Original scientific paper

Hardware and Software of Computer Vision IoT Solutions Leveraging Raspberry Pi Boards

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***Abstract* — This paper presents a survey of Internet of Things (IoT) applications using the Raspberry Pi (RPi) Single Board Computer (SBC) alongside Computer Vision (CV) techniques from the field of Artificial Intelligence (AI). It presents and compares solutions across several IoT application areas, offering an overview of the associated hardware, software, CV methods, and algorithms. The study explores IoT applications in the following areas: Smart Healthcare, Face and emotion recognition, Wildlife, Smart Agriculture, Smart Homes, Security, Smart Cities, Autonomous Vehicles, Robotics, Manufacturing, and Retail. Each area is analyzed with respect to the integration of RPi and CV, showcasing their contributions to enhancing operational efficiency and enabling innovative solutions. The presented solutions use different RPi boards, from RPi 3A+ up to the latest RPi 5.**

***Keywords* — Computer Vision (CV), Edge AI, Embedded AI, Internet of Things (IoT), Raspberry Pi (RPi), smart systems.**

I. Introduction

THE domain of smart systems has emerged as one of the most rapidly advancing fields over the past decade. Applications of the Internet of Things (IoT) encompass diverse areas, including Smart Healthcare, Face and emotion recognition, Wildlife, Smart Agriculture, Smart Homes, Security, Smart Cities, Autonomous Vehicles, Robotics, Manufacturing, and Retail, [1]. The ongoing evolution of smart systems within the IoT ecosystem has been significantly bolstered by advancements in Artificial Intelligence (AI) and Machine Learning (ML), as well as Computer Vision (CV) and Deep Learning (DL) algorithms, [2]. These technologies have enabled these systems to achieve enhanced levels of intelligence and decision-making capabilities.

In pursuit of more cost-effective, compact, and energy-efficient solutions, AI IoT systems can be developed through suitable embedded platforms, such as the Raspberry Pi (RPi) Single Board Computer (SBC). Such systems can be effectively supported by data centers, cloud computing, and edge AI frameworks.

This paper presents a comprehensive overview of IoT applications developed using Raspberry Pi (RPi) and computer vision (CV), primarily within the framework of Edge AI systems. While other review papers explore the intersection of CV, IoT, and processing elements, they often focus solely on application domains without providing detailed insights into the hardware and software components of such systems [3], or they offer only general solutions for using RPi in CV applications [4]. In contrast, this paper provides a detailed summary of applications across various smart system domains, emphasizing both hardware and software elements. Furthermore, it clarifies the relationship between application areas and common solution types, highlighting the most frequently used software platforms and CV algorithms.

Section II delineates definitions, and primary components, of IoT. Section III introduces the RPi embedded device and its capabilities. Section IV provides an overview of CV tasks and methodologies. Section V presents selected applications in the areas of living things and systems. Lastly, Section VI culminates the discussion with final conclusions and an outline of the paper's contributions.

II. Internet of Things

The Internet of Things (IoT) is a network of physical objects that are not usually connected to the Internet. These objects can include devices, vehicles, buildings, and various other items that are embedded with necessary electrical components, sensors, actuators, software, and network interfaces.

The IoT facilitates a range of activities, such as collecting and storing data, exchanging and processing information, and utilizing data in different ways. The core elements of the IoT can be classified into categories like identification, sensing, communication, computation, services, and semantics.

In this paper, particular emphasis is placed on the components related to sensing and computation, which are fundamental to the IoT's operation. The processing units serve as the main computational components in IoT systems, and there are a variety of hardware solutions available, including ESP232, Arduino, Raspberry Pi (RPi), Beaglebone, Intel Galileo, NVIDIA Jetson Nano, and Adafruit FONA. These processing units enable IoT devices to perform complex tasks such as data analysis, real-time decision-making, and automation. As the IoT continues to

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evolve, these computational elements will play a crucial role in shaping the future of connected devices and systems.

