

ECE 445
SENIOR DESIGN LABORATORY
DESIGN DOCUMENT

**Real Time Traffic Monitoring and
Congestion Analysis Using Raspberry Pi
and Computer Vision**

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1. Introduction

1.1 Problem Statement

Traffic congestion is a persistent issue in many urban, suburban, and campus environments. Accurate and timely traffic information can help improve transportation planning, reduce delays, and support safer road usage. However, conventional traffic monitoring infrastructure is often expensive, difficult to deploy, and impractical for small-scale or temporary installations. In many cases, traffic conditions are still observed manually or through systems that provide video feeds without automated analysis.

The problem addressed by this project is the lack of a low-cost, deployable, and intelligent traffic monitoring solution that can automatically interpret live road activity. A standalone camera can capture roadway footage, but without embedded processing it cannot directly provide useful metrics such as vehicle count, traffic density, or congestion status. For localized monitoring scenarios, such as campus roads, parking lot entrances, or neighborhood intersections, there is a need for an embedded system that can both observe traffic and convert that observation into actionable information in real time.

This project proposes a Raspberry Pi-based traffic monitoring system that captures live video, detects vehicles, counts traffic flow, and estimates congestion conditions. The system is intended to provide a practical and economical prototype for automated traffic observation. By integrating image acquisition, embedded processing, and dashboard-based visualization, the project aims to demonstrate that meaningful traffic analytics can be achieved without relying on large-scale commercial infrastructure.

1.2 Solution Overview & Visual Aid

The proposed solution is an embedded real-time traffic monitoring system built around a camera and a Raspberry Pi processing unit. The camera continuously captures live roadway video, and the Raspberry Pi processes the incoming frames to identify vehicles and extract traffic-related statistics. Instead of functioning as a passive video recorder, the system actively converts visual input into useful traffic information.

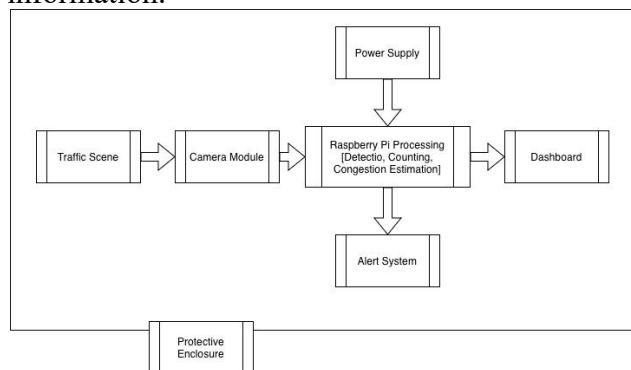


Figure 1. High-level system block diagram of the proposed traffic monitoring system.

At a high level, the system operates in five stages. First, the camera acquires live images of the target road segment. Second, the embedded processor performs image preprocessing and vehicle detection on each frame. Third, detected vehicles are tracked or counted over time to estimate traffic flow. Fourth, the processed results are used to derive higher-level metrics such as traffic

density or congestion level. Finally, these metrics are displayed on a real-time dashboard, and an alert is generated when traffic exceeds a predefined threshold.

This design emphasizes low cost, portability, and modularity. The Raspberry Pi serves as the edge computing platform, which allows the system to operate without requiring constant cloud connectivity. The enclosure and mounting structure make the device more suitable for outdoor or semi-outdoor deployment. In addition, the dashboard component allows users to interpret system output more easily by presenting the processed traffic data in a clear and accessible way.

The solution is intended to demonstrate a complete workflow from image sensing to decision support. Rather than focusing on only one algorithmic component, the system integrates hardware, software, analytics, and user-facing visualization into a unified traffic monitoring platform.

1.3 High-Level Requirements List

The following high-level requirements define the expected functionality and performance of the proposed system.

Functional Requirements

1. The system shall capture live video of a roadway using an onboard camera module.
2. The system shall process video frames on an embedded computing platform.
3. The system shall detect vehicles present in the captured video stream.
4. The system shall count vehicles over time within a defined region of interest.
5. The system shall estimate traffic density or congestion level based on processed visual data.
6. The system shall display traffic information on a real-time dashboard.
7. The system shall generate an alert when congestion exceeds a predefined threshold.
8. The system shall support deployment in a stable mounted configuration suitable for outdoor or semi-outdoor operation.

Non-Functional Requirements

1. The system should operate in near real time under normal test conditions.
2. The system should be implemented using low-cost and commercially accessible components.
3. The system should be modular so that sensing, processing, and visualization components can be modified independently.
4. The system should maintain reasonable detection and counting performance under typical daytime lighting conditions.
5. The system should be compact and portable enough for practical field deployment.
6. The system should be designed with consideration for electrical safety, environmental exposure, and user privacy.

