

DEVELOPING A REAL-TIME OBJECT DETECTION SYSTEM ON FPGA

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Master student: NGUYEN Trung Kien

Committee

Arnaud BOURNEL	Chairman
<i>Université Paris-Saclay</i>	
Pierre DUHAMEL	Reporter
<i>CNRS, Laboratory of Signals and Systems</i>	
NGUYEN Linh Trung	Examiner
<i>VNU University of Engineering and Technology</i>	
BUI Duy Hieu	Examiner
<i>VNU Information Technology Institute</i>	
Erwan LIBESSART	Examiner
<i>CentraleSupélec</i>	

Thesis supervision

BUI Duy Hieu	Thesis supervisor
<i>VNU Information Technology Institute</i>	
TRAN Thi Thuy Quynh	Co-supervisor of the thesis
<i>VNU University of Engineering and Technology</i>	
Erwan LIBESSART	Co-supervisor of the thesis
<i>CentraleSupélec</i>	

ABSTRACT

AUTHORSHIP

Hanoi, January 22nd, 2024

Author

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List of Abbreviations

Abbreviation	Definition
IoT	Internet of Things
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AMD	Advanced Micro Devices
mAP	Mean Average Precision
ASIC	Application Specific Integrated Circuit
AVC	Advanced Video Coding
CBAM	Convolutional Block Attention Module
CNN	Convolutional Neural Network
COCO	Common Objects in Context
CPU	Central Processing Unit
DMA	Direct Memory Access
FPGA	Field Programmable Gate Array
FPS	Frames Per Second
GB	Gigabyte
GE	Gate equivalents
GPU	Graphics Processing Unit
HD	High Definition
HOG	Histogram of Oriented Gradients
LTS	Long Term Support
MJPEG	Motion JPEG
MOT15	Multiple Object Tracking Benchmark 2015
MOTC	Multiple Object Tracking Challenge
MPSoC	MultiProcessor System On Chip
NMS	Non-Maximum Suppression
OS	Operating System
PASCAL	Pattern Analysis Statistical Modelling and Computational Learning
PETS09	Performance Evaluation of Tracking and Surveillance 2009
PTZ	Pan-Tilt-Zoom
RAM	Random Access Memory
RCNN	Regional Convolutional Neural Network
RGB	Red Green Blue
SIFT	Scale-Invariant Feature Transform
SPP	Spatial Pyramid Pooling
SRAM	Static Random Access Memory
SSD	Single Shot Detector
SVM	Support Vector Machine

TSMC	Taiwan Semiconductor Manufacturing Company
UHD	Ultra High Definition
VNU	Vietnam National University
VOC	Visual Object Classes
YOLO	You Only Look Once
ZCU106	Zynq UltraScale+ ZCU106 Evaluation Kit

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Introduction

Chapter 1. Real-time Object Detection System

This chapter provides an overview of the application of Internet of Things (IoT) technology in monitoring and alerting fire detection systems, primarily in the context of increasingly serious fire problems that require critical attention. It begins with an introduction to IoT and the importance of its role in improving monitoring skills and its value in fire situations. In addition, this chapter also focuses on the main objective of the thesis: to explore and employ the full potential of IoT-connected hardware devices in both IoT applications and real-world scenarios. This chapter is organized into three sections. Section 1.1 provides an overview of the IoT and its applications in fire monitoring systems. *Section 1.2* discusses the current situation and limitations of existing fire monitoring systems. *Section 1.3* presents modern fire detection methods using current technologies, along with their limitations.

1.1. Introduction to the Internet of Things (IoT) and Its Applications for Fire Monitoring Alert Systems

In recent years, fire accidents have become increasingly dangerous, causing critical damage to both human life and property. Traditional fire monitoring systems, which often rely on manual checks or local alerts, are limited in their ability to respond quickly and effectively, especially in complex or remote environments. To handle this issue, we need smart and effective solutions to improve it in time.

The IoT is one exciting technical development that resolves these issues. As its name suggests, IoT refers to a network of smart devices that can communicate and connect with each other, exchanging data. These devices can collect, transmit, and process data in real-time, thereby enabling automation and making personal decisions.