III. Raspberry Pi

For this paper, the Raspberry Pi (RPi) Single Board Computer (SBC) was chosen as the primary hardware component due to its versatility and wide usage in various fields, [5]. There are several compelling reasons for this selection. The Raspberry Pi has become a staple in education, particularly in areas such as programming, electronics, telecommunications, and control systems. Its presence in educational institutions and its popularity among students, teachers, researchers, and industry professionals have made it a widely recognized tool. Because of its compact form, efficiency, low power consumption, and affordability, the RPi has become an ideal choice for many IoT applications.

In terms of connectivity, the Raspberry Pi offers a wide array of communication options. The specific set of connections depends on the model, but for the more recent versions, common features include multiple USB ports, Mobile Industry Processor Interface (MIPI), Camera Serial Interface (CSI) for camera attachments, High-Definition Multimedia Interface (HDMI) for video output, RCA connectors for audio, and a Micro SDHC card slot for data storage. Additionally, it supports Ethernet (10/100/1000 Mbit/s), Wi-Fi (IEEE 802.11 b/g/n/ac), Bluetooth (2/4/5/Low Energy), and General Purpose Input/Output (GPIO) pins. These GPIO pins, which range from 20 to 40 depending on the model, allow users to interface with a wide range of external components and sensors. Some of these pins are specially designed to support functions like I^2C (Inter-Integrated Circuit), SPI (Serial Peripheral Interface), UART (Universal Asynchronous Receiver-Transmitter), Pulse Code Modulation (PCM), and Pulse Width Modulation (PWM).

Moreover, the RPi is capable of connecting to both on-device servers and the Cloud, providing the flexibility to serve in various roles within an IoT ecosystem. It can function as an Edge device, enabling the processing and analysis of data directly on the device itself. This is particularly useful for applications that require real-time processing, such as ML and CV.

The Raspberry Pi was originally developed by the Raspberry Pi Foundation in 2012, with the aim of promoting computer science education. Since then, several versions of the device have been released, with the most notable being versions 1 through 5, launched between 2012 and 2023. In addition to these, smaller models like the Raspberry Pi Zero (2015) and Pico (2021) were introduced to offer even more compact solutions for specific applications.

The Raspberry Pi 3A+ and 3B models, with their ARM Cortex-A53 processors (1.2 GHz and 1.4 GHz) and 512 KB of L2 cache, offer good performance for basic CV tasks. However, their Broadcom VideoCore IV GPU, delivering 24 GFLOPS, limits their ability to handle more demanding CV applications, such as real-time high-resolution video processing.

In comparison, the Raspberry Pi 4 and 4B feature ARM Cortex-A72 processors (1.5 GHz) and 1 MB L2 cache, significantly improving performance. The Broadcom VideoCore VI GPU, with 48 GFLOPS, allows for more complex CV tasks.

The Raspberry Pi 5 offers the highest performance with an ARM Cortex-A76 processor (1.8 GHz), 1 MB L2 cache, and a 600 MHz GPU that delivers 64 GFLOPS. This makes it ideal for demanding CV applications requiring AI/ML acceleration, such as real-time video processing, robotics, and CV in industrial settings.

IV. Computer Vision

Computer Vision (CV) is a significant sub-field of Artificial Intelligence (AI) focused on enabling machines to interpret and understand images and videos, using a combination of geometry, physics, statistics.

CV tasks are generally categorized into several key areas, including recognition, motion analysis, scene reconstruction, and image restoration, [6]. Recognition is one of the core tasks in CV, where the goal is to determine whether a specific object, feature, or activity is present in the image data. This includes object recognition (identifying objects in an image), object classification (sorting objects into predefined categories), identification of individual instances of objects, and detection of regions of interest within an image [6].

Motion analysis focuses on tracking the movement of objects within a video stream or a series of images. This can involve optical flow estimation, object tracking, and gesture recognition, and is used in applications such as video surveillance, robotics, and augmented reality. Scene reconstruction aims to create a three-dimensional (3D) model of a scene from two-dimensional (2D) images or video, which is valuable for applications like autonomous driving and virtual reality. Image restoration focuses on improving the quality of an image, which can include tasks like removing noise, deblurring, and enhancing low-resolution images, often critical in medical imaging or satellite imagery [6].