2. Design

2.1 Block Diagram

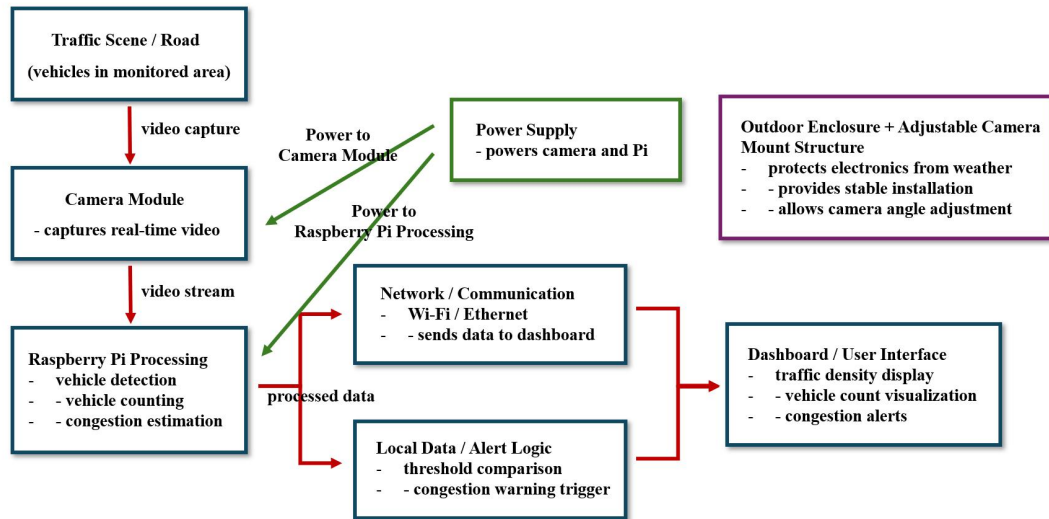


Figure 1. Overall block diagram of the real-time traffic monitoring system.

The overall system is designed as a modular real-time traffic monitoring system consisting of several interconnected subsystems, including the camera module, Raspberry Pi processing unit, communication module, dashboard interface, and power supply system.

The camera module captures real-time traffic video from the monitored roadway and streams the data to the Raspberry Pi. The Raspberry Pi performs vehicle detection, counting, and congestion estimation using computer vision algorithms. The processed data are then transmitted through a network communication module (Wi-Fi or Ethernet) to a remote dashboard for visualization.

Additionally, a local alert logic subsystem evaluates traffic density against predefined thresholds to generate congestion warnings. The system is powered by a dedicated power supply module, which ensures stable operation of both the camera and processing unit.

This modular architecture allows each subsystem to operate independently while maintaining efficient data flow and integration across the entire system.

