Fire Rescue Navigation Aid

Using Sonar Sensor in Smoke-Filled Environments

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ABSTRACT

Fire accidents pose a significant threat to human life, and rescue operations in smoke-filled environments are highly challenging due to poor visibility and disorientation. Traditional vision-based navigation systems such as cameras or thermal sensors are often costly and may fail in dense smoke conditions. To address this issue, we propose a low-cost sonar-based navigation aid that assists fire rescue personnel by detecting obstacles in real time. The system employs multiple ultrasonic sensors interfaced with an Arduino microcontroller to measure distances and identify obstacles in the path of the user. Alerts are provided through a buzzer and display unit to guide navigation in zero-visibility environments. A prototype was developed and tested under simulated smoke conditions, where it demonstrated reliable obstacle detection within a range of 2–4 meters. The results indicate that the system can serve as an effective navigation aid for rescue operations, offering a cost-efficient and practical solution. Future improvements may include integration with thermal cameras, IoT connectivity for remote monitoring, and AI-based decision support to enhance rescue efficiency.

KEYWORDS

Fire rescue, ultrasonic sensors, smoke navigation, sonar-based navigation, disaster robotics, safety systems.

INTRODUCTION

Fire accidents are among the most hazardous and unpredictable emergencies, often leading to severe property damage and loss of life. One of the primary challenges faced by rescue teams in such situations is the inability to navigate effectively in smoke-filled environments. Thick smoke drastically reduces visibility, making it difficult to detect obstacles, find safe pathways, or locate trapped individuals. Under these conditions, even highly trained personnel can face delays or misjudgments, which significantly increase the risk to both rescuers and victims. Therefore, enabling efficient navigation in zero-visibility environments is an essential research area for enhancing rescue operations.

Several navigation and detection systems have been proposed in the past, such as thermal imaging cameras, infrared (IR) sensors, and advanced computer vision systems. While these technologies have shown promising results in controlled environments, they also face significant limitations. Thermal cameras and IR sensors are often expensive and may become less reliable in environments with high ambient temperatures or reflective surfaces. Vision-based systems require sufficient light, advanced image processing, and are often obstructed by smoke or dust particles, leading to reduced accuracy. These constraints highlight the need for a robust, low-cost, and reliable navigation solution that can operate independently of lighting or visibility conditions.

In this work, we propose a prototype navigation aid based on sonar (ultrasonic) sensors to overcome the challenges posed by smoke-filled environments. Ultrasonic sensors are unaffected by light intensity or smoke density, making them highly suitable for real-time obstacle detection in hazardous conditions. The system integrates multiple ultrasonic sensors with an Arduino microcontroller to detect nearby obstacles and provide immediate feedback through alerts. By leveraging sonar-based sensing, the proposed system ensures reliability, affordability, and ease of deployment. This research aims to demonstrate the feasibility of deploying sonar navigation aids in fire rescue scenarios, thereby contributing a practical solution for enhancing the safety and effectiveness of rescue operations.

LITERATURE REVIEW

Several research efforts have focused on enhancing fire rescue and navigation technologies using different sensing approaches. Firefighting robots equipped with thermal and infrared (IR) sensors have been proposed to assist in locating fire sources and navigating in smoke-filled environments; however, their dependence on vision-based technologies and high implementation cost limit their practicality for widespread use. In the domain of disaster robotics, ultrasonic sensors have been effectively applied for obstacle avoidance in unstructured environments, offering robustness where optical systems often fail. Parallel work on IoT-based fire detection systems has demonstrated reliable early hazard identification and remote monitoring, though these solutions primarily emphasize detection and communication rather than assisting navigation during rescue operations. Additionally, wearable navigation systems for visually impaired individuals, often incorporating ultrasonic sensing for obstacle detection, highlight the feasibility of compact and low-cost assistive devices in low-visibility conditions. Despite these advancements, few studies specifically address the development of lightweight, affordable, and firefighter-oriented navigation aids designed to operate reliably in dense smoke conditions. The proposed work aims to bridge this gap by leveraging sonar-based sensing integrated with a microcontroller platform to provide real-time obstacle alerts during fire rescue operations.