Computer vision systems vary by application but generally follow a standard pipeline: image acquisition, preprocessing, feature extraction, detection and segmentation, high-level analysis, and decision-making. Visual data is first captured via sensors or cameras. Preprocessing enhances image quality through noise reduction, contrast adjustment, and normalization. Feature extraction identifies key elements such as edges, textures, and motion. Detection and segmentation isolate relevant objects or regions based on visual attributes. High-level analysis includes validation, parameter estimation, and recognition tasks. Finally, decision-making interprets the processed data to classify objects, verify conditions, or trigger responses [6].

There are various CV algorithms and models designed to perform these tasks, ranging from traditional feature-based methods to cutting-edge DL architectures. Traditional feature-based methods include well-established algorithms like Scale Invariant Feature Transform (SIFT), Speeded Up Robust Features (SURF), Features from Accelerated

Segment Test (FAST), Hough transforms, and Geometric hashing. These approaches typically focus on detecting and matching key features (such as edges, corners, or regions) across images [6].

In recent years, DL techniques, particularly Convolutional Neural Networks (CNNs), have become dominant in CV. CNNs are capable of automatically learning hierarchical features from images. Other DL architectures such as Recurrent Neural Networks (RNNs) and Generative Adversarial Networks (GANs) are also gaining popularity. RNNs are well-suited for video analysis and tasks requiring temporal sequence processing, while GANs are often used for image generation, enhancement, and style transfer [6].

However, while DL models like CNNs, RNNs, and GANs provide exceptional performance in terms of speed and accuracy, they come at the cost of requiring substantial computational power and memory capacity. This has led to the development of specialized hardware and optimization techniques [6], [7].

Several algorithms used within CV include: Classification algorithms, such as Logistic Regression, K-Nearest Neighbors (KNN), Support Vector Machines (SVMs), Decision Trees, and Random Forests, are used to assign labels to images based on learned features. Regression algorithms, like Linear Regression, SVMs, Decision Trees, and Random Forests, are applied when the goal is to predict continuous values. Image classification tasks are often handled by advanced architectures like ResNet, which enables the network to recognize and classify images with high accuracy. Object detection is commonly performed using algorithms like You Only Look Once (YOLO), Single Shot Detector (SSD), SSD Mobilenet, RetinaNet, AlexNet, Fast Region-based CNN (R-CNN), and Faster R-CNN. These algorithms are capable of identifying and locating objects within an image in real-time. Semantic segmentation algorithms like SegNet and U-Net classify each pixel in an image into a predefined category (e.g., background, object, etc.), which is important for tasks like medical imaging and autonomous driving. Instance segmentation is more advanced, involving algorithms like Mask R-CNN, which not only segments the image into regions of interest but also distinguishes between different instances of the same object class, [6], [8].

V. IoT Applications of Raspberry Pi and Computer Vision for People and Living Things

The applications of the Internet of Things (IoT) extend across a broad spectrum of industries, but focusing specifically on those that utilize low-cost, low-energy solutions with Raspberry Pi (RPi) narrows this scope. The potential for integrating Computer Vision (CV) algorithms into Edge devices is rapidly expanding, making it increasingly feasible to deploy CV techniques for real-time, on-device processing. This paper presents a comprehensive survey of IoT applications leveraging RPi and CV, offering a comparative analysis of their key characteristics across various domains.

VI. Hardware and Software Components of Computer Vision IoT Solutions with Raspberry Pi

IoT applications encompass a broad range of domains. However, by focusing on those that employ low-cost and energy-efficient solutions using Raspberry Pi (RPi), the scope of this field is significantly narrowed. The potential for implementing computer vision (CV) algorithms on edge devices is rapidly expanding and evolving. This paper presents a comprehensive survey of IoT applications that utilize RPi in conjunction with CV, providing a comparative analysis of their key features across various sectors. The applications are categorized into two main subgroups: those related to people and living beings, and those involving systems.

A. Computer Vision IoT Applications of Raspberry Pi for people and living things

This section is dedicated to the areas of application that involve people or other living things, such as animals and plants. These include: Smart Healthcare, Face and emotions recognition, Smart Homes and Surveillance, Wildlife, Smart Agriculture.