Unlike standalone devices that work independently, a true IoT system (Figure 1) is a scalable and integrated system where multiple devices work together for a common goal. In the context of fire detection, this goal is always monitoring environmental conditions, identifying early signs of fire, and sending real-time alerts, even when no one is present at that location.

By providing features such as remote monitoring, automated notifications, and log data, IoT-based systems significantly enhance responsiveness and overall safety. Therefore, using IoT for fire monitoring systems is both useful and essential for enhancing early detection and minimizing damage.



Figure 1. An IoT system with interconnected smart devices.

1.2. Current situation and Limitations of the monitoring fire alert system

Fire accidents are now common and can occur in various types of environments, ranging from crowded residential areas to industrial zones, forests, etc.... In an industrial environment, the use of flammable materials, high electricity consumption, and poor ventilation are common reasons that increase the risk of fire. In a residential area, the complex and overloaded electrical network increases the chance of short circuits and electrical fires. In a forest environment, rising global temperatures make it more flammable, and also human activities, such as camping or purposeful burning of the forest, increase the risk of fire. As mentioned, the fire can occur anywhere, any time, whether in crowded urban areas or isolated natural areas.

Therefore, deploying fire monitoring systems with sensors and data-collecting modules in large areas is expensive and challenging. Traditional systems, which rely on wired connections or require continuous human monitoring, are not

realistic, especially in large areas or remote and harsh environments. These systems will face problems such as processing complex data and false fire alerts. This is really a big challenge for the fire warning system. The solution using IoT with sensor data can help provide more accurate and useful results.

Currently, traditional fire monitoring and alert systems are still widely used and have not been fully replaced by IoT-based systems. Although some improvements have been made, many issues and limitations still exist, such as detection delays, limited coverage range, and high maintenance requirements. As a result, developing a fire detection and monitoring system that uses fire, temperature, and humidity sensors combined with wireless communication technologies is a creative, possible, worthy solution to consider.

1.3. Related Works

The development of fire monitoring and alert systems based on IoT has gained increasing attention in recent years. This section presents several existing works and discusses their limitations, highlighting the gap that this project aims to address.

Nowadays, IoT systems typically use various sensors, ranging from tiny microcontrollers to large ones, and are on the way to merging machine learning in the new era of AI, which is now very popular. I plan to use AI in my future work. Back to this section – “Related Works”, I believe that anyone who reads this thesis someday will find it easy to refer to the paper I will share below:

In the first paper [1] (2023), the authors proposed an IoT-based fire detection and monitoring system using temperature, flame, and smoke sensors with an ESP32 microcontroller, and implemented a LoRa Network to detect and alert on forest and farm. In paper [2] (2013), the authors have used an Arduino-based home fire alarm system with a GSM module and temperature sensor to detect fire and send SMS alerts, enhancing user safety and property protection. In the next paper [3] (2025), the authors developed a smart IoT-based system using the same list of sensors as paper 1 to detect fire, but in addition, using Arduino UNO and a gas sensor. The system was implemented on the Blynk platform and uses GSM to send alerts. Paper

[3] (2017), the authors designed an STM32-based wireless fire detection system using a block of sensors and embedded wireless communication technologies like Wi-Fi to detect fire. Next paper [4] (2019) shows a big improvement in the application of robots. Pages 267–278 of the paper focus on the use of robots in fire monitoring and alert systems. The project utilizes STM32 and STC89C51 microcontrollers, drones, to connect air and ground monitoring systems and facilitate communication through ZigBee. This paper [5] (2021) focuses more on the alerting part. The authors use ESP32 and PIR sensors to detect fire and movement, sending alerts through a Telegram bot to a smartphone, with feature alarms by image and temperature parameters. When AI becomes popular, some papers nowadays are applying it in IoT systems to detect and alert fire. For example, paper [6] (2023) presents a system that combines IoT devices with YOLOv5 to enable early forest fire and real-time detection, aiming to reduce false alarms and enhance safety during dry seasons. While the approach in [6] is already technically advanced, [7](2025) adds a suggestive improvement to fire monitoring and alert systems by using IoT and machine learning, and also combining various sensor types, to improve detection accuracy and support remote monitoring. Although this recent work represents the development, the core concept of fire detection systems has already been explored in earlier studies.. Indeed, a paper from 2013 [9] discusses a real-time fire alarm system developed using Raspberry Pi and Arduino Uno. This system features include smoke detection, room image capture, and alert through SMS and a web interface. It only sends alerts to firefighters after user confirmation to reduce false alarms. Although this paper was from 2013, its implementation was quite complete – features like login were already added. However, the web design is still basic and a little bit outdated. However, about implementation, it was a meaningful success, and the authors’ idea was forward-thinking.