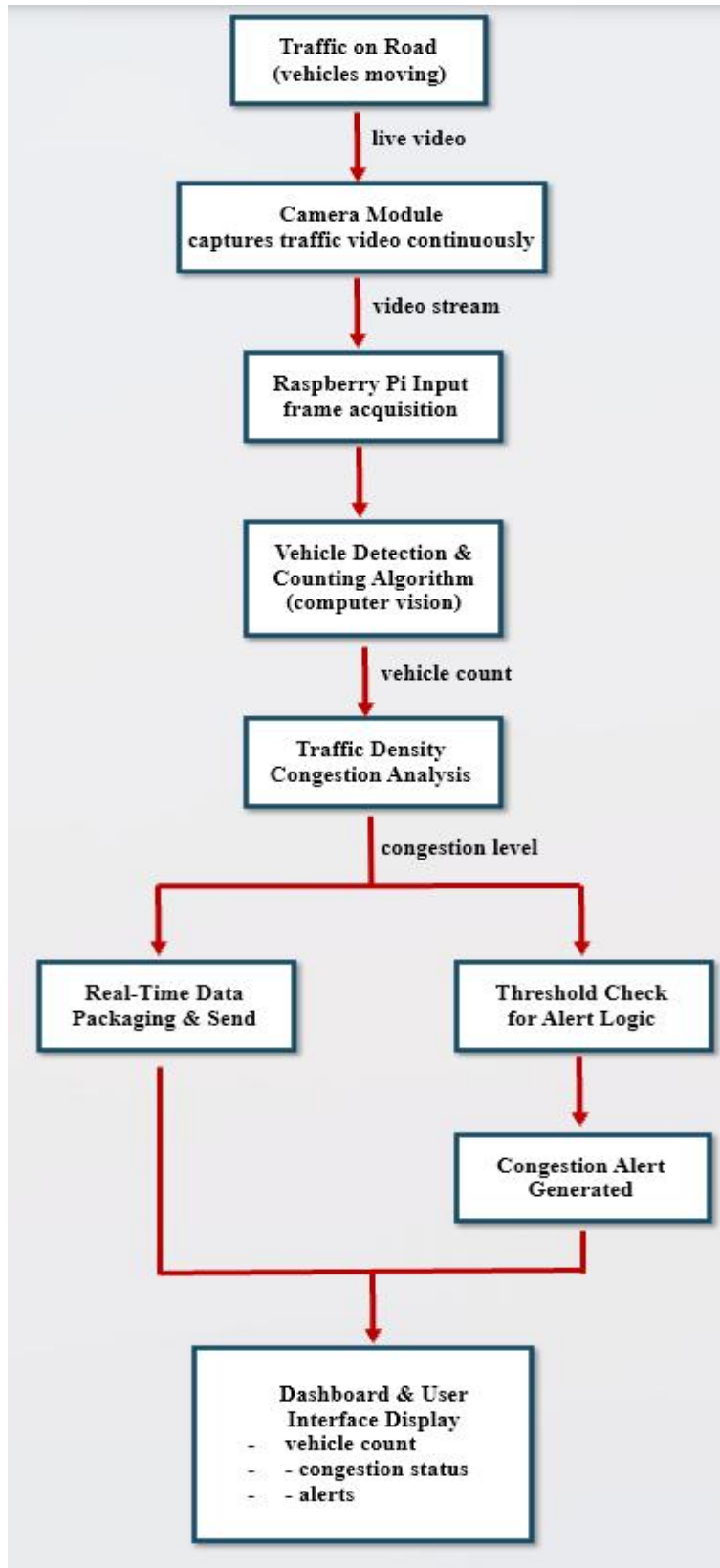


Figure 2. Working principle diagram of the real-time traffic monitoring system.

2.2 Physical Design and System Layout

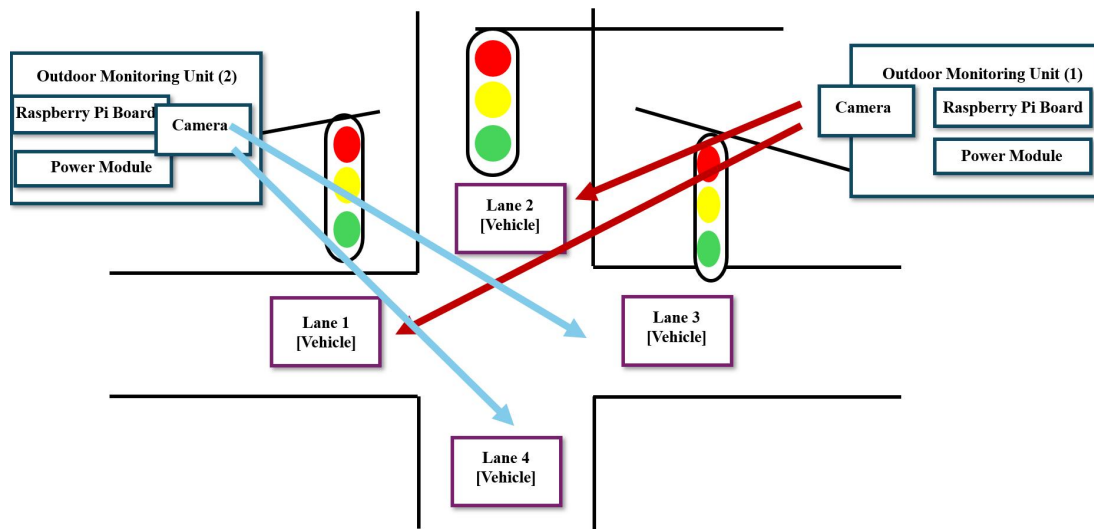


Figure 3. Physical design diagram and system layout of the real-time traffic monitoring system.

The physical design of the system consists of multiple roadside monitoring units installed to cover different traffic lanes. Each unit integrates a camera module, Raspberry Pi board, and power module within a compact enclosure.

The cameras are positioned to monitor multiple lanes simultaneously, ensuring full coverage of the traffic scene. Each monitoring unit operates independently while transmitting data to a centralized dashboard for real-time analysis.

The system layout is designed to optimize field of view and minimize blind spots. By deploying multiple units along the roadside, the system achieves scalable coverage and improved accuracy in traffic monitoring.

This distributed architecture enhances reliability, as failure in a single unit does not compromise the overall system performance.

