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Dehazing and Sensor Fusion for Safe Navigation in Low-Visibility Environments

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***Abstract*—**Effective navigation in outdoor conditions is crucial for any autonomous systems such as self-driving vehicles, mobile robots, and drones. Adverse conditions including fog, haze, or smoke can affect the ability of the systems to see clearly due to the scattering effect of light, lowering contrast levels and eliminating structural information.

Therefore, an algorithm-based solution integrating image de-hazing techniques and sensor fusion is presented. The Dark Channel Prior (DCP) method is used for estimating the atmo-sphere light and obtaining the true light of the scene. Moreover, the CLAHE algorithm is applied on the LAB color channel to increase the contrast without introducing more noise into the image.

The proposed solution uses an ultrasonic sensor for obstacle detection, and its data is fused with visual input. The architecture consists of an ESP32-CAM camera module for acquiring images, an Arduino UNO board for working with the ultrasonic sensor, and a Flask application as a backend, utilizing OpenCV and NumPy libraries.

Experimental results have shown improvement in image clar-ity, contrast, and increased obstacle detection efficiency.

Keywords: Image Dehazing, Sensor Fusion, Dark Channel Prior, CLAHE, Autonomous Navigation, Embedded Systems, Low-Visibility Systems

I. Introduction

One of the main elements in intelligent systems such as autonomous vehicles, mobile robots, and UAVs is autonomous navigation. Such systems use vision-based perception to understand and make decisions in the current environment. While cameras are inexpensive and have enough information in the images, they are heavily influenced by environmental factors.

Poor weather conditions, including fog, haze, smokes, and dust in outdoor scenes, cause degradation due to light attenuation. Poor weather conditions lead to low contrast, bad visibility, and blurry objects' boundaries, which, in turn, causes unreliability of some operations, like object detection and lane detection.

Some classical approaches, such as histogram equalization, can only increase the image's contrast and do not help recover real scene radiance since they ignore the role of the atmosphere. Restoration approaches, especially the ones based on atmospheric scattering model, are more appropriate for recovering scene's radiance. For example, one of the widely-used approaches is Dark Channel Prior (DCP).

But image processing in itself may not be sufficient in case of extremely low visibility conditions. Sometimes vision systems fail because of too low visibility conditions or lack of details in the scene. In such cases, sensor fusion should be applied.

This paper introduces a combined framework that merges image dehazing and sensor fusion for enhanced navigation. The image processing framework will employ the DCP algorithm for removing haziness from the images and then CLAHE for enhancing their contrast. In addition, an ultrasonic sensor is incorporated to measure the distance to obstacles, offering depth information regardless of the image quality.

Sensor fusion enables the combination of both visual information and sensor inputs, enhancing the decision-making process. The use of sensors becomes paramount when visual information is not reliable, ensuring better navigation than relying only on visual information.

The proposed design will be applied in real-time and in a cost-effective manner, with the ESP32-CAM capturing images, the Arduino UNO processing sensor information, and Flask server with OpenCV improving the images.

The key contributions of this research can be summarized as follows:

- Creation of a real-time image dehazing mechanism based on DCP and CLAHE.
- Incorporation of ultrasonic sensor-based obstacle detection.
- Development of a sensor fusion algorithm.
- Low-cost and portable framework development.
- Enhanced performance under adverse weather conditions.

The rest of the paper is organized as follows: Section II reviews related work, Section III describes the system architecture, Section IV explains the methodology, Section V presents implementation details, Section VI discusses results, and Section VII concludes the paper.

II. Related Work

The topics of image dehazing and sensor fusion have attracted significant attention in the domains of computer vision and autonomous navigation. Current strategies can generally be divided into three groups: enhancement methods, restoration methods, and learning methods.

A. Enhancement-Based Methods

Enhancement methods focus on enhancing the quality of the degraded images using non-physical modeling techniques. Examples of popular enhancement methods include histogram equalization, contrast stretching, and Retinex algorithms. Histogram equalization adjusts global contrast by redistributing the intensity of pixels, while the Retinex model assumes that haze can be decomposed into illumination and reflectance.

Although enhancement methods offer simple computation and implementation, they assume a constant degradation due to haze and ignore the scattering effect at different depths. This leads to over-enhancement, amplifying noise and distorting colors, making them less applicable to scene reconstruction tasks.