As mentioned at the beginning of Section 1.3, my thesis does not apply AI in the IoT system. However, this will be explored in future work. To recognize and expand on the ideas presented from the science papers, many of which use wireless

technologies such as Wi-Fi or GSM. This thesis proposes enhancing current approaches by applying radio communication to an IoT-based fire detection and alert system. Once again, I am grateful to these “giants” whose pioneering work has allowed this small idea of a thesis to be developed.

1.4. Conclusions

An IoT system is an essential technology with applications in monitoring and fire detection. Achieving real-time monitoring, high accuracy, processing all scenarios, and overcoming hardware limitations creates serious difficulties. The use of IoT brings a promising solution, enabling real-time monitoring, remote access, and automated alert notifications. This project aims to inherit and integrate the ideas from those previous works, while also contributing further improvements to develop a more responsive and reliable fire alert system. It also introduces new innovations to improve the system’s flexibility and performance in real-life situations. In Chapter 2 *In System Architecture Design*, a proposal will be presented, focusing on the integration of hardware and software components, including sensor modules, communication systems, and control logic. All of which will be implemented through software to build the proposed IoT-based fire monitoring solution.

Chapter 2. System Architecture Design

The first chapter of this thesis provided an overview of IoT technology and its applications in fire detection and monitoring. It also discussed the current state of fire accidents occurring in many places today, highlighting the need for more efficient solutions. Furthermore, with the current state of fire, the thesis proposed a new direction by enhancing existing ideas with the use of radio communication. While many previous systems deploy on Wi-Fi or GSM, this thesis focuses on using HC-12 wireless modules for *long-range, low-cost, low-power* communication. The main goal is to develop an IoT-based system that monitors, detects fires, and alerts in real-time.

Building on this ideal, *Chapter 2* presents the proposed system architecture, which consists of both hardware and software components designed to work together for efficient fire monitoring. The system includes: Raspberry Pi and STM32 microcontrollers, HC-12 modules for communication, and a variety of sensors to collect fire-related data. This chapter has three main sections: *Section 2.1 Hardware System Architecture*: in this section, an overview of the hardware components used in this thesis will be presented, including sensors, microcontrollers, and the central processing unit. Each component will be explained with the reason why it is used and a summary of its advantages and disadvantages. *Section 2.2: Software & Firmware System Architecture*: This part details how the software & firmware work across the system. It begins with sensor-side firmware, which includes collecting data, encoding, and transmission. On the server side, it explains how data is received, decoded, stored, and visualized through a Flask-based web application. This section also includes user authentication, account management, and how software sends alerts (using Fuzzy Logic and Threshold Evaluation). *Section 2.3 Conclusions*: This final section summarizes all components introduced in *Chapter 2* and prepares for the system implementation and evaluation that will follow in later chapters, *Chapter 3: Implementation Results and Evaluation*.

2.1. Hardware System Architecture

This section introduces the hardware components used at both the *sensor node* and *the central processing unit*. It explains what each component is, its role in the system, and the reasons behind choosing it for the demo. Subsections cover specific components, including fire sensors, temperature and humidity modules, STM32 for edge processing, and the Raspberry Pi for central control and web server hosting. The following *section 2.2* will discuss the data flow in depth, and how each part works together.

2.1.1. Sensor Node Architecture

(1) Flame Sensor

Flame sensors are a type of detector used to identify the presence of fire or flames, which is possible because fires typically occurs various types of radiation – including *visible light* (such as red, orange, and blue), *infrared radiation* (heat), and maybe *ultraviolet radiation* – and flame sensors are specifically designed to detect the infrared spectrum in the 760 nm to 1100 nm range.