2.3 Mechanical Enclosure and Mounting Design

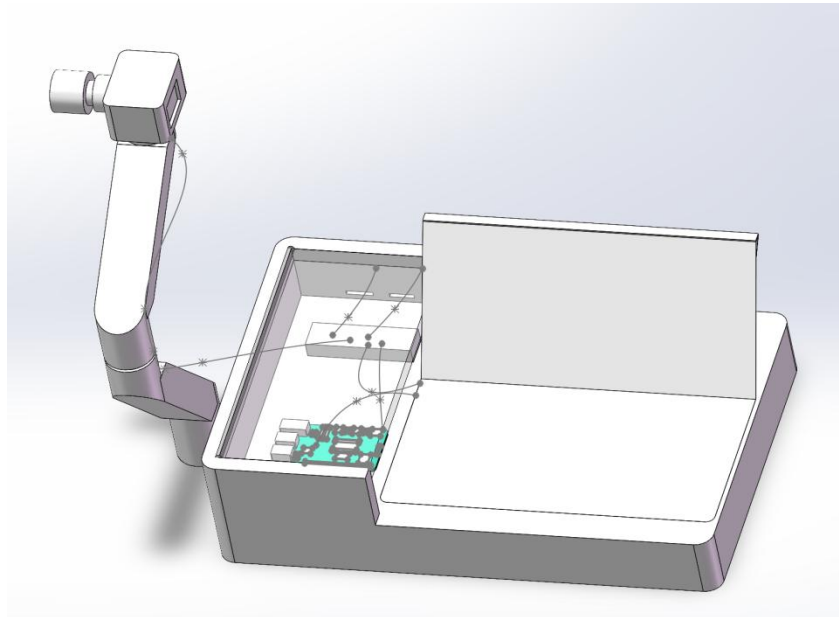


Figure 4. Isometric view of the outdoor enclosure and adjustable camera mounting structure.

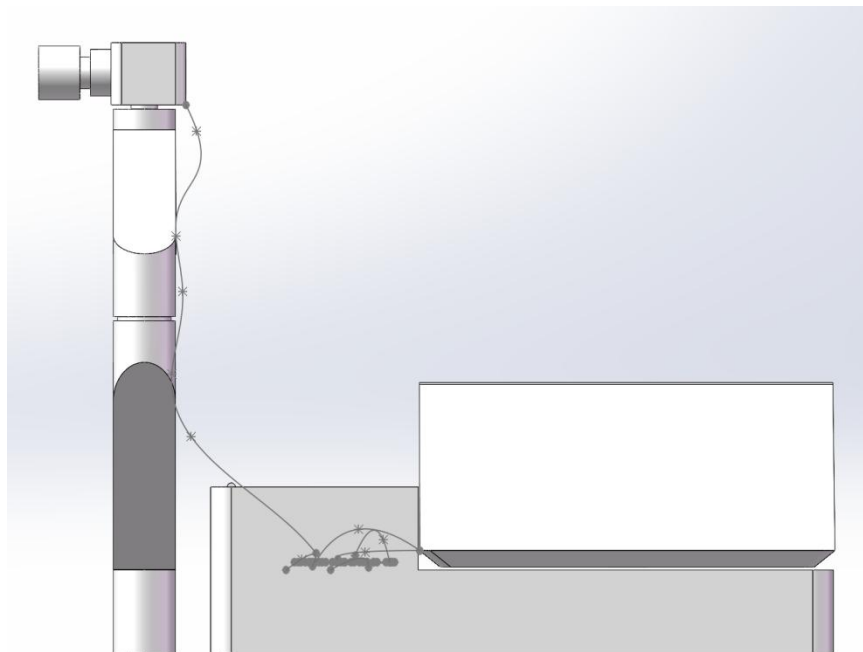


Figure 5. Side view of the outdoor enclosure and camera mounting assembly.

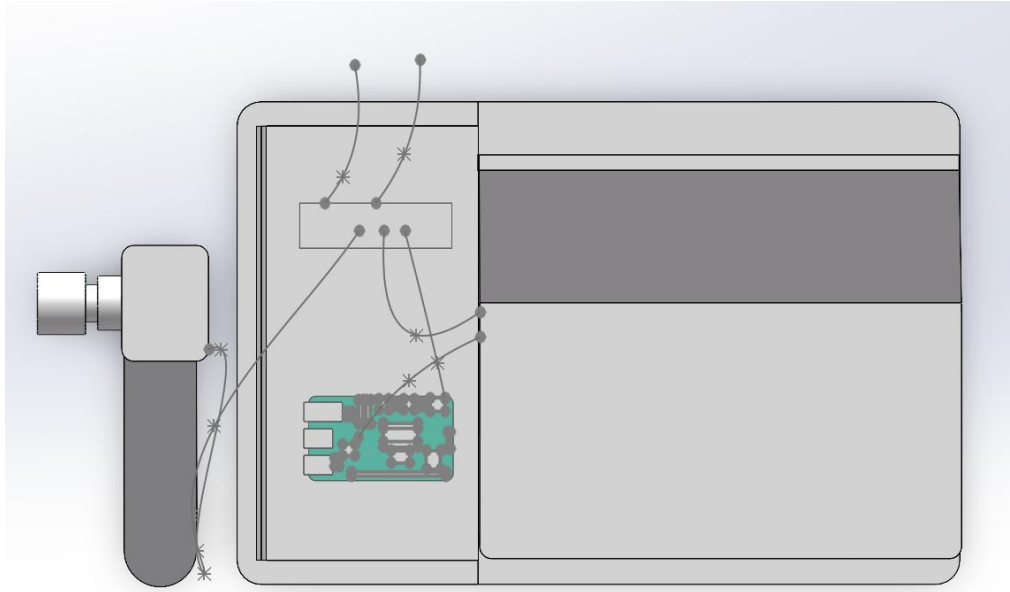


Figure 6. Top view of the outdoor enclosure showing internal component layout and wiring configuration.