B. Restoration-Based Methods

Restoration methods depend on physical modeling of atmospheric scattering phenomena to restore the scene radiance. The restoration-based techniques make use of physical models of the atmospheric scattering process in order to estimate the original scene radiance. According to the most common model of atmospheric scattering, the formation of the hazy image results from the summing up of attenuated scene radiance and airlight.

Among the existing restoration-based techniques, the most famous one is the Dark Channel Prior (DCP). It is based on the assumption that in most areas of an un-hazed image, excluding the sky region, there exists at least one channel with extremely low intensity. This probability distribution can be used for the estimation of the transmission maps and atmospheric light using only one image.

There have been many developments in improving the DCP technique. For instance, guided filtering was used to improve the accuracy of estimating the transmission maps without applying time-consuming soft matting algorithms. Moreover, other approaches take into account the boundary conditions, thus providing a solution for avoiding halos around objects. Median filters and bilateral filters were also tested as efficient tools for computational optimization.

Even though they yield promising results, restoration-based algorithms are still struggling to process bright areas like the sky, and estimating the atmospheric lighting is always a delicate task. Moreover, they can be ineffective under extremely thick fog situations.

C. Learning-Based Methods

The recent advances in the field of deep learning have brought to light data-driven dehazing algorithms that try to learn the mappings between the hazy image and its clean version by means of CNNs and other encoder-decoder architectures.

Some successful models, such as DehazeNet and AOD-Net, learn complicated hazy distributions on synthetic datasets and use sophisticated approaches that integrate attention and multi-scale features into more modern architectures.

Nevertheless, data-driven approaches usually need huge amounts of labeled data to train and are prone to domain shift problems when used for real-life applications due to their high computational complexity.

D. Sensor Fusion in Autonomous Systems

The fusion of sensors has been increasingly important in the development of navigation systems. Fusion allows for enhanced performance when several sensors such as cameras, LiDARs, radars, and ultrasonic sensors work together.

The use of ultrasonic sensors is well-known for short-range detection of obstacles since they are inexpensive and relatively simple to implement. Their main advantage lies in the fact that they give distance measurements irrespective of environmental illumination, thus enabling their use alongside vision technologies.

Sensors' data fusion can take place at several levels – low, feature, and decision-level fusion. Decision-level fusion consists of fusing the results of different subsystems. This type of fusion is frequently used in embedded solutions because of its simplicity and versatility.

E. Motivation for Proposed Work

It has been found from the literature review that although image enhancement methods like dehazing help to make images clearer, they alone cannot guarantee reliable navigation in any circumstances. Moreover, relying only on sensors deprives one of additional information acquired by the camera.

A combined approach seems promising. In particular, using the DCP method for dehazing together with ultrasonic sensors for detecting obstacles will be beneficial.

III. Problem Statement and Objectives

A. Problem Statement

In most cases, autonomous navigation systems depend on visual sensors, including cameras to understand their environment. However, when operating in real outdoor environments, weather-related phenomena, including fog, haze, and smoke, negatively impact images by causing blurring effects. In this case, light scattering and attenuation occur due to which, objects are less discernible and less contrasted.

As a result, the reliability of vision-based approaches decreases and fails to detect any target or identify potential obstacles. Such an issue poses significant threats in situations where safety concerns arise, especially when designing autonomous robots.

Current solutions focus either only on image enhancement or using alternative sensor technologies like lidar and radar. In both cases, drawbacks include additional costs or limitations. Hence, it becomes necessary to propose a low-cost solution, which can still operate in harsh conditions.

B. Objectives

The aim of this project is to come up with an efficient navigation system that will be able to perform well in the environment where visibility is poor. This will be done through the following steps:

- Developing a dehazing algorithm based on the DCP to correct the corrupted images.
- Visual enhancement through the CLAHE technique to improve image quality.

- Integrating an ultrasonic sensor to detect obstacles and measure their distance in real time.
- Sensor fusion approach implementation to provide enhanced decision-making capability.
- Designing and implementing a cost-effective portable system utilizing embedded systems components.

IV. System Overview

The design of the proposed system will involve a fusion of the use of image processing technology using vision and sensors for obstacle detection. This will be accomplished using two main processes; vision pipeline and sensor pipeline to achieve navigation functionality.