In Figure 2, the PISAFE (Figure 2) flame sensor is a solution for detecting fire using Wi-Fi connectivity and wide-area fire detection (up to 100 meters), while also meeting fire safety certification standards. However, the cost of it is really high, so this sensor will not be used in the context of this thesis.

Instead, to align with the project’s budget and for demo purposes, the **KY-026** flame sensor (Figure 3) is selected. Despite its small size and lower cost, the KY-026 is a good option for demo and educational applications for flame detection in this thesis.



Figure 2. Flame sensor PISAFE.

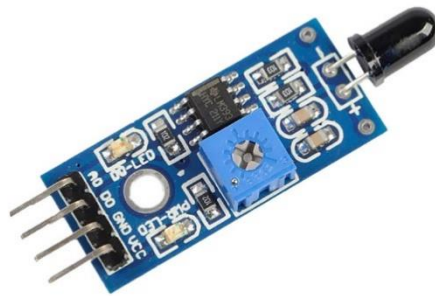


Figure 3. Flame sensor KY-026.

(2) Temperature & Humidity Sensor

A temperature and humidity sensor is a type of sensor used to collect environmental data. When a fire occurs, such as when flammable materials or electrical wires are burning, the temperature of the fire will increase continuously, and the humidity drops quickly. In the process of fire detection and monitoring, just using the flame sensor's evaluation is not enough. Therefore, combining data from both the Temperature & Humidity Sensor and the Flame Sensor can provide a more accurate

result and enhance the fire detection system's reliability, helping to reduce false and prevent incorrect fire alarms. Nowadays, there are many types of sensors collecting environmental data, like Honeywell 5809SS [9] (Figure 4). Similar to the flame sensor, this system is designed to be low-power and low-cost, and as the main objective of the thesis is for demo purposes. Therefore, it uses the DHT11 (Figure 5) sensor to collect temperature and humidity data. The DHT11 is a widely used and accessible sensor in educational environments, especially in university-level projects.



Figure 4: Honeywell 5809SS heat detector.

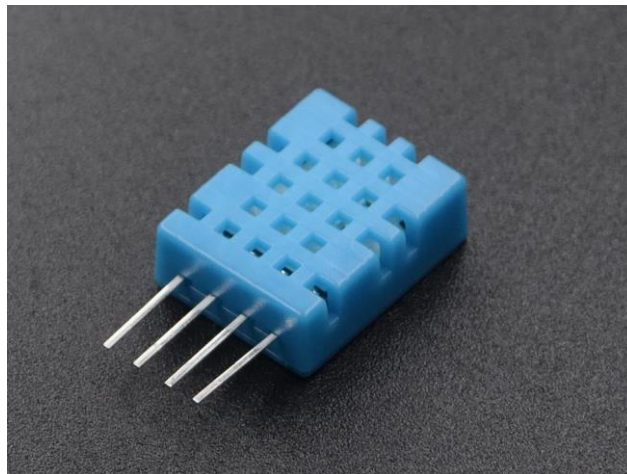


Figure 5: DHT11 - Temperature & Humidity Sensor.

(3) Edge processor

In an IoT system, the edge processor is a lightweight microcontroller responsible for collecting data from a block of sensors, such as flame sensors,

temperature and humidity sensors. Each microcontroller that handles the data from one or more sensors can call a sensor node within the system.

Usually, edge processors use microcontrollers like the ESP32 (Figure 6), ESP8266, or other microcontrollers, which are favored because of its programming and integration. However, in this thesis, the selected edge processor is the STM32, specifically the STM32F103C8T6 (Figure 7). Although programming the STM32 may be more complex compared to ESP-based microcontrollers, but it is chosen to support the research and application of this work. Additionally, STM32's UART communication mode is effective for serial data transmission, making it an right choice for handling sensor data and transmitt data in this system.