The mechanical subsystem consists of an outdoor enclosure and an adjustable camera mounting structure, which together provide environmental protection and flexible camera positioning. The enclosure houses the Raspberry Pi board, power module, and internal wiring. It is designed to protect sensitive electronic components from environmental factors such as rain, dust, and temperature variations. Internal component placement is optimized to ensure efficient cable routing and system reliability.

The camera mounting mechanism adopts a multi-joint articulated structure that allows adjustable orientation of the camera. This design enables the camera to be positioned at different angles and heights to suit various installation conditions. The joints are designed to maintain sufficient stiffness to prevent vibration and ensure stable imaging during operation.

By integrating structural protection with adjustable positioning capability, this subsystem ensures reliable long-term outdoor operation and consistent data acquisition performance.

2.4 Adjustable Camera Mount Subsystem

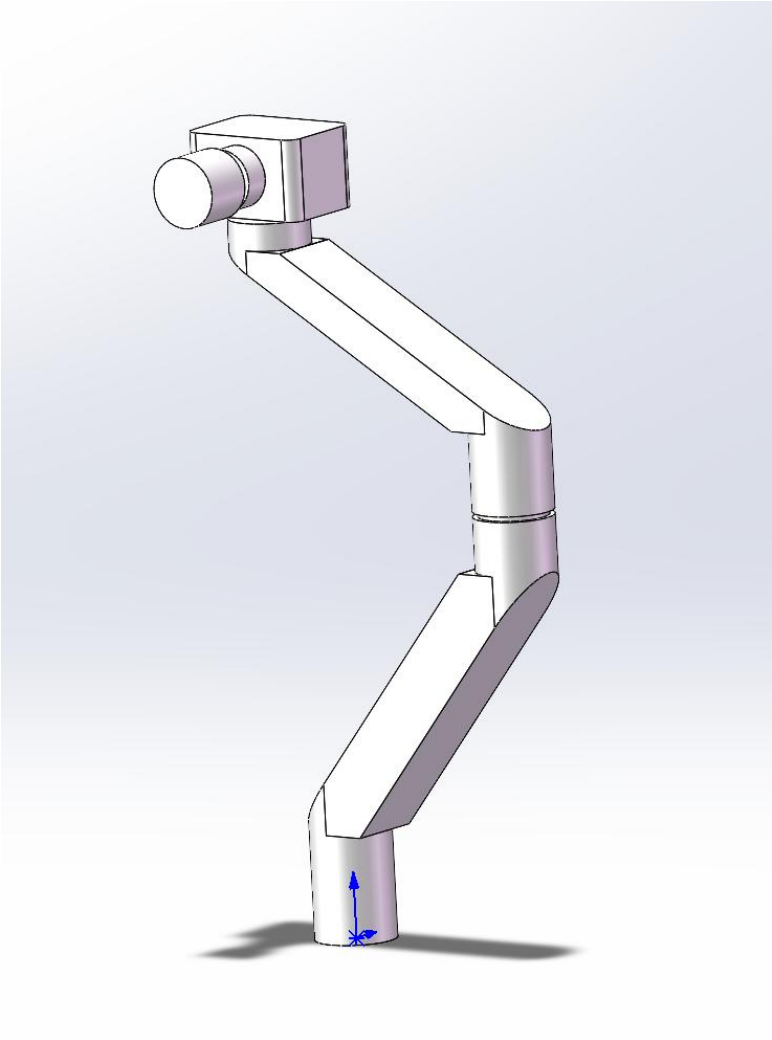


Figure 7. Isometric view of the adjustable camera mounting structure.

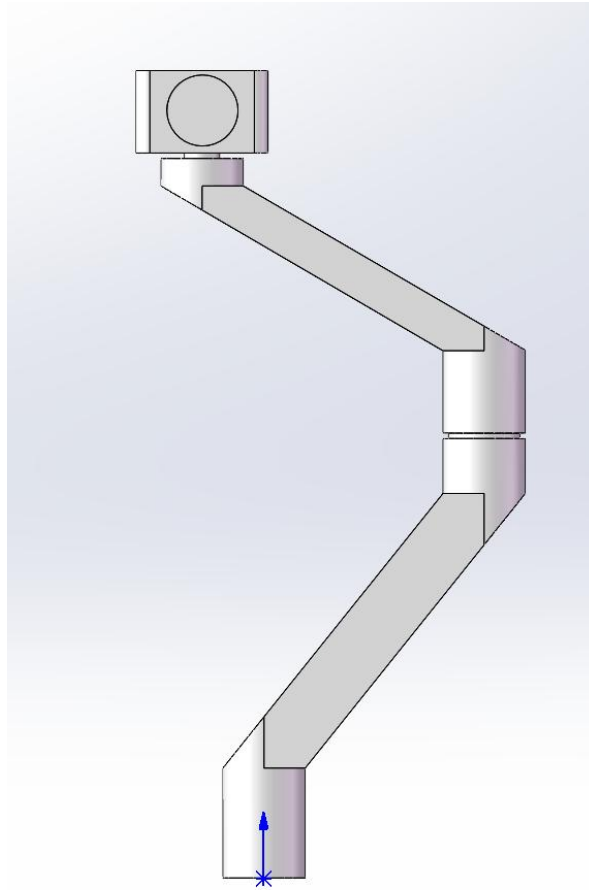


Figure 8. Side view of the adjustable camera mount showing joint configuration and range of motion.

