methods further enhanced detection performance. Cai et al. [25] and Shi et al. [26] proposed video-based fire and smoke detection systems combining spatial and temporal features for improved accuracy. Chen et al. [19] also introduced an early fire detection method based on image processing techniques.

Desai et al. [1] proposed a fire-fighting robot integrating flame sensors and water pumping mechanisms for automated suppression. Laly James et al. [2] developed an autonomous fire-fighting robot with improved mobility and obstacle avoidance capabilities. Abdul Kareem et al. [3] introduced FI-BOT, a smart fire-fighting robot using Arduino and multiple sensors for detection and extinguishing. Devansh V. Desai et al. [4] presented a robotic system combining detection and suppression techniques for efficient fire control. Shubham Shinde et al. [5] developed an Arduino-based fire-fighting robot focusing on cost-effective implementation.

The proposed Smart Fire-Fighting Robot with Raspberry pi 5 addresses this gap by combining advanced fire detection techniques, obstacle avoidance mechanisms, dual fire suppression systems, and real-time IoT-based alert notifications for enhanced safety and reliability.

PROPOSED SYSTEM ARCHITECTURE

The proposed Smart Fire-Fighting Robot is designed as an integrated system that combines intelligent fire detection, autonomous navigation, fire suppression mechanisms, and realtime communication. The overall architecture of the system is shown in Fig. 2. The Raspberry Pi 5 acts as the central controller that coordinates all sensing, processing, and actuation tasks within the robot.
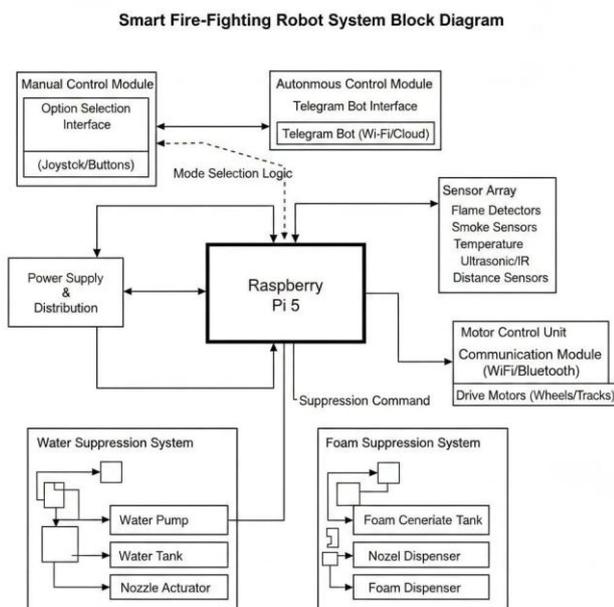
Figure 2: Block diagram of the proposed Smart Fire-Fighting Robot system architecture.

The system continuously monitors environmental conditions using multiple sensors including flame sensors, temperature sensors, and gas sensors. These sensors provide real-time data to the Raspberry Pi 5, enabling the system to detect fire, smoke, or abnormal temperature levels. Ultrasonic sensors are also incorporated to detect obstacles and allow safe navigation of the robot toward the fire location.

Based on the collected sensor data, the Raspberry Pi evaluates the severity of the detected fire and activates the appropriate suppression mechanism. For low-intensity fires such as paper, wood, or cloth fires, a water sprinkler system is activated to reduce the temperature and extinguish the flames. For high-temperature or electrical fires, the system activates a foam-based fire suppression mechanism.

The foam generation process used in the proposed system is illustrated in Fig. 3. When dry ice (solid CO_2) is placed in hot water, heat energy transfers from the water to the dry ice, causing sublimation. During this process, the dry ice rapidly converts from a solid state directly into carbon dioxide gas. The cold CO_2 gas cools surrounding water vapor present in the air, resulting in condensation and the formation of dense foglike foam. This foam spreads across the fire surface, reduces oxygen availability, absorbs heat, and effectively suppresses combustion.
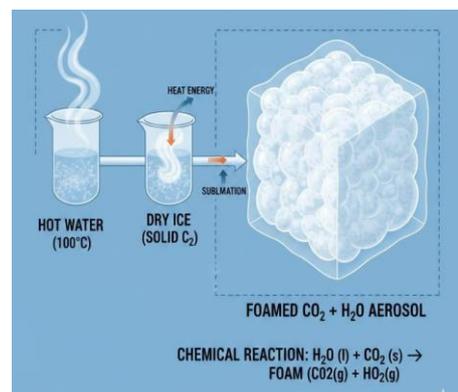

Figure 3: Foam formation using hot water and dry ice for fire suppression.