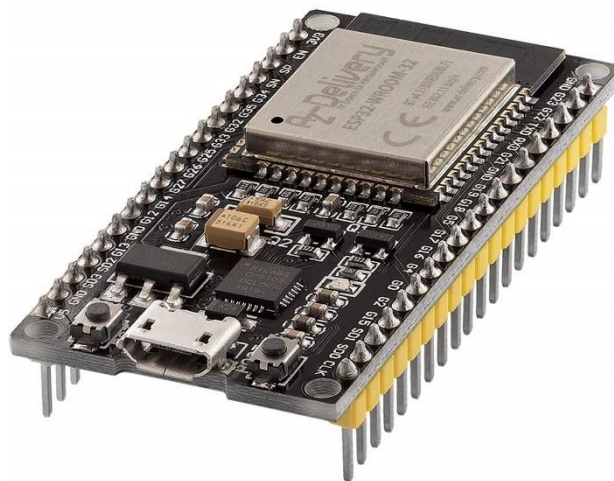


Figure 6: ESP32 Microcontroller.



Figure 7: STM32F103C8T6 Microcontroller.

(4) *Wireless Communication Module*

This module plays an important role in the main idea of this thesis. In the proposed IoT system, the wireless communication module is the part that transmits data between sensor nodes and the central processing unit. Several types of wireless communication technologies were reviewed in *Section 1.3 Related Work*, including Wi-Fi, Zigbee, Cellular, and LoRa.

Among them, Wi-Fi, Zigbee, and Cellular require an existing communication infrastructure such as routers, gateways, or mobile network towers. On the other hand, LoRa can operate in two modes: LoRaWAN, which is based on centralized infrastructure (gateways and network servers), and LoRa (peer-to-peer), which can communicate directly between nodes without any infrastructure.

Despite the advantages of LoRa in terms of long-range communication and energy efficiency, it often comes at a higher cost and requires more complex configuration. In opposition, the HC-12 module offers a low price and is easy to configure, making it suitable for the goals and scope of this thesis project. In the *2.1.1 Node System Architecture*, the HC-12 module is placed in the transmission (Tx) block. After the sensor data is collected and processed by the STM32F103C8T6 microcontroller, the resulting data packet is transmitted to the HC-12 module (Figure 8), which then sends the data wirelessly via radio frequency (RF) communication.

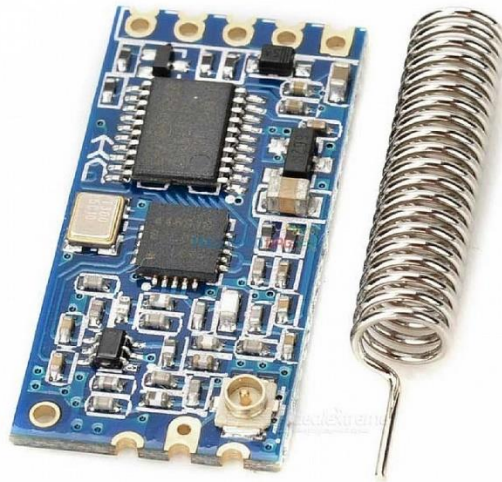


Figure 8: HC-12 Wireless Communication Module.

2.1.2. Central Processing Unit System Architecture

(1) Wireless Communication Module

In the *2.1.2 Central Processing Unit System Architecture*, the HC-12 module (Figure 8) is placed in the receiver (Rx) block. After the data is transmitted from the node to the central processing unit through radio communication, the HC-12 module at the receiver receives incoming signals and transmits them to the central processor for handling.

(2) Central processing unit

In this section, the central processing unit is using for handling incoming data after it has been wirelessly transmitted to the receiver block (in this case, the HC-12 module). There are many types of CPUs suited of performing logical data processing and running a web server. However, with the objective of this thesis, the system using the Raspberry Pi 5 (Figure 9) to explore its practical application in real-world IoT scenarios.

The Raspberry Pi 5 is a single-board computer (SBC) — as the name implies, it is a complete computer built on a single circuit board. With only a power supply and an external monitor, it can working as a fully like a computer. It supports many type of operating systems like : Raspberry Pi OS, Raspberry Pi Lite, Ubuntu,...etc..., among which Pi OS being the most commonly used.