The adjustable camera mount subsystem is responsible for enabling precise alignment of the camera toward the monitored traffic area. It consists of a multi-link articulated mechanism with several rotational joints, allowing flexible adjustment in both vertical and horizontal directions. The design is inspired by robotic arm and tripod head mechanisms, providing multiple degrees of freedom for camera positioning. This allows the system to adapt to different roadside installation scenarios and optimize the camera's field of view.

The mounting structure is designed to balance adjustability and mechanical stability. Once the desired angle is set, the joints can maintain their position without significant drift, ensuring consistent monitoring performance.

This subsystem plays a critical role in ensuring accurate data capture, as improper camera alignment can significantly affect vehicle detection accuracy and congestion estimation.

2.5 Subsystem Requirements

The traffic monitoring system shall meet the following subsystem-level requirements to ensure reliable real-time performance, accurate traffic analysis, and stable outdoor operation.

2.5.1 Camera and Vision Subsystem

The camera and vision subsystem is required to provide reliable video input and accurate vehicle detection capability. The camera shall provide a horizontal field of view of at least 90° with a tolerance of $\pm 5^\circ$ to ensure sufficient coverage of multiple traffic lanes. The system shall process video at a minimum frame rate of 15 frames per second to support real-time monitoring. In addition, the system shall be capable of detecting vehicles within a range of 0 to 30 meters, achieving a detection accuracy of at least 90% under normal lighting conditions. The total processing latency from frame capture to detection output shall not exceed 100 ms to maintain responsiveness for real-time traffic analysis.

2.5.2 Raspberry Pi Processing Subsystem

The Raspberry Pi processing subsystem is required to perform real-time vehicle detection, counting, and congestion estimation. Each frame shall be processed within 100 ms to maintain real-time system performance. The system shall be capable of continuous operation for at least one hour without crash or restart, ensuring reliability during deployment. The vehicle counting accuracy shall maintain an error within $\pm 5\%$ compared to ground truth measurements. Furthermore, the system shall update congestion estimation at a rate of at least 1 Hz to provide timely traffic condition feedback.

2.5.3 Communication Subsystem

The communication subsystem is required to transmit processed data from the Raspberry Pi to the dashboard reliably and with low latency. The system shall ensure that data transmission delay does not exceed 1 second to support real-time visualization. The communication link, whether using Wi-Fi or Ethernet, shall maintain a data transmission success rate of at least 95% under normal operating conditions. Additionally, the system shall support continuous data transmission for at least 30 minutes, during which packet loss shall not exceed 5%.

2.5.4 Mechanical Enclosure Subsystem

The mechanical enclosure subsystem is required to provide protection for internal electronic components and ensure stable system operation in outdoor environments. The enclosure shall achieve a protection level equivalent to IP54 or higher to resist dust and water exposure. The system shall operate reliably within an ambient temperature range of -10°C to 50°C . All internal components shall be securely mounted such that their displacement does not exceed ± 2 mm under normal operating conditions. The enclosure shall also support continuous outdoor operation for at least 8 hours without performance degradation.

2.5.5 Adjustable Camera Mount Subsystem

The adjustable camera mount subsystem is required to provide flexible positioning and stable fixation of the camera. The mounting structure shall allow a pitch adjustment range of at least $\pm 45^\circ$ to accommodate different installation scenarios. After adjustment, the mount shall maintain angular stability with a deviation not exceeding $\pm 2^\circ$ to ensure consistent camera alignment. The structure shall support the camera weight without mechanical deformation exceeding ± 1 mm. In

addition, the mounting mechanism shall withstand environmental vibrations without noticeable displacement, ensuring stable imaging performance during operation.

2.6 Tolerance Analysis

The most critical factor affecting the performance of the traffic monitoring system is the accuracy of camera alignment in the adjustable mounting subsystem. Any angular deviation in the camera orientation will introduce positional error in the captured image, which directly impacts the accuracy of vehicle detection and traffic density estimation. Since the system relies on visual information for analysis, even small misalignments can propagate into significant measurement errors at longer distances.

To evaluate the impact of mounting error, a simplified geometric model is considered. Assuming the camera is installed at a height of approximately 5 meters and monitors traffic at a horizontal distance of 20 meters, the positional error caused by angular deviation can be approximated. For a small angular error θ , the horizontal displacement error d can be expressed as:

$$d \approx L \cdot \tan(\theta)$$

where L represents the distance from the camera to the monitored region. When $\theta = 2^\circ$, the resulting displacement is:

$$d \approx 20 \times \tan(2^\circ) \approx 0.7 \text{ m}$$

This level of positional error is acceptable for lane-level traffic monitoring, as typical lane widths range from 3 to 3.5 meters. Therefore, the system can tolerate small angular deviations without significantly affecting detection performance or congestion estimation accuracy.

