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Real-Time Data Processing Method of IoT Based on Edge Computing

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Abstract: With the surge in IoT devices, traditional cloud computing models expose problems such as high transmission delay and high bandwidth pressure in real-time data processing, making it difficult to meet the needs of scenarios such as industrial control and intelligent transportation. This paper proposes a real-time data processing method for IoT based on edge computing, which realizes efficient local data processing through layered architecture design, core technology research and process optimization. In the industrial IoT scenario, this method reduces the equipment downtime from 12 hours per month to 4.8 hours, and shortens the data processing delay from 200-300 milliseconds to 10 milliseconds; in the smart city scenario, the average travel time on the main road is reduced by 20%, and the traffic congestion index is reduced by 18%; in the field of agricultural IoT, irrigation water consumption is reduced by 35%, and crop yields are increased by 15%. Studies have shown that this method can effectively reduce data processing delays by 60%-95%, increase system throughput by 35%, and significantly improve resource utilization efficiency, providing a reliable solution for the in-depth application and development of IoT technology.

Keywords: Edge Computing; Internet of Things; Real-Time Data Processing; System Architecture; Task Scheduling.

1. Introduction

The Internet of Things technology is penetrating into all areas of society at an unprecedented speed. From smart homes to Industry 4.0, from smart agriculture to smart transportation, the number of connected IoT devices is growing exponentially. The International Data Corporation (IDC) predicts that by 2025, the number of connected IoT devices will exceed 41.6 billion, and the amount of data generated daily will reach 79ZB. The real-time data continuously generated by these devices contains huge value. For example, industrial equipment operation data can be used for predictive maintenance, and traffic flow data can optimize urban traffic scheduling. However, in the traditional cloud computing model, data needs to be transmitted remotely to the data center for processing, which is difficult to meet the real-time requirements and will cause network congestion and high transmission costs [1]. Edge computing deploys computing resources at the edge of the network close to the data source to realize local data processing, effectively reduce latency and relieve network pressure, which is of great significance to promoting the application of IoT technology in real-time scenarios.

At present, the real-time data processing of the Internet of Things mostly relies on the cloud computing model, which has obvious disadvantages when processing large-scale real-time data. On the one hand, the delay caused by remote data transmission cannot meet the real-time response requirements of scenarios such as industrial automation and autonomous driving; on the other hand, massive data transmission consumes a lot of network bandwidth and increases enterprise operating costs [2]. Although some companies have tried to introduce the concept of edge computing, they still face many challenges in practical applications. Edge nodes have limited computing resources and it is difficult to handle complex data tasks; there is a lack of efficient coordination mechanism between different edge nodes, and the efficiency of data interaction is low; at the same time, data security and privacy protection are more complex in edge environments, and existing technologies are difficult to deal with effectively.

Edge computing has significant advantages in IoT applications. First, it reduces data transmission delays [3]. For example, in industrial robot control scenarios, edge computing can shorten the control command response time from hundreds of milliseconds to tens of milliseconds, greatly improving control accuracy and system stability. Second, it reduces network bandwidth pressure [4]. By screening and preprocessing the original data at the edge node and uploading only key data, the data transmission volume can be reduced by more than 70%. Third, it improves data processing reliability [5]. In the event of network failure, the edge node can operate independently to ensure the continuity of data processing. In addition, edge computing can better realize data localization storage and privacy protection, which meets the needs of sensitive data processing.

2. Edge computing and the theory of real-time data processing in the Internet of Things

2.1. The concept and architecture of edge computing

Edge computing is a distributed computing model that extends computing, storage and network capabilities to the edge of the network. Its architecture is mainly composed of the perception layer, edge layer and cloud layer [6]. The perception layer includes various types of IoT terminal devices, which are responsible for data collection; the edge layer consists of edge servers, smart gateways and other devices, which undertake real-time data analysis and processing tasks; the cloud layer serves as a powerful computing and storage backup to handle complex tasks that the edge layer cannot complete. This layered architecture enables data to be initially processed close to the source, reducing transmission requirements and improving overall system efficiency.