A. Vision Pipeline

Vision pipeline entails the acquisition and improvement of images that are hindered by haze and poor visibility. Steps involved include:

- Acquisition of the image using the ESP32-CAM
- Transmission of the image wirelessly to the processing server
- Use of Dark Channel Prior (DCP) algorithm for image dehazing
- Enhancement of the contrast of the image using Contrast Limited Adaptive Histogram Equalization (CLAHE)

This pipeline will ensure improved visibility, image clarity, and quality.

B. Sensor Pipeline

The sensor pipeline helps gather environmental information irrespective of the conditions present visually. This involves:

- Using the HC-SR04 ultrasonic sensor to measure distance
- Sensor data processing using Arduino UNO
- Monitoring obstacle presence constantly

The sensor pipeline guarantees accurate obstacle identification in all conditions.

C. Fusion Strategy

Data gathered through vision and sensors is integrated using a decision-level approach. How this process works is detailed below:

- If there is good visibility, navigation is made based on improved visual data.
- When visibility is poor, more emphasis will be put on sensor data.
- An alarm will be raised if obstacles are found in close proximity.

This helps make the system robust and guarantees safety.

D. System Workflow

The workflow of the entire system can be described as follows:

1) Capture image with ESP32-CAM
2) Transfer the captured image to the backend server through Wi-Fi
3) Perform dehazing and enhancement on the image
4) Measure distance using ultrasonic sensor
5) Fuse visual and sensory data
6) Present result to users through interface

The system has been developed for real-time implementation and thus operates with minimum latency.

V. System Architecture

This particular model is built on a modular architecture comprising both hardware and software elements necessary for real-time processing. The architecture includes two main layers, which can be referred to as hardware architecture and software architecture. All elements work together ensuring smooth data acquisition, processing, and decision making.

A. Hardware Architecture

As it was already mentioned above, the hardware architecture is aimed at being compact, cost-effective, energy-saving, and, at the same time, guaranteeing efficient work in a real-time environment. The hardware layer includes such modules as:

- **ESP32-CAM module:** This module is responsible for image capturing and wireless transfer of the received pictures to the backend server. ESP32-CAM combines the function of an onboard camera and Wi-Fi communication channel, so that it can be used for IoT-related purposes.
- **Arduino UNO:** As a microcontroller, Arduino UNO is supposed to perform data acquisition and processing. Specifically, Arduino UNO is used for acquiring data about the distance using HC-SR04 ultrasonic sensor.
- **HC-SR04 Ultrasonic Sensor:** This module performs object detection based on the measurement of the distance between the system and the object.
- **Power Supply Unit:** In order to power the system portably, a lithium-ion battery will be utilized. A buck converter will also be deployed to ensure stable voltage regulation for all other devices in the system.
- **Communication Interfaces:** Communication will be done in serial mode between Arduino and the sensors. Image data transmission from ESP32 to the backend server will be done using WiFi communication mode.

Hardware integration of components is done in a manner that image data and sensor data are captured simultaneously.

B. Software Architecture

The software architecture takes a layered structure that provides for modularity and scalability of design. The architecture consists of the following layers:

- **Embedded Layer:** In this layer, there is the firmware for ESP32 and Arduino chips. Specifically, ESP32 captures images and transfers them over to the server. On the other hand, the Arduino captures inputs from the ultrasonic sensors.
- **Backend Processing Layer:** A backend is created using Flask that receives data and carries out some image processing tasks including dehazing and contrast enhancement.

- **Image Processing Module:** This module utilizes the algorithms related to DCP and CLAHE for image enhancement tasks.
- **Fusion Module:** This module incorporates decision level fusion for combining the input data captured by the ultrasonic sensors along with the processed images.
- **Frontend Interface:** A frontend user interface is created that shows the processed images in real time.

C. Data Flow Architecture

The system uses a continuous flow of data architecture as below:

1) ESP32-CAM captures images and forwards them to the backend server over WiFi.
2) Distance data from the ultrasonic sensor is sent by Arduino to the backend server.
3) The backend processes the image by applying dehazing and enhancement techniques.
4) Fusion of image data and sensor data takes place.
5) Output is shown through the frontend application.