The robot is also equipped with mobility and communication modules. DC motors controlled through a motor driver allow the robot to move toward the fire source. The system supports both manual control through a Bluetooth interface and autonomous operation based on sensor inputs.

To enhance safety and monitoring, the robot integrates IoTbased communication. When a fire is detected, alert messages are sent to users through a Telegram Bot and GSM-based SMS notifications. In addition, a buzzer provides immediate local warning while an ESP32-CAM module enables live video streaming for remote monitoring.

By integrating sensing modules, intelligent processing, mobility systems, suppression mechanisms, and communication technologies, the proposed architecture provides a reliable and efficient solution for automated fire safety management in industrial, commercial, and residential environments.

METHODOLOGY

The proposed Smart Fire-Fighting Robot operates through a sequence of sensing, decision-making, navigation, and fire suppression processes. The system continuously monitors environmental conditions using multiple sensors and automatically activates the appropriate firefighting mechanism when a

fire hazard is detected. The methodology of the proposed system is divided into four major stages: environmental monitoring, fire detection and classification, navigation toward the fire source, and fire suppression with alert generation.

Initially, the flame sensor, gas sensor, and temperature sensor continuously collect environmental data and transmit it to the Raspberry Pi 5. The Raspberry

Pi processes this data in real time to identify abnormal conditions such as flame presence, smoke, or rapid temperature increase. If the detected values exceed predefined thresholds, the system confirms the presence of fire.

After confirming a fire event, the system classifies the fire based on temperature intensity. Low or moderate temperature fires are handled using a water sprinkler mechanism, while high-temperature or electrical fires trigger the foam-based suppression system. At the same time, the robot moves toward the fire source while avoiding obstacles using ultrasonic sensors.

Once the robot reaches an appropriate distance, the selected suppression system is activated to extinguish the fire. Simultaneously, the system sends alert notifications to the user through Telegram Bot and GSM SMS, and live monitoring is enabled using the ESP32-CAM module.

A. *Algorithm 1: Fire Detection*

Algorithm 1 Fire Detection Algorithm

1: Initialize Raspberry Pi and sensor modules

2: Read flame sensor value

3: Read temperature sensor value

4: Read gas sensor value

5: if flame detected OR gas level exceeds threshold OR temperature exceeds threshold then

6: Fire condition = TRUE

7: else

8: Fire condition = FALSE

9: end if

10: return Fire condition =0

B. *Algorithm 2: Fire Classification*

Algorithm 2 Fire Classification Algorithm

1: if temperature ¡ predefined threshold then

2: Fire Type = Low Intensity

3: Activate Water Sprinkler

4: else

5: Fire Type = High Intensity

6: Activate Foam Suppression

7: end if=0

C. *Algorithm 3: Robot Navigation*

Algorithm 3 Navigation and Obstacle Avoidance

1: Start robot movement

2: while fire source not reached do

3: Read ultrasonic sensor

4: if obstacle detected then

5:   Stop robot

6:   Change direction

7: else

8:   Move forward

9: end if

10: end while=0

D. *Algorithm 4: Alert and Monitoring*

Algorithm 4 Alert Generation

1: if fire detected then

2: Send Telegram notification

3: Send GSM SMS alert

4: Start ESP32-CAM live streaming

5: end if=0

The integration of these algorithms enables the robot to detect fire conditions, make intelligent decisions, navigate safely, and respond effectively to hazardous situations. This methodology ensures fast response time, reliable monitoring, and efficient fire suppression.

RESULTS AND DISCUSSION

The increasing frequency of fire accidents in industrial, commercial, and residential environments demands intelligent, fast, and reliable fire safety solutions. In response to this need, the proposed Smart Fire-Fighting Robot using Raspberry Pi 5 was successfully designed and implemented to detect and suppress fire hazards autonomously while minimizing human risk.