2.2. Analysis of requirements for real-time data processing in the Internet of Things

Real-time data processing in the Internet of Things has distinct characteristics and strict requirements. In terms of real-time performance, scenarios such as industrial monitoring and intelligent security require data processing response time to be controlled in seconds or even milliseconds; in terms of data diversity, it covers structured sensor data, semi-structured log information and unstructured image and video data; at the same time, data processing must ensure accuracy and reliability to avoid decision-making errors due to data errors [7]. In addition, as data sensitivity increases, data privacy protection and secure transmission become indispensable requirements.

2.3. The synergistic relationship between edge computing and real-time data processing of the Internet of Things

Edge computing and real-time data processing of the Internet of Things are interdependent and develop in a coordinated manner. Edge computing provides technical support for real-time data processing of the Internet of Things, meets real-time requirements through localized computing capabilities, and optimizes data transmission processes [8]. The Internet of Things provides a wealth of application scenarios for edge computing, prompting the continuous innovation of edge computing technology. The organic combination of the two can give full play to their respective advantages and promote the development of the Internet of Things system in an efficient and intelligent direction.

3. Core technologies for real-time data processing of the Internet of Things based on edge computing

3.1. Data collection and preprocessing technology

Data collection requires the formulation of unified standards and protocols for different types of equipment to ensure accurate data collection and transmission. In the preprocessing stage, noise and erroneous data are removed through data cleaning, data standardization is achieved through format conversion, and normalization is used to eliminate data dimension differences [9]. For example, in smart grid data collection, preprocessing can increase data accuracy from 85% to 98%, laying a good foundation for subsequent processing.

3.2. Edge node computing resource management technology

Edge node computing resources are limited, and efficient management technology is required. Resource monitoring obtains the CPU, memory and other resource usage status in real time; task scheduling uses a dynamic priority algorithm to allocate computing resources according to the urgency of the task and resource requirements; resource allocation is combined with a load balancing strategy to avoid node overload [10]. For example, in the processing of smart city traffic data, reasonable resource management can increase the processing efficiency of edge nodes by 40%.

3.3. Real-time data storage and cache technology

Real-time data storage requires high concurrent read and write capabilities. The commonly used time series database InfluxDB can meet the real-time data storage needs of the Internet of Things. The cache technology adopts a multi-level cache architecture to store frequently accessed data in the cache, reducing the access pressure on the back-end storage. In the smart home scenario, the cache technology can increase the data access speed by more than 5 times.

3.4. Data security and privacy protection technology

Data security and privacy protection are crucial in edge computing environments. End-to-end encryption technology is used to ensure data transmission security, attribute-based access control (ABAC) is used to achieve refined permission management, and blockchain technology is used to achieve traceability of data operations. In the medical Internet of Things scenario, these technologies can effectively prevent patient privacy leakage.

4. Design of real-time data processing method for IoT based on edge computing

4.1. System architecture design

The architecture of the real-time data processing system for IoT based on edge computing adopts a layered distributed design, consisting of a perception layer, an edge layer, and a cloud layer. Each layer is both independent and closely coordinated to form an organic whole (Figure 1).