Based on this analysis, the allowable angular tolerance for the camera mounting subsystem is specified as $\pm 2^\circ$. This requirement ensures that the positional error remains within acceptable limits for reliable vehicle detection. Additionally, structural rigidity of the mounting mechanism must be sufficient to prevent vibration-induced deviations exceeding this tolerance during operation.

The analysis demonstrates that the proposed mechanical design is capable of maintaining the required alignment accuracy, and therefore the system is feasible for real-world deployment under the specified operating conditions.

2.7 Subsystem Verification

The performance of each subsystem in the traffic monitoring system is verified through a series of controlled experiments and measurements to ensure that all design requirements are satisfied under realistic operating conditions. Each verification procedure is designed to directly correspond to the requirements defined in Section 2.5 and to quantitatively evaluate system performance.

2.7.1 Camera and Vision Subsystem Verification

The camera and vision subsystem is verified by evaluating its field of view, frame rate, detection accuracy, and processing latency. The field of view is measured by placing calibration markers at known positions and calculating the angular coverage, ensuring that it falls within the specified tolerance range. The frame rate and processing latency are measured by recording timestamps over a sequence of at least 1000 frames, and the average processing time is verified to remain

below 100 ms per frame. Vehicle detection accuracy is evaluated by comparing detection results against manually labeled ground truth data collected under normal lighting conditions, and the system is required to achieve at least 90% accuracy within the specified detection range of 0 to 30 meters.

2.7.2 Raspberry Pi Processing Subsystem Verification

The processing subsystem is verified by testing its real-time performance, reliability, and counting accuracy. The system is operated continuously for at least one hour while monitoring CPU usage and system stability to ensure no crashes or interruptions occur. Vehicle counting accuracy is assessed by comparing the system output with manually counted vehicle data over multiple test intervals, and the error is required to remain within $\pm 5\%$. The update rate of congestion estimation is verified by measuring the time interval between consecutive outputs, ensuring that updates occur at a frequency of at least 1 Hz.

2.7.3 Communication Subsystem Verification

The communication subsystem is verified by measuring transmission delay, data integrity, and reliability. The end-to-end delay is measured by timestamping data at the Raspberry Pi and comparing it with the reception time at the dashboard, ensuring that the delay does not exceed 1 second. Data transmission success rate is evaluated over continuous operation by comparing sent and received packets, and the system is required to maintain a success rate of at least 95%. Long-duration transmission tests are conducted over at least 30 minutes to ensure that packet loss remains below 5% under normal operating conditions.

2.7.4 Mechanical Enclosure Subsystem Verification

The enclosure subsystem is verified through environmental and structural testing. Water resistance is evaluated by exposing the enclosure to controlled water spray conditions and confirming that no moisture enters the internal compartment. Dust resistance is assessed by operating the system in a dusty environment and inspecting internal components for contamination. Structural stability is verified by inspecting component positioning before and after operation to ensure that displacement does not exceed ± 2 mm. Temperature tolerance is evaluated by operating the system within the specified temperature range and confirming stable performance.

2.7.5 Adjustable Camera Mount Subsystem Verification

The camera mounting subsystem is verified by evaluating its adjustability, stability, and resistance to vibration. The adjustable angle range is measured using a protractor or digital angle measurement tool to confirm that it meets the required $\pm 45^\circ$ range. Angular stability is tested by fixing the camera at a set angle and measuring any deviation over time, ensuring that the deviation remains within $\pm 2^\circ$. Structural deformation is assessed by applying the camera load and measuring displacement, which must remain within ± 1 mm. Additionally, vibration tests are conducted by simulating environmental disturbances and verifying that the camera position remains stable without noticeable drift.

3. cost

component	Cost(in rmb)
Raspberry Pi components(8GB), including camera	1969
Camera backup structure	10
Outdoor water-proof battery source	25
Water-proof shell	35
PCB component	50
Mobile motor to expand the scope of operations	80
total	2169