The comparison of these applications is presented in Table 1. These results highlight the unique attributes of each area, illustrating exact hardware system around RPi that is used and CV technologies, algorithms and software tools that are necessary to achieve proposed solutions.

IoT-based Healthcare applications have become increasingly prominent, both in terms of the number of implementations and their market impact. RPi solutions include patient and health monitoring [9], mobility assistance [10], elderly care [11], support for individuals with visual impairments [12], assistance for those with hearing impairments [13], and solutions for COVID-19 monitoring and management [14]. Face and emotions recognition system using RPi is presented in [15].

IoT applications in Smart Homes utilizing RPi enable the connection and control of various home appliances. CV-based IoT applications using RPi are primarily focused on Surveillance, specifically for home intruder detection, [16], [17].

Instead of human CV tasks, in this category animals and plants are also included. One solution for an automated video capture of animals is presented in [18].

In Smart Agriculture, RPi and CV are applied across various domains, including: vision-based monitoring systems for assessing plant quality and health, [19]; intelligent systems for optimizing irrigation and fertilization, [20]; pest detection and monitoring, [21], [22]; visual inspection, grading, classification, and defect detection, [23]; and detecting the phase of ripeness, harvesting, picking, and packing, [24].

TABLE 1: HARDWARE, CV METHODS, AND SOFTWARE TOOLS FOR IOT APPLICATIONS FOR PEOPLE AND LIVING THINGS.

Category and Reference	***Hardware***	***CV Methods***	***Software Tools***
Healthcare [9]	RPi, NodeMCU, camera	CNN	Python, OpenCV
Healthcare [10]	RPi, RPi camera	DNN	Python, OpenCV
Healthcare [11]	RPi 3B, RPi camera	Image features extraction	Python, OpenCV
Healthcare [12]	RPi, Coral USB accelerator, server with NVIDIA Titan graphics	Object detection and segmentation	Python, TensorFlow
Healthcare [13]	RPi, Web camera	CNN	Python, OpenCV
Healthcare [14]	RPi, RPi camera	CNN	Python, TensorFlow
Face and emotion recognition [15]	RPi, ATmega 32 microcontroller, galvanic sensor, camera	Haar cascade, Gradient boosting classifier	Python
Surveillance [16]	RPi 4, RPi camera, motion temperature, and humidity sensors	CNN	Python, OpenCV
Surveillance [17]	RPi 4, RPi camera, motion sensors	Haar cascade	Python, SimpleCV
Wildlife [18]	RPi 3A+, Camera module, waterproof casing, power	MobileNet-V1, TripleNet-S, EfficientNet B0, MobileNetV3-small	Python
Agriculture [19]	RPi, Arduino Mega 2560, robot car, IR sensor	CNN	Python, OpenCV
Agriculture [20]	RPi 4B, Temperature, humidity, pressure, EC and PH sensors, water flow meter, electric valve, head pump, control display	FCN, CNN, VGG-16	Python, C, OpenCV, PyTorch
Agriculture [21]	RPi 4B, Camera module	YOLOv4	Python, OpenCV
Agriculture [22]	RPi 4B, Camera module	YOLOv4-tiny	Python, OpenCV
Agriculture [23]	Google AIY Vision Kit (RPi Zero, vision bonnet, RPi camera), RPi 3B, touch-screen display	ResNet, DenseNet, MobileNetV2, NASNet, EfficientNet	Python, OpenCV
Agriculture [24]	RPi, Collaborative robot UR5, Zivid Two 3D industrial camera	YOLO	Python, OpenCV

B. Computer Vision IoT Applications of Raspberry Pi for systems

This section is dedicated to the areas of application that involve systems, such as: Smart Cities, Autonomous Vehicles, Robotics, Manufacturing, and Retail. The comparison of hardware and software solutions of these applications is presented in Table 2.

Several IoT Smart Cities applications utilizing RPi and CV technologies are outlined in Table 2. These solutions focus on smart lighting systems [25], [26], and intelligent traffic crossings [27], [28], recycling [29], disaster management [30], and crack detection for roads and bridges [31].