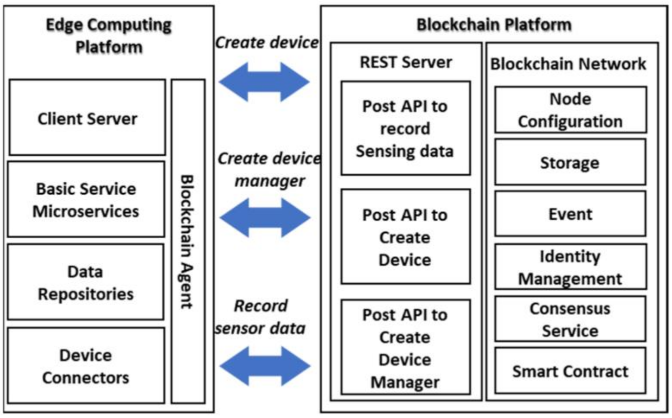

Fig.1 System architecture

As the source of data, the perception layer brings together a large number of heterogeneous IoT devices, such as industrial sensors, smart cameras, and wearable devices. These devices continuously collect various types of information in the physical world using different communication protocols (such as MQTT, CoAP) and data formats. For example, in smart agriculture scenarios, soil moisture sensors, light intensity sensors, etc. collect farmland environmental data in real time; on industrial production lines, vibration sensors and current sensors monitor the operating status of equipment [11]. In order to achieve unified management of equipment and efficient data collection, the perception layer introduces edge agent technology. Through the edge agent, it adapts to different device protocols and converts raw data into a standardized format, laying the foundation for subsequent processing.

The edge layer is the core processing layer of the entire architecture, consisting of multiple edge nodes, which are distributed at the edge of the network and have computing, storage, and network communication capabilities. The edge layer adopts a microservice architecture design, splitting the data processing function into independent microservice modules, such as data cleaning services, real-time analysis services, and cache services. Each microservice module can be dynamically deployed and expanded according to actual needs to improve the flexibility and maintainability of the system. At the same time, a P2P communication mechanism is established between edge nodes to achieve data sharing and task collaboration. For example, in an intelligent transportation system, edge nodes at adjacent intersections can exchange traffic flow data with each other and collaboratively optimize the signal light timing scheme.

As the "brain" of the system, the cloud layer is responsible for complex computing task processing and global data management. For tasks such as large-scale data mining and deep learning model training that the edge layer cannot handle, the edge nodes will upload the relevant data to the cloud. The cloud layer uses containerization technology (such as Docker) and orchestration tools (such as Kubernetes) to achieve elastic allocation and efficient management of computing resources. In addition, the cloud layer is also responsible for remote monitoring and management of edge nodes, and implements configuration updates and software upgrades of edge nodes through policy delivery.

4.2. Data processing process optimization

The optimized data processing process covers five links: data collection, edge preprocessing, edge computing, cloud layer deep processing, and result feedback, forming a closed-loop processing mechanism. In the data collection link, in addition to the conventional active collection method, an event-driven collection strategy is also introduced. When the perception layer device detects a specific event (such as equipment failure, abnormal environmental parameters), data collection is immediately triggered to improve the pertinence and real-time performance of data collection. The edge preprocessing link is a key step in data processing, including data cleaning, format conversion and feature extraction. Data cleaning removes noise data through outlier detection algorithms (such as the 3σ principle); format conversion unifies data in different formats into JSON or XML standard formats; feature extraction uses algorithms such as principal component analysis (PCA) to extract key features of the data, reduce data dimensions, and reduce data transmission volume. For example, in a video surveillance scenario, the edge node can perform target detection on the original video stream and only extract key frames containing moving targets for transmission to subsequent processing links. The edge computing link adopts a hierarchical processing strategy based on the task type and real-time requirements. For tasks with extremely high real-time requirements (such as industrial equipment failure warning), they are directly processed at the edge node; for tasks with high computational complexity but relatively low real-time requirements (such as equipment performance trend analysis), the edge node first performs preliminary processing and then uploads the intermediate results to the cloud. The cloud layer deep processing link uses big data analysis and artificial intelligence technology to deeply mine and analyze the data uploaded by the edge layer. For example, a machine learning algorithm is used to establish an equipment failure prediction model to provide support for production decisions. The processing results are finally fed back to the edge layer or perception layer devices to achieve closed-loop data processing.