For storage, it uses a microSD card, supporting capacities up to 1 TB, however a normal and reliable setup runs from 32 to 256 GB. The Pi 5 is powered by a quad-core ARM Cortex-A76 processor, provides high performance for embedded applications. In this thesis, the Raspberry Pi 5 equipped 8 GB of RAM, making it the same to many standard desktop PCs.

About connectivity, it provides USB ports, Ethernet, Wi-Fi, Bluetooth, a 3.5 mm audio jack, camera ports and also 2 micro HDMI for connecting screen and support to 4k HD. Importantly, it also features a 40-pin GPIO header, including 26 programmable GPIO pins, with the rest used for power (3.3V/5V - VCC) and ground connections (GND). These GPIO pins allow the Pi to connect with sensors, LEDs, buzzers, and communication modules like the HC-12.

With its wide features, fast performance, and flexibility, the Raspberry Pi 5 is an excellent choice for developing modern IoT systems.



Figure 9: Single board Computer - Raspberry Pi 5.

(3) Touchscreen Monitoring Interface

In a typical IoT-based monitoring system, external touchscreen displays are often connected to the Central Controller Unit (Raspberry Pi 5), especially when building a web-based application. These interfaces enable users to easily interact with the system and monitor its status in real time (Figure 10).

Although this project does not focus on physical user interfaces, adding a touchscreen in the demo setup improves system visualization and user interaction.

Therefore, a touchscreen NoName A (Figure 11) is used. It works well with the custom monitoring software in this project. This addition helps users understand the system more clearly, test it more easily, and consider improvements for future development.



Figure 10: Touchscreen Monitoring.



Figure 11: NoName A Touchscreen.

2.2. Software & Firmware System Architecture

Section 2.1 focuses on introducing the hardware components used in this thesis, along with the reasons for their selection and their unique benefits. *Section 2.2. Software & Firmware System Architecture* discusses the working flow of the full system implementation. *Section 2.2* is divided into two subsections: *Section 2.2.1.*

Firmware at the Node explains how data is handled at the sensor node after collecting data from flame, temperature, and humidity sensors. It also provides the standard requirements for protecting the privacy and security of data during wireless transmission. *Software at the Central Processing Unit* uses software to receive, decode, and process incoming data packets. The decrypted data will be uploaded in real-time onto a web-based platform. This subsection also covers user administration, data logging, notification handling, and other system operations, which will be described in further depth.

2.2.1. *Firmware at the Node*

(1) Sensor Data Collection

a) DHT11

b) KY-026

(2) Encoding Message

a) Frame Packing

b) Security Coding

c) Channel Coding

d) Spreading

e) Frame Synchronization

(3) Wireless Transmission

2.2.2. *Software at the Central Processing Unit*

(1) Wireless Receiver

Trước tiên về cài đặt thì bên khối thu các thông số về AT đã được nêu rõ trong Wireless Transmission rồi. Sau khi bản tin được gửi qua vô tuyến bên khối thu của Central Processing Unit sẽ nhận dữ liệu. Dữ liệu sẽ hợp lệ khi bên khối phát bắt được 2 byte đầu là 0xEB và 0x90.

(2) Decoding Message

a) Frame Synchronization Decode

Input: Frame Sync packing.

Output: Message unpack Frame Sync

After going through the processes of framing, encryption, and spreading, the message becomes significantly confused, making it difficult for the receiver to identify the beginning or structure of the transmission. Therefore, as the final step, two header bytes (0xEB and 0x90) are added after LFSR encoding.

a method where the primary gradient vector was split into two vectors, as shown in Figure 14. The values of these two vectors for pixel $I(x,y)$ were calculated using, which takes into account the values of the four surrounding pixels $I(x+1,y)$, $I(x-1,y)$, $I(x,y+1)$, and $I(x,y-1)$.