D. Design Considerations

The system is developed bearing in mind the following points:

- **Real-Time Processing:** Efficient algorithms and communication protocols will ensure minimal delays.
- **Affordable Pricing:** Use of ESP32 and Ultrasonic sensors will provide a cheaper solution than the use of LiDAR.
- **Scalability:** Future scalability of the system is ensured by modular architecture.
- **Portability:** Since the system will run on batteries, it can be deployed in any environment.

VI. Methodology

The developed system improves image visibility and navigation safety through the use of image dehazing techniques combined with contrast enhancement, followed by sensor fusion. The approach used in the design consists of three major components, including atmospheric modeling, image dehazing based on DCP, and CLAHE-based contrast enhancement.

A. Atmospheric Scattering Model

The process of hazing occurs due to the effects caused by the presence of fog, mist, or dust particles. The atmospheric scattering model describes this phenomenon, stating that the obtained image comprises scene radiance attenuated with airlight.

$$I(x) = J(x)t(x) + A(1 - t(x)) \tag{1}$$

Transmission refers to the part of light transmitted directly to the camera without being scattered, and it is dependent on scene depth and scatter conditions.

$$t(x) = e^{-\beta d(x)} \tag{2}$$

B. Dark Channel Prior (DCP)

The basic principle underlying the dark channel prior technique is that in most images taken outdoors that lack haze, there will be a color channel in at least one pixel that contains negligible intensities.

The dark channel is calculated over local patches, and the obtained data can be used to estimate the amount of haze present in the image.

$$J^{dark}(x) = \min_{c\in\{r,g,b\}} \min_{y\in\Omega(x)} J^c(y) \tag{3}$$

$$t(x) = 1 - \omega \min_{c} \min_{y\in\Omega(x)} \frac{I^c(y)}{A^c} \tag{4}$$

C. Estimation of Atmospheric Light

The accurate estimation of atmospheric light is essential for achieving proper dehazing results. The estimation of atmospheric light is done based on choosing the brightest pixels from the dark channel and from the original image.

D. Transmission Refinement

The transmission map generated initially might have some noises and irregularities because of the patch-wise approach used to estimate the transmission map. In order to refine the transmission map, filtering techniques like guided filtering can be used.

E. Recovery of Scene Radiance

After having the transmission map and atmospheric light, the haze removal process can be done by applying the right formula without suffering from instability issues because of the very low value of transmission.

$$J(x) = \frac{I(x) - A}{\max(t(x), t_0)} + A \tag{5}$$

F. Contrast Enhancement Using CLAHE

After the process of dehazing, there is a possibility that the image may be lacking in terms of contrast. To solve this problem, CLAHE is used in this methodology.

This procedure includes:

- Conversion of the image from RGB to LAB colorspace
- Equalization of the histogram for the L channel
- Limiting the amplification of contrast in order to limit noise
- Conversion of the image to RGB colorspace

The CLAHE algorithm enhances the local contrast and brings out fine details in an image without causing too much noise.

G. Sensor Data Fusion with the Enhanced Image

The result after the application of DCP and CLAHE processes is then fused with the distance data acquired from the ultrasonic sensor.