4.3. Task Scheduling and Resource Allocation Strategy

Task scheduling and resource allocation strategy are the core of ensuring the efficient operation of the system. Task scheduling adopts a hybrid scheduling algorithm based on priority and load balancing. First, the priority is assigned to the task according to the real-time requirements of the task, the amount of data and other factors; then, the CPU utilization, memory usage and other resource status of the edge node are monitored in real time, and the task is assigned to the node with lighter load. For example, for emergency control tasks in industrial production, the highest priority is given and it is preferentially allocated to edge nodes with sufficient resources. In terms of resource allocation, a genetic algorithm is introduced for optimization. With task completion time and resource utilization as the objective function, the optimal resource allocation scheme is searched through genetic operations such as selection, crossover, and mutation. In practical applications, this strategy can effectively improve the resource utilization of edge nodes and reduce task execution time. In addition, a dynamic resource adjustment mechanism is designed. When the edge node resources are insufficient, it can request resource expansion from the cloud or negotiate with adjacent nodes to share resources.

4.4. Construction of performance evaluation index system

In order to scientifically evaluate system performance, a multi-dimensional evaluation index system including data processing delay, throughput, resource utilization, system reliability and data security was constructed. Data processing delay is measured by measuring the time interval from data collection to processing completion, reflecting the real-time performance of the system; throughput is measured by the amount of data processed per unit time, reflecting the processing capacity of the system; resource utilization is evaluated by calculating the usage ratio of resources such as CPU, memory, and disk to evaluate the rationality of resource allocation; system reliability is quantified by indicators such as mean time between failures (MTBF) and mean time to repair (MTTR); data security is evaluated from aspects such as data encryption strength and access control policy effectiveness. Through actual testing and simulation experiments, data of each indicator is collected, and the indicator weight is determined by using the analytic hierarchy process (AHP) to comprehensively evaluate system performance and provide data support for system optimization.

5. Case analysis

5.1. Application case in the scenario of industrial Internet of Things

In the smart factory of a large automobile manufacturer, the production process covers multiple links such as stamping, welding, painting, and assembly, involving hundreds of precision equipment and sensors. In the traditional data processing mode, the equipment operation data needs to be transmitted to the cloud for processing, with a delay of up to 200-300 milliseconds, which is difficult to meet the needs of real-time monitoring and fault warning of equipment. After introducing the IoT real-time data processing solution based on edge computing, edge computing nodes are deployed in each production workshop. Each node is equipped with a high-performance processor and large-capacity memory for real-time processing of equipment data.

Taking the welding workshop as an example, the welding robots in the workshop are equipped with current sensors, voltage sensors and vibration sensors, generating thousands of data per second. The edge computing node uses edge proxy technology to uniformly convert sensor data of different protocols into a standard format, and uses the 3σ principle to clean the data and remove abnormal fluctuation data. At the same time, the principal component analysis (PCA) algorithm is used to extract key features, reducing the data dimension by more than 80%. For fault warning tasks with extremely high real-time requirements such as abnormal welding current and excessive robot vibration amplitude, the edge node directly analyzes and processes locally. Once an abnormality is detected, an audible and visual alarm is immediately triggered, and the alarm information is pushed to the handheld terminal of the equipment maintenance personnel through the internal network of the workshop. The entire response process is controlled within 10 milliseconds. For complex tasks such as equipment performance trend analysis, the edge node first performs preliminary processing and then uploads the processed intermediate results to the cloud.

After half a year of operation, the solution has achieved remarkable results in improving factory production efficiency and equipment management level. The specific data changes are shown in Table 1.

Table 1. Industrial Internet of Things scenario data analysis

Core indicators	Traditional model data	Edge computing model data
Equipment downtime (hours/month)	12	4.8
Overall equipment effectiveness (OEE)	82%	89%
Data processing delay (milliseconds)	200 - 300	10

In the edge computing mode, the downtime of equipment failure is greatly reduced, which means that the stability of the production line is significantly enhanced; the improvement of the overall efficiency of the equipment directly reflects the more adequate utilization of production resources; and the data processing delay drops sharply from the original 200-300 milliseconds to 10 milliseconds, which can almost achieve real-time feedback of the equipment status, providing a strong guarantee for precise production.