The field of Autonomous Vehicles requires substantial computational capabilities from the hardware employed. However, there are several solutions that utilize RPi. These include car models [32], web-controlled and partially autonomous vehicle systems [33], vision-based autonomous landing systems for unmanned aerial vehicles [34], intelligent traffic management [35], and traffic signs recognition [36].

TABLE 2: HARDWARE, CV METHODS, AND SOFTWARE TOOLS FOR IOT APPLICATIONS FOR SYSTEMS.

Category and Reference	***Hardware***	***CV Methods***	***Software Tools***
Smart Cities [25]	RPi 4, RPi camera module	CNN	Python, OpenCV
Smart Cities [26]	RPi 4, RPi camera module, LED lamps	YOLO v3, fuzzy sets	Python, OpenCV
Smart Cities [27]	RPi 4, RPi camera modules, speakers, motor, actuators	CNN SSD MobileNet v2, CNN-based classification model	Python, OpenCV
Smart Cities [28]	RPi, RPi camera modules, speakers, motor, actuators	CNN SSD MobileNet v2, CNN-based classification model	Python, OpenCV
Smart Cities [29]	RPi 4, Robotic arm, NVIDIA Jetson Nano, Brushless DC Motors (BLDC), TB6560 stepper motor, camera, LiDAR, TPU	YOLOv8	Python, PyTorch
Smart Cities [30]	RPi 4, Servomotor, camera	SSD MobileNet V2, EfficientDet D0	Python
Smart Cities [31]	RPi 4, ultrasonic sensor, RPi camera, Wi-Fi module	CNN object detection, MobileNet V2	Adafruit Cloud, Push Bullet, Twilio

Category and Reference	***Hardware***	***CV Methods***	***Software Tools***
Autonomous Vehicles [32]	RPi, RPi camera, car model with Arduino UNO, DC motor, micro servo motor	Hough line and transform, Sobel operator	MATLAB/ Simulink Package for RPi
Autonomous Vehicles [33]	RPi, RPi camera, Arduino UNO, Sonar Module	Haar Feature Classifier, Hough line and transform	Python, OpenCV, Apache Server
Autonomous Vehicles [34]	RPi, RPi camera, UAV	Pose estimation	Python, OpenCV
Autonomous Vehicles [35]	RPi 3B+, RPi 4, Google Coral Dev Board, Jetson Nano	YOLOv8, YOLOv5, YOLO with DETR, EfficientDet, Detection Transformer (DETR)	Python, TensorFlow, PyTorch, RoboFlow
Autonomous Vehicles [36]	RPi 4, camera	Haar-like cascade, CNN	Python
Robotics [37]	RPi 5, Universal Robos UR3e robotic arm, RPi camera, Robotiq 2F-85 actuator, Fin Ray Effect (FRE) fingers	TensorFlow Object Detection API	Python, TensorFlow
Robotics [38]	RPi 5, DVS camera, touch sensor, digital motor	Spiking Neural Networks (SNNs)	Brian2 software
Manufacturing [39]	RPi, RPi camera	Edge detection, dilation and erosion algorithms	Python, OpenCV
Retail [40]	RPi, Webcam, barcode scanner, Arduino, buzzer, ultrasonic sensors, load cell sensor	Channel and Spatial Reliability Tracking (CSRT)	Python, OpenCV

RPi is used for CV on robotic arm [37] and as tool for implementation of neuromorphic robotics [38].

Smart solutions in the domains of manufacturing and retail are primarily focused on sorting and defect detection [39], as well as optimizing the processes of shopping and payment [40].

VII. Conclusion

This paper offers a comprehensive summary of RPi CV IoT applications, highlighting their hardware and software components. For the RPi boards, solution span over older 3A+ model to the latest RPi 5 model, that was released little over one year ago. It serves as a resource for students, researchers, and developers, enabling them to quickly familiarize themselves with the technologies and deliver the desired functionalities in their new systems. The paper provides an overview of the underlying technologies, including the components and applications of IoT, the characteristics and communication of RPi, and the methods and algorithms associated with CV. The paper also contributes a comparative analysis of the key components across the presented solutions, with a particular emphasis on the prevalence of convolutional neural networks (CNNs).

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