4.Schedule

week	Zetong Lang	Yiyang Cheng	Ding Jiang	Yucong Gao
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week	Zetong Lang	Yiyang Cheng	Ding Jiang	Yucong Gao
3.2	Design outdoor enclosure specifications and weather-proof requirements	Research camera mounting solutions and structural support	Review Raspberry Pi power requirements and design power distribution plan	Set up Raspberry Pi development environment and test basic camera functionality
3.9	Create CAD model for waterproof enclosure with ventilation and access panels	Design motor mount and pan/tilt mechanism for camera positioning	Design PCB layout for power management and sensor integration	Develop initial image processing algorithms for vehicle detection (YOLO/OpenCV)
3.16	Finalize enclosure design, prepare 3Dprinting/fabrication files	Complete motor control mechanism design and test simulations	Develop wiring schematic for all electrical components	Implement vehicle counting algorithm and tracking logic
3.23	Fabricate/3D print enclosure components and assembly	Build motor control framework and test movement range	Order and receive PCB components,begin soldering	Create real-time dashboard interface for traffic visualization
3.30	Install waterproofing seals and test enclosure against water ingress	Integrate motor with camera mount and calibrate positioning	Complete PCB assembly and test all electrical connections	Develop congestion alert system and data logging features
4.6	Joint assembly: Install camera, motors, and all components into enclosure		Wire all electrical components and test power system stability	Integrate software modules and test image processing pipeline
4.13	Test mechanical durability and weather resistance	Calibrate motor controls for optimal camera angles	Troubleshoot electrical issues and improve power efficiency	Optimize detection algorithms for accuracy and speed
4.20	Conduct outdoor field testing and structural adjustments		Perform real-world testing of vehicle detection accuracy	Monitor power consumption and battery performance
4.27	Make final adjustments to enclosure based on field tests	Fine-tune motor response and reduce vibration	Optimize power management for extended operation	Debug software issues and improve dash board UI/UX
5.4	System integration testing and verification against project deliverables			
5.11	Prepare Final Demonstration			

5. Ethics and Safety

5.1 Ethics

Because this project involves camera-based monitoring of public or semi-public spaces, ethical considerations are an important part of the design. Although the primary goal of the system is to measure traffic flow and congestion rather than identify individuals, any device that captures live visual data may raise concerns related to privacy, surveillance, and misuse of information.

One major ethical concern is privacy. A roadway camera may unintentionally capture pedestrians, cyclists, vehicle license plates, or other identifying details. For this reason, the system should be designed to minimize unnecessary collection of personally identifiable information. The project should emphasize aggregate traffic analysis rather than identity-based recognition. If video data is stored, retention should be limited, and access should be restricted to authorized users only. If long-term storage is not required for system evaluation, then processed traffic statistics should be retained instead of raw video whenever possible.

Another ethical issue is the potential misuse of collected data. Even if the original purpose of the system is benign, captured footage or processed traffic records could be repurposed in ways that exceed the scope of the project. To reduce this risk, the intended function of the system should be clearly stated as traffic monitoring and congestion analysis only. The project should avoid features such as facial recognition, driver identification, or behavioral profiling, since such capabilities are outside the scope of this work and introduce greater ethical risk.

Algorithmic limitations must also be acknowledged. Detection and counting performance may vary depending on lighting, weather, occlusion, and camera angle. As a result, the system may produce false positives, false negatives, or inaccurate congestion classifications. Ethically, it is important not to present system output as infallible. The dashboard and project documentation should describe the system as an assistive monitoring tool rather than a substitute for formal transportation authority decisions or safety-critical control systems.

5.2 Safety

In addition to ethical concerns, the project must also address physical and operational safety. Since the system is intended for real-world deployment and includes electronics, mounting hardware, and power delivery, safe design practices are necessary to reduce the risk of injury, equipment failure, or hazardous operation.

The first safety consideration is mounting and structural stability. The camera and enclosure must be securely attached so that the device does not shift position, fall, or obstruct the surrounding environment. If deployed near a roadway, the unit must not block drivers' visibility or interfere with pedestrian movement. A stable mounting angle is also important for technical reliability, since movement of the camera may reduce detection accuracy and generate incorrect traffic measurements.

Electrical safety is another critical concern. The Raspberry Pi, power supply, and wiring must be insulated and protected from accidental short circuits. Exposed conductors should be avoided, and cable routing should be arranged to prevent strain, disconnection, or water exposure. If the device is used outdoors, the enclosure should provide protection against rain, dust, and incidental contact. Thermal safety should also be considered, since prolonged operation in warm outdoor conditions may cause overheating. Adequate ventilation or passive cooling should therefore be included in the design.

Operational safety must also be considered at the system level. Because the project produces alerts and congestion classifications, inaccurate outputs could mislead users if they are interpreted as authoritative traffic control instructions. For this reason, the system should be described as a monitoring and decision-support tool only. It should not directly control road infrastructure, traffic signals, or vehicles. Any alerts generated by the system should be treated as informational rather than safety-critical commands.

Finally, maintenance and testing should be performed safely. The system should be powered down before major hardware adjustments are made, and outdoor installation should follow standard precautions for working near roads and exposed electrical equipment. These safety practices help ensure that the project remains appropriate for demonstration and evaluation in a university engineering context.

Finally, transparency is important. Users and evaluators should understand what the system measures, what it does not measure, and what assumptions are built into the analysis. Clear documentation of system capabilities and limitations helps prevent overreliance and supports responsible deployment.

Reference

C. Huang, Z. Zhang, B. Mao and X. Yao, "An Overview of Artificial Intelligence Ethics" in IEEE Transactions on Artificial Intelligence, vol. 4, no. 04, pp. 799-819, Aug. 2023, doi: 10.1109/TAI.2022.3194503.