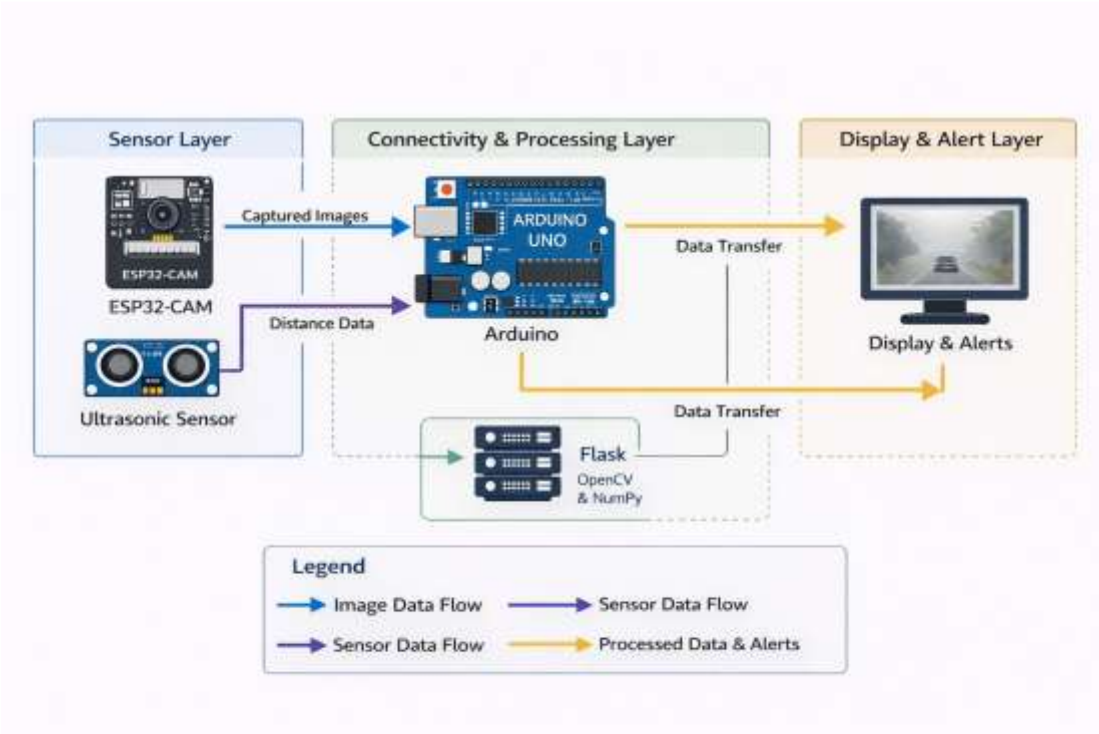

Fig. 1. System Architecture Diagram

H. Complete Methodology Process Flow

The whole procedure involved can be summarized in the following list:

1) Obtain hazy image from ESP32-CAM
2) Atmospheric Light Estimation
3) Dark Channel Computation
4) Transmission Map Estimation
5) Transmissions Optimization
6) Scene Radiance Recovery
7) CLAHE for Contrast Enhancement
8) Distance Sensor Data Acquisition
9) Sensor Data Fusion

VII. Algorithm and Data Flow

This section describes the step-by-step procedure followed by the proposed system, including the image dehazing algorithm, contrast enhancement, and sensor fusion logic. The overall workflow ensures real-time processing and reliable navigation under low-visibility conditions.

A. Overall Algorithm

The proposed system operates by combining image processing with sensor-based decision-making. The algorithm can be summarized as follows:

1) Capture image using ESP32-CAM
2) Transmit image to backend server via WiFi
3) Compute dark channel of the image
4) Estimate atmospheric light
5) Estimate transmission map
6) Refine transmission map using filtering
7) Recover scene radiance (dehazed image)
8) Apply CLAHE for contrast enhancement
9) Acquire distance data from ultrasonic sensor
10) Apply sensor fusion logic
11) Generate final output and display results

B. DCP-Based Dehazing Algorithm

Input: Hazy Image $I(x)$
Output: Dehazed Image $J(x)$

1) Convert image into RGB channels
2) For each pixel, compute minimum intensity across channels
3) Apply minimum filter over local patches to obtain dark channel
4) Identify brightest pixels in dark channel
5) Estimate atmospheric light A
6) Normalize image using atmospheric light
7) Estimate transmission map $t(x)$
8) Apply filtering to refine transmission map
9) Recover final image using atmospheric model

C. CLAHE Enhancement Algorithm

Input: Dehazed Image
Output: Enhanced Image

1) Convert image from RGB to LAB color space
2) Extract L (lightness) channel
3) Divide image into small tiles
4) Apply histogram equalization on each tile

5) Limit contrast to avoid noise amplification
6) Interpolate neighboring tiles for smooth transitions
7) Merge channels and convert back to RGB

D. Sensor Fusion Algorithm

The sensor fusion mechanism combines visual data with distance measurements to ensure reliable navigation.