The developed system integrates multiple sensors including flame sensors, temperature sensors, and gas sensors to continuously monitor the surrounding environment. During experimental testing, the robot successfully detected fire presence, abnormal temperature rise, and hazardous gases in real time. Once a high-intensity flame was detected, the Raspberry Pi 5 processed the sensor data and activated the foam-based fire suppression mechanism, extinguishing the fire within a short response time. The implemented robotic platform is shown in Fig. 4.
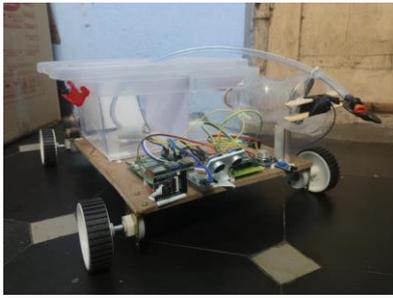
Figure 4: Smart Fire-Fighting Robot using Raspberry Pi 5.

Additionally, the foam-level monitoring system ensured that sufficient extinguishing material was available before activation, thereby improving system reliability. The IoT-enabled alert mechanism functioned efficiently by sending instant SMS notifications to users or authorities whenever critical conditions were detected. The robot demonstrated stable performance in both autonomous and manual control modes, allowing flexible operation in environments such as industrial plants, warehouses, and residential areas.

The Raspberry Pi 5 provided high processing speed, reliable multitasking capability, and seamless communication between sensors, actuators, and alert systems. Overall, the experimental results confirm that the proposed system is efficient, reliable, and capable of significantly reducing response time during fire emergencies.

E. Robot Movements

The robot was tested to evaluate its navigation capabilities and obstacle avoidance behavior. The primary objective was to enable the robot to patrol the environment and detect fire hazards efficiently.

Movement Sequence

- Forward movement at a controlled speed of approximately 10–15 cm/s.
- Left turn when an obstacle is detected on the front-left side.
- Right turn when an obstacle is detected on the front-right side.
- Backward movement when obstacles block the front path.
- Resume forward movement once the path becomes clear.

During testing, the robot demonstrated smooth navigation and reliable obstacle avoidance, ensuring collision-free movement. The robot movement interface and operational behavior are illustrated in Fig. 5.
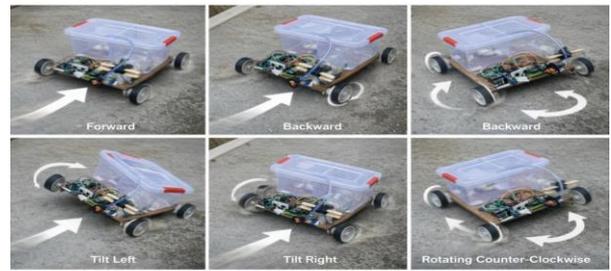

Figure 5: Robot movement and control interface.

The system supports both manual and automatic modes. Manual mode allows direct user control, while automatic mode enables the robot to operate independently using sensor inputs.

F. Fire Detection and Suppression (Low Temperature)

The system was tested for low-intensity fire scenarios such as paper or cloth fires. The flame sensor initially detects the presence of fire, while the temperature sensor confirms the fire intensity.

When the temperature remains below the predefined threshold of 36°C, the Raspberry Pi activates the water sprinkler system to suppress the fire. The suppression process is illustrated in Fig. 6.

Figure 6: Water sprinkler activation during low-temperature fire detection.

The system continuously monitors the flame and temperature values to ensure that the fire is completely extinguished. Once the flame disappears and the temperature returns to a safe level, the water sprinkler is automatically turned off as shown in Fig. 7.

Figure 7: Automatic shutdown of sprinkler after fire suppression.

Experimental observations showed that the water suppression mechanism effectively controlled low-intensity fires without requiring human intervention.

G. Fire Detection and Suppression (High Temperature)

High-temperature or electrical fire conditions were also tested. When the temperature exceeded the threshold value, the system classified it as an intense fire scenario and activated the foam-based fire suppression system.

The foam was generated using a combination of hot water and dry ice, producing dense foam capable of covering the fire surface and reducing oxygen supply. The activation of the foam system is illustrated in Fig. 8.
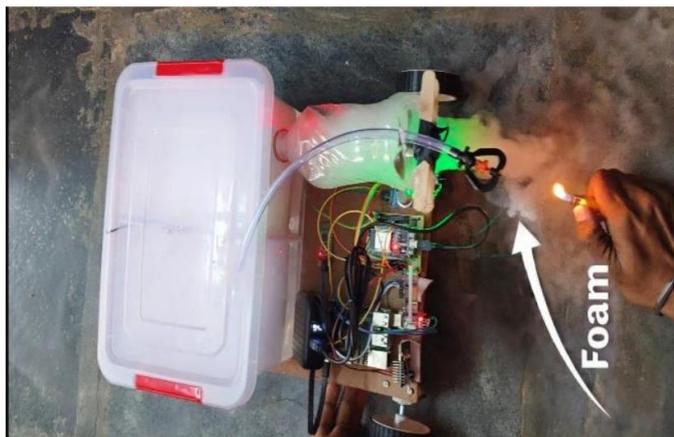

Figure 8: Foam-based fire suppression mechanism.