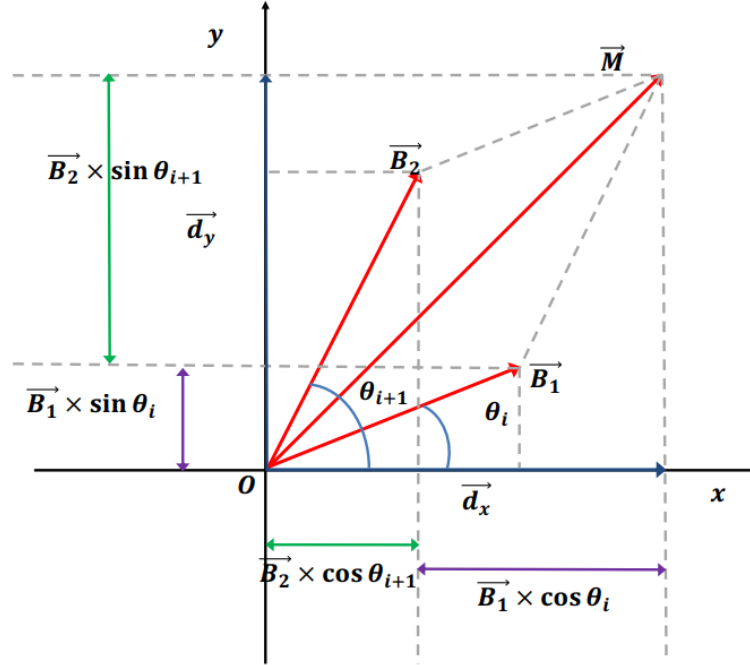


Figure 15 - Decomposition of a vector into the form of two vectors [18].

Two magnitudes are the solutions of the two equations:

$$\|B_{\theta_i}\| = \frac{\sin(\theta_{i+1}) d_x - \cos(\theta_{i+1}) d_y}{\sin(20)}; \|B_{\theta_{i+1}}\| = \frac{\cos(\theta_i) d_y - \sin(\theta_i) d_x}{\sin(20)}$$

This thesis uses this technique to improve the HOG-SVM algorithm and decrease the number of calculations needed to process each sliding window.

real-time applications with power constraints.

As mentioned above, the Object Detection Block will include Bilinear Interpolation Scale Generator Module, HOG-SVM module, combine module, and NMS module.

to form a block, and the cell histograms are normalized using block data.

(a) Gradient calculation and Histogram generation

This

).

Algorithm 1 – Gradient calculation.

will generate all the histograms for the input image used for the next step.

Algorithm 2 – Histogram generation.

(b) Descriptor generation and Result

After

generation.

The combining

remove redundancies. This block is crucial to this thesis's proposed object detection system.

2.3.

2.4. Conclusions

In this

architecture offers a promising pipeline for efficient and accurate human detection for real-world applications.

Chapter 3. Implementation and Evaluations

In the previous

3.1. Experiment setup environment

3.1.1. Mean Average Precision

(1) Mean Average Precision (mAP)

an object

(2) Mean Average Precision (mAP)

Average

Here is a summary of the steps to calculate the AP:

1. Generate the prediction scores using the model.
2. Convert the prediction scores to class labels.
3. Calculate the confusion matrix—TP, FP, TN, FN.
4. Calculate the precision and recall metrics.
5. Calculate the area under the precision-recall curve.
6. Measure the average precision.

The mAP is calculated by finding Average Precision(AP) for each class and then averaging over several classes.

$$mAP = \frac{1}{N} \sum_{i=1}^N AP_i$$

3.1.2. Frame rate

3.2. Experimental results

3.2.1. Input: PETS09-S2L1 [19]

(1) Input description

-S2L.

(2) Result

and mAP graphs per frame of input PETS209-S2L.

(3) Analysis

low mAP score.

3.2.2. Input: TUD-Stadtmitte [20]

(1) Input description

Input racteristic in the photo is that the moving object is only human moves in groups.

(2) Result

In of 51

(3) Analysis

The system can process images in near-real-time but faces significant challenges in accurately identifying and tracking human groups in urban pedestrian settings. The moderate precision combined with low recall and mAP scores suggests that the system might misidentify groups or miss them altogether.

3.2.3. Input: TUD-Campus [21]

(1) Input description

TUD-Campus.

(2) Results

In the

D-Campus.

(3) Analysis

The system

fast.

3.3. Conclusions

Conclusions and Perspective

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