5.2. Application cases in smart city scenarios

The traffic management department of a first-tier city is facing the problem of severe traffic congestion and low traffic efficiency. The average daily traffic volume on the main roads of the city exceeds 200,000 vehicles, and the traditional fixed-time traffic lights cannot adapt to the dynamically changing traffic flow. To improve this situation, the department deployed edge computing devices at 200 major intersections in the city, and each device integrated a video analysis module, a data processing module and a communication module.

The edge computing device collects intersection traffic video data in real time through high-definition cameras, and uses deep learning target detection algorithms (such as YOLO) to identify, track and count vehicles in the video, and can process 30 frames of high-definition video images per second. The edge nodes at adjacent intersections exchange traffic flow data through a P2P communication mechanism to collaboratively optimize the signal light timing scheme. For example, when it is detected that the length of the vehicle queue on a certain road section exceeds the threshold, the edge node will automatically extend the green light duration and synchronize the information to the edge nodes at the upstream and downstream intersections to adjust their signal light timing.

The cloud platform uses big data analysis technology to conduct in-depth mining of the city's traffic data, build a traffic flow prediction model, and plan traffic diversion plans in advance. After one year of operation, the city's traffic conditions have been greatly improved. The relevant data comparison is shown in Table 2.

Table 2. Smart city scenario data analysis

Core indicators	Traditional model data	Edge computing mode data
Average travel time on main roads (minutes)	25	20
Traffic congestion index	-	Down 18%
Traffic accident rate	-	Down 12%

The average travel time on the main roads has been reduced by 20%, which directly reflects the powerful ability of edge computing in optimizing traffic efficiency; the traffic congestion index has dropped by 18%, which means that the smoothness of urban roads has been greatly improved; and the traffic accident rate has dropped by 12%, which provides better protection for citizens' travel safety and fully demonstrates the application value of edge computing in the field of smart transportation.

5.3. Application cases in agricultural Internet of Things scenarios

A modern large farm has 5,000 acres of planting area, and crops include wheat, corn and other grain crops. Under the traditional agricultural management model, operations such as irrigation and fertilization rely on manual experience, resulting in serious waste of water resources and uneven crop growth. In order to achieve precision agricultural management, the farm deployed an edge computing-based Internet of Things system, installed soil moisture sensors, weather stations, light intensity sensors and other equipment in the field, and deployed edge computing servers in the farm's central computer room. The soil moisture sensor collects soil moisture data every 10 minutes, and the weather station monitors meteorological information such as air temperature, humidity, wind speed, and rainfall in real time. The edge computing server adapts different sensor protocols through the edge agent to pre-process the collected data. When the soil moisture is lower than the threshold required for crop growth, the edge node immediately triggers the irrigation system to automatically start, and accurately controls the irrigation time and water volume according to meteorological data and soil conditions. At the same time, the image recognition technology is used to monitor the growth of crops. The camera installed in the field takes crop images, and the edge node analyzes the images to identify the symptoms of crop diseases and pests. Once an abnormality is found, it pushes early warning information to farm managers in a timely manner and provides corresponding prevention and control suggestions.

6. Conclusion

This study focuses on the real-time data processing method of the Internet of Things based on edge computing, and constructs a complete theoretical and practical system. By designing a hierarchical distributed system architecture, optimizing the data processing process, proposing task scheduling and resource allocation strategies, and combining core technologies such as data collection preprocessing and resource management, remarkable results have been achieved in multiple scenarios such as industry, smart city market, and agriculture. In industrial scenarios, equipment downtime is reduced by 60%, and the overall efficiency of equipment is increased by 8.5%; the travel time on the main roads of smart cities is shortened by 20%, and the traffic accident rate is reduced by 12%; the resource utilization efficiency in the agricultural field is greatly improved, and the production cost is significantly reduced.

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