The foam spreads over the burning material, absorbs heat, and blocks oxygen, effectively stopping combustion. After the fire intensity decreases and temperature drops below the threshold, the system automatically turns off the foam mechanism as shown in Fig. 9.
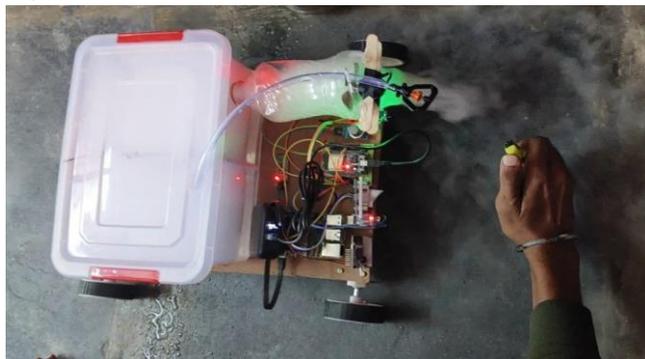

Figure 9: Automatic shutdown of foam suppression system.

The experiments confirmed that foam-based suppression provides faster coverage and prevents re-ignition in high temperature fire conditions.

H. Fire Alert via Telegram Bot and GSM

To enhance emergency communication, the system integrates both GSM-based SMS alerts and Telegram-based IoT notifications. When fire is detected, the Raspberry Pi 5 sends real-time alerts to users through both communication channels.

The GSM-based alert system successfully transmitted warning messages such as "FIRE DETECTED PLEASE CHECK" to the registered mobile number, as illustrated in Fig. 10.

Figure 10: Fire alert notification via GSM SMS.

Similarly, the Telegram Bot provided instant alerts along with sensor readings and system status updates as shown in Fig. 11.

Figure 11: Fire alert notification via Telegram bot.

Experimental trials confirmed reliable communication and minimal delay in message delivery, making the system effective for remote monitoring.

I. Buzzer Alert System

In addition to remote alerts, a local buzzer warning system was implemented to provide immediate on-site alerts. When the flame or temperature sensor detected hazardous conditions, the Raspberry Pi instantly triggered the buzzer. The alert remained active until the fire condition was cleared or the system was reset.

The buzzer alert mechanism is illustrated in Fig. 12.

Figure 12: Local buzzer alert during fire detection.

The buzzer response time was nearly instantaneous, ensuring rapid warning to nearby personnel.

Overall, the experimental results demonstrate that the proposed Smart Fire-Fighting Robot effectively detects fire hazards, navigates autonomously, activates appropriate suppression systems, and provides reliable real-time alerts.

CONCLUSION

This paper presented the design and implementation of a Smart Fire-Fighting Robot using Raspberry Pi 5 capable of detecting and suppressing fire hazards autonomously. The developed system integrates multiple environmental sensors, including flame, gas, and temperature sensors, to continuously monitor surroundings and identify fire conditions in real time. By analyzing sensor data, the Raspberry Pi 5 intelligently determines the severity of the fire and activates an appropriate suppression mechanism.

A dual fire suppression system consisting of a water sprinkler and a foam-based extinguisher was successfully implemented. Experimental results demonstrated that the water sprinkler effectively controlled low-intensity fires, while the foam-based system provided efficient suppression for hightemperature or electrical fires. The integration of obstacle detection and motor control enabled the robot to navigate safely toward the fire source in both manual and autonomous modes.

The proposed system also incorporated IoT-based communication through Telegram Bot and GSM modules, allowing real-time alerts and remote monitoring. Additionally, the buzzer alert mechanism provided immediate local warnings, improving overall safety. The results confirm that the system is reliable, responsive, and capable of reducing human exposure to dangerous fire situations.

Overall, the Smart Fire-Fighting Robot with Raspberry pi 5 offers a cost-effective and intelligent solution for modern fire safety applications in industrial plants, warehouses, laboratories, and residential environments. Future improvements may include the integration of advanced computer vision techniques, machine learning-based fire prediction, improved navigation using SLAM algorithms, and enhanced autonomous decision-making capabilities for large-scale fire management.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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