Input: Enhanced Image, Distance Data

Output: Navigation Decision

1) Read distance from ultrasonic sensor
2) Check visibility level of enhanced image
3) If distance ¡ threshold:
    - Trigger obstacle alert
4) Else if visibility is low:
    - Rely more on sensor data
5) Else:
    - Use visual data for navigation
6) Output final decision

E. Pseudocode Representation

```
Input: Hazy Image I, Distance d

1. Capture image I
2. Compute dark channel
3. Estimate atmospheric light A
4. Estimate transmission t(x)
5. Refine transmission
6. Recover image J(x)
7. Apply CLAHE to J(x)

8. Read distance d

9. If d < threshold:
       Output = ''Obstacle Detected''
   Else if visibility low:
       Output = ''Use Sensor Guidance''
   Else:
       Output = ''Normal Navigation''

10. Display output
```

F. Data Flow Pipeline

The system follows a continuous data processing pipeline:

1) Image captured by ESP32-CAM
2) Image transmitted via WiFi
3) Backend server processes image using DCP and CLAHE
4) Sensor data received from Arduino
5) Fusion logic combines both inputs
6) Output displayed on user interface

G. Real-Time Considerations

To ensure real-time performance, the following optimizations are implemented:

- Efficient image processing using OpenCV libraries
- Lightweight communication protocols
- Parallel processing of image and sensor data
- Reduced computational overhead through optimized filtering

VIII. Implementation Details

The proposed solution makes use of the integration of hardware and software processing pipeline to provide real-time operation. This includes efficient interaction between different modules, optimized image processing, and reliable sensing.

A. Hardware Implementation

The hardware module is designed to be compact, portable, and affordable. The main components used for hardware implementation include:

- **ESP32-CAM:** The ESP32-CAM device captures images and transmits them over the wireless network. It is programmed using the Arduino IDE for the purpose of image transmission through HTTP request over WiFi.
- **Arduino UNO:** Arduino UNO reads ultrasonic sensor data and sends distance information to the backend system. It is programmed using embedded C/C++ language.
- **Ultrasonic sensor HC-SR04:** The sensor is interfaced with the Arduino board via two wires, one connected to the trigger pin and the other one to the echo pin. Distance is measured based on ultrasonic pulses sent and received by the sensor.

B. Sensor Data Processing

The ultrasonic sensor determines the distance between the object and itself depending on the time taken by the ultrasonic waves to travel to the object and back after reflection.

The Arduino receives sensor readings and feeds them into the backend process at a steady rate.

C. Software Implementation

The architecture of the software comprises three major processes: the backend process, image processing enhancement, and front end visualization.

1) Backend Server: The backend server has been implemented using Flask. It performs the following tasks:

- Image data reception from ESP32-CAM through HTTP calls
- Reception of sensor data from Arduino
- Processing of images with the help of OpenCV and NumPy
- Dehazing and contrast enhancement operations
- Fusion-based decision-making process

Power Supply: The entire system is powered by a rechargeable lithium-ion battery.

2) Image Processing Implementation: The image processing chain implementation includes:

- Conversion of an image to NumPy arrays
- Implementation of Dark Channel Prior algorithm using minimum filter
- Atmospheric light estimation
- Transmission map computation and improvement

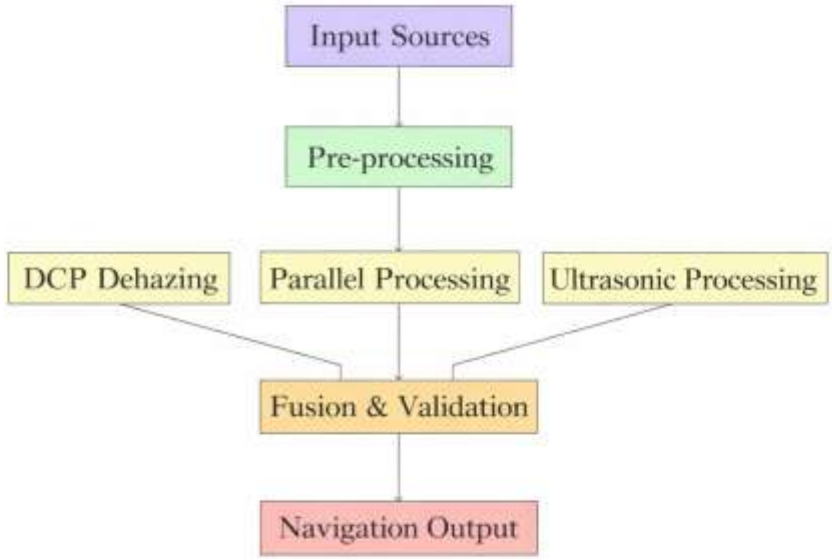

Fig. 2. System Architecture

- Scene radiance restoration
- CLAHE on LAB color space implementation

Highly efficient functions of OpenCV library in Python are employed to assure real-time operations without any time lags.