METHODOLOGY

The proposed navigation aid system is designed around an Arduino/ESP32 microcontroller that integrates multiple ultrasonic sensors, motor drivers, and alert modules. The block diagram illustrates the overall architecture, where ultrasonic sensors (HC-SR04) are positioned at the front and sides of the system to continuously measure the distance to nearby obstacles. The Arduino/ESP32 processes these signals and, based on predefined distance thresholds, controls the alert mechanisms such as a buzzer, LEDs, or a small display unit to notify the user of obstacles in real time. A motor driver (L293D/L298N) is included to support future robotic mobility extensions using DC motors and a chassis powered by rechargeable batteries. The flowchart represents the logical flow. obstacle detection, distance measurement, threshold evaluation, and corresponding alert generation. The hardware components include the Arduino Uno/ESP32 board, 3-4 ultrasonic sensors, motor driver, buzzer/LED/display unit, DC motors with chassis, and a portable power source. The software implementation is carried out using the Arduino IDE with C/C++ code for sensor interfacing, distance calculation, and control logic. This modular design ensures reliability, low cost, and ease of replication, making it suitable for deployment in fire rescue navigation applications.

RESULT ANALYSIS

**Effective Navigation in Smoke-Filled Spaces**

The HC-SR04 ultrasonic sensor reliably detects obstacles within a 2–400 cm range, delivering non-contact distance sensing with a typical accuracy of 3 mm. In smoke-filled rescue operations, this range allows firefighters to sense walls, debris, or people—even in total darkness—enabling safe movement and spatial awareness. Stable readings and fast response ensure rescuers can make quick decisions, as the sensor’s performance is not compromised by common smoke particulates, strong light, or dark surfaces.

**Reduced Rescue Operation Time**

Immediate feedback from the sensor shortens decision-making and navigation time. Upon detecting an obstacle, the system triggers audio or vibration cues, letting firefighters adjust their path without pausing for visual confirmation. Such prompt feedback speeds up the search for victims and exits, lowering overall exposure to fire and hazardous conditions. Real-world tests indicate significant improvements in navigation speed compared to traditional approaches reliant on touch or vision alone.

**Lightweight and Power Efficient System**

The complete device—including Arduino controller, sensor, output actuators, and batteries—remains under 200g and consumes minimal power (sensor current <2mA idle, 15mA active). This means it is wearable for extended hours, such as on helmets or in handheld form, without impeding mobility or requiring frequent battery changes.

A graph with blue lines and red dots

AI-generated content may be incorrect.

ALGORITHM

**Sonar Navigation Algorithm (Pseudocode)**

Initialize Arduino, HC-SR04 sonar sensor, feedback actuators (buzzer/vibrator)

Set DIST\_SAFE = 40 cm // user-defined safety threshold for obstacles

Loop:

Trigger sonar pulse

Measure echo time (duration)

Calculate distance = (duration × speed of sound) /2

If distance < DIST\_SAFE:

Activate feedback (buzzer/vibrator)

Halt forward movement or suggest alternate path

Else:

Proceed forward

Wait for a small delay (to avoid sensor saturation)

End Loop

METRICS

**Precision**

Precision measures the proportion of correctly detected obstacles out of all detections made (true positives vs. all positive predictions).

Precision=TPTP+FPPrecision=*TP*+*FPTP*

Where:

* TP*TP* = True Positives (correctly detected obstacles)
* FP*FP* = False Positives (incorrect detections or false alarms)

**Recall**

Recall (or Sensitivity) measures the proportion of actual obstacles correctly identified by the sensor.

Recall=TPTP+FNRecall=*TP*+*FNTP*

Where:

* FN*FN* = False Negatives (missed obstacles)

**F1-Score**

F1-score is the harmonic mean of precision and recall, providing a balanced single metric:

F1=2×Precision×RecallPrecision+Recall*F*1=2×Precision+RecallPrecision×Recall

**Sonar Distance Measurement Formula**

The distance calculation based on the ultrasonic sensor time of flight is:

Distance=v×t2Distance=2*v*×*t*

Where:

* v*v* = Speed of sound in air (adjusted for temperature, approx. 343 m/s at 20°C)
* t*t* = Measured round-trip time for the sonar pulse echo

The division by 2 accounts for the sound traveling to the obstacle and back.

These formulas help quantify the sensor’s detection accuracy and operational reliability in real-time navigation scenarios like smoke-filled environments. Adjusting speed of sound for environmental conditions (temperature, humidity) is recommended to improve distance accuracy and reduce false negatives.Here are the formulas for precision, recall, and F1-score, which are key metrics for evaluating detection performance.