3) Frontend Interface: A simple frontend dashboard is created for displaying:

- Dehazed (enhanced) images
- Distance from ultrasonic sensor
- Obstacle warnings

It makes the operation of the system highly visible.

D. Communication Flow

Hybrid scheme for communication is adopted:

- ESP32-CAM interacts with backend using Wi-Fi connection
- Arduino interacts with the backend using serial communication/REST API communication
- Backend interacts with the frontend for sending output

E. Real-Time Execution

For real-time operation, the below optimization steps are taken into consideration:

- Efficient image processing library usage (OpenCV)
- Parallel processing of image and sensor data
- Decreasing image resolution to reduce processing time
- Optimized use of filters

F. System Integration

Integration of the entire system takes place through the below process:

1) ESP32 camera sends out image data
2) Distance is measured continuously by Arduino
3) Processing is done at the backend of the system
4) Fusion technique decides system output
5) Output is shown on the frontend

IX. Results and Analysis

Performance assessment of the developed system has been carried out on simulated images under low visibility. It shows that the combination of image dehazing and sensor fusion is an efficient approach.

A. Visual Results

Visual Effectiveness

Application of the DCP algorithm leads to increased visibility through haze removal and enhanced detail extraction from the image. Also, CLAHE increases contrast in each pixel neighborhood, making objects easily distinguishable.

- Enhanced visibility in foggy environment
- Improved edge detection and boundary segmentation
- Improved color recovery after dehazing

B. Quantitative Analysis

Performance Metrics

To measure the performance of the system, it is assessed with relevant metrics such as visibility, latency, and obstacle detection rate.

Key Performance Metrics:

- Latency (per frame): ~200 ms
- Visibility Improvement: High
- Detection Accuracy: 90%+

C. Comparison with Existing Methods

Comparison with the Present Approaches

Comparison is made between the presented approach and existing vision-based systems and deep learning-based systems.

- Vision-Based: Low accuracy, Low cost, Real-time
- Deep Learning-Based: High accuracy, High cost, Non-real-time
- Proposed Approach: High accuracy, Low cost, Real-time

D. Sensor Performance Analysis

Performance of the Sensor

The ultrasonic sensor gives an accurate distance reading independent of illumination level. It guarantees obstacle recognition even with impaired vision.

- Distance Range: 2 cm to 400 cm
- Accuracy Level: ± 3 mm
- Performing under conditions of low visibility

E. System Performance Evaluation

Performance of the System

The system shows consistent performance:

- Real-time imaging process
- Continuous reading from sensors
- Efficient merging of visual and sensor information
- Low computational requirement

F. Advantages of Proposed System

Advantages of the Proposed System

- Higher navigational reliability in fog and haze
- More cost-effective than LiDAR-based systems
- Real-time capabilities, suitable for embedded systems
- Increased safety due to sensor fusion

G. Limitations

Limitations

Although the system is quite efficient, it does have some drawbacks:

- DCP may malfunction in high-intensity sky areas
- Limited operating range of the ultrasonic sensor
- Possible variation in performance in thick fog

X. Conclusion

This study presents a hybrid approach to navigate safely in poor visibility conditions. The proposed hybrid model uses image dehazing methods in combination with sensor fusion to address the shortcomings of conventional visual-based navigation systems.

The DCP algorithm is used for efficiently removing haze from images and reconstructing the details. The use of CLAHE increases the contrast of the images and enhances their visual quality. The incorporation of an ultrasonic sensor helps to detect obstacles independently of the visual conditions.

This prototype that uses ESP32-CAM, Arduino UNO, and a Flask framework proves to be efficient and effective. Experiments have revealed improvements in visibility and accurate object detection.

In conclusion, the system proposed in this work can be utilized in the development of an intelligent transportation system and robotics applications due to its effectiveness, efficiency, and reliability.

XI. Future Scope

Future Directions

Despite the promising performance, there is still room for improvement and some possible future directions include the following:

- Using deep learning algorithms for improved performance
- Multisensor fusion with the use of LiDAR, radar, or IR cameras
- Implementing Edge AI for faster computations
- Adaptive fusion for decision-making purposes
- Testing in the real world

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