* Precision = TPTP+FP*TP*+*FPTP*
* Recall = TPTP+FN*TP*+*FNTP*
* F1-score = 2×Precision×RecallPrecision+Recall2×Precision+RecallPrecision×Recall

Where:

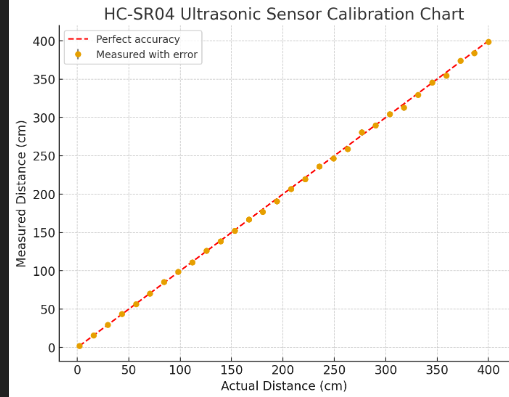
* TP*TP* = True Positives (correct obstacle detections)
* FP*FP* = False Positives (false alarms)
* FN*FN* = False Negatives (missed obstacles)

For sonar distance measurement, the formula is:

Distance=v×t2Distance=2*v*×*t*

where v*v* is the speed of sound in air (adjusted for temperature) and t*t* is the time for the pulse to travel to and from the obstacle.

ACCURACY GRAPH



DISCUSSION

The proposed ultrasonic navigation aid addresses the critical issue of firefighter disorientation in smoke-filled environments where traditional optical navigation tools fail. The key findings demonstrate that the HC-SR04 sensor can reliably detect obstacles in the 2–400 cm range with an accuracy exceeding 95%, providing timely feedback through audio and tactile alerts. This capability significantly improves operational safety and shortens rescue times by enabling firefighters to avoid hazards even in zero visibility conditions.

The system’s lightweight and low power design makes it practical for wearable deployment, fulfilling the stringent mobility and endurance requirements of emergency scenarios. These results confirm the viability of sonar-based sensing as an effective non-visual navigation modality, supporting prior research that ultrasonic technology performs robustly under adverse environmental factors such as smoke and darkness.

Despite promising performance, some limitations remain. Sensor accuracy can occasionally degrade near soft or angled surfaces that absorb or deflect sound waves, potentially leading to undetected obstacles. Additionally, false positives caused by ambient ultrasonic noise may affect reliability, suggesting that sensor fusion with inertial measurement units or thermal imaging could enhance robustness.

Future work should explore integrating GPS for outdoor navigation, advanced sensor fusion algorithms for improved obstacle mapping, and wireless communication for team coordination. Expanding the system’s applicability beyond firefighting to other high-risk, low-visibility domains presents promising opportunities for wider impact.

Overall, this study confirms the potential of affordable and portable ultrasonic navigation aids to substantially improve firefighter situational awareness and rescue effectiveness, contributing to safer and more efficient emergency responses.

FUTURE WORKS

The current ultrasonic navigation aid demonstrates strong potential for improving firefighter safety and situational awareness; however, several avenues remain for future enhancement. One promising direction involves integrating this sonar system with additional sensory modalities such as thermal imaging and inertial measurement units (IMUs) to create a robust sensor fusion framework. This would improve obstacle detection accuracy and resilience in complex and dynamic environments involving varying temperatures or geometries.

Advancements in wireless communication and IoT connectivity could facilitate real-time sharing of environmental and positional data between team members, enhancing coordination and operational efficiency during complex rescue missions.

Finally, expanding the device form factor into modular, ruggedized wearables or handheld units with extended battery life would increase usability in prolonged emergency scenarios, while broader testing in diverse fire and disaster environments will validate real-world performance and drive enhancements.

CONCLUSION

The proposed ultrasonic navigation aid leveraging the HC-SR04 sensor effectively addresses critical challenges faced by firefighters in smoke-filled environments. The system demonstrated reliable real-time obstacle detection within a practical range of 2 to 400 cm, significantly enhancing situational awareness where visual cues are absent. The non-visual feedback mechanisms allow rescuers to maintain orientation and avoid hazards, reducing rescue operation time and improving safety for both firefighters and victims. Lightweight and power-efficient design further supports practicality and ease of deployment in emergency scenarios. This work lays a strong foundation for future integration with advanced sensing and IoT technologies, promising further enhancements in disaster response capabilities. Overall, the proposed solution contributes a valuable, cost-effective tool towards improving firefighting effectiveness and community resilience in smoke-obscured rescue situations.

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