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Dynamic resource provisioning for cyber-physical systems in cloud-fog-edge computing

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Abstract

Cyber-Physical Systems(CPS) serves as an interdisciplinary effort that incorporates cyber vector as well as physical vector. The latter can generate exponentially growing amounts of data. How to process CPS big data systematically and efficiently is the key to the breakthrough of offering prospective and personalized services for each individual user and entity involved. In recent years, much research has been proactively conducted on advancing specific scenario or algorithm. However, few surveys value their integration. For good measure, the synthesis remains a fundamental challenge. Subsequently, we fill the gap in the literature by constructing cloud computing, fog computing and edge computing as a whole to inspire on new architectures and cross utilizations. Moreover, bringing the enthusiasm of traditionally solitude entities into play is crucial. In this exploratory study, we examine definitions of CPS as well as the three aforementioned computing paradigms and then shed new light on comprehensively established frameworks. We also survey on the application level of Cloud-Fog-Edge Computing in CPS respectively and dive into diversified algorithms and strategies to embed big data applications into a more intelligent and convenient society with current deficiencies and future research directions followed.

Keywords: Cyber-physical system, Dynamic resource Provisioning, Edge computing

Introduction

With the upgrading of smartphones, tablets and televisions on a stable, sustained and coordinated development, the explosion of end devices inevitably produces massive amount of data, as well as the consequent data processing and data security requirements [1]. As is known to all, services such as image, audio, social networking, video gaming and other interactive applications are gaining momentum. Moreover, the data containing users' historical behavior trajectory and demand preferences are complicated and heterogeneous, revealing the four key characteristics of current data flow: volume, variety, velocity and veracity(4V), so the processing of big data is worthy of attention [2].

On the one hand, people's everyday life generate overwhelming amount of real-time data. On the other hand, the plentiful data reversely affect people's mentality and behaviors and elevate people's mental health and well-being [3]. Admittedly, even when an individual is sleeping like a log, his wearable devices are operating hard to track sleep stages, sleep pattern and sleep quality, predicting daytime side effects and negative health and social outcomes. These data will be presented on the dashboard of smartphone applications to better quality of life, as is illustrated in Fig. 1.

The smooth operation of cloud data centers utilizes lots and lots of electricity resources and as a common sense, every single institution and organization should react in response to sustainable development to cherish a greener planet [4]. On top of that, some may transfigure the introduction of remote data centers so that they

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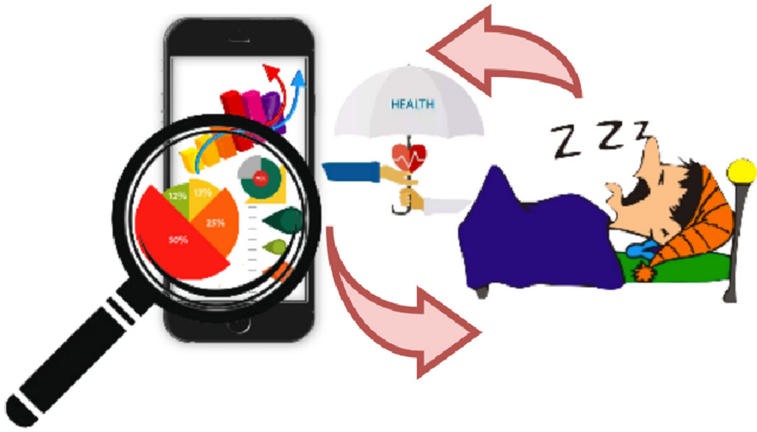

Fig. 1 The interactions between real-time data and people's mentality and well-being

neglect the transmission cost including time and expenditure, which gives rise to latency and mismanagement. For good measure, uncertainties like node failure, networking fluctuation, performance degradation are prone to occur despite existing network is on a constant improvement.

These failures breed complaint and dissatisfactions among users. Therefore, a thorough and rigorous analysis balancing energy consumption, latency and uncertainty is supposed to be thought over for enhanced Quality-of-Experience(QoE) [5].

Cyber-Physical Systems(CPS) is the unity of computers and physical processors [6]. At the physical level lie sensors and CPS nodes which utilize sensors for ambient data like temperature, humidity and illumination, running state data like speed, vibration and displacement and Work-In-Progress(WIP) data like location, size and quality. CPS shares the characteristics of real-time, distributed, diversified, as well as high reliability, strong security, human participation perception, cognitive analysis, intercommunication across systems and so on. Therefore, it is the basis to realize intelligent management that plans all elements in the system as a whole [7].

Honored with rich and powerful data processing ability and distributed computing storage ability, cloud computing serves as an impetus to higher parallel data processing ability and guarantees the reliability of operation [8]. Generally, cloud data centers have a greater quanlity of servers compared with traditional computing servers. In this pattern, end devices account for the preprocessing stage and then decide the proportion of tasks dispatched to cloud centers for executing.

Additionally, CPS also necessitates low delay and real-time services, and what we are about to discuss can perfectly meet these requirements. Fog computing is the expansion of cloud computing to decentralized edge network. As with edge computing, not only the data processing pressure is alleviated in cloud centers, but the system delay is reduced exceedingly [9]. Moreover, since no more offloading is called for and that data processing takes place locally, the security of data can be guaranteed to a maximum degree [10]. However, it is just the outstanding features of each aformentioned paradigm that shadow current research bottlenecks and pursue a novel architecture regarding the 4Vs of big data. Based on such motivation, therefore, the combination of cloud computing, fog computing and edge computing is put forward and discussed to configure the big data generated and shared in CPS.

In this light, the major contribution of this exploratory survey is mapped out including the following:

(1) Describe the definitions of CPS, cloud computing, fog computing, edge computing and dynamic resource provisioning and examine on their overlapping areas including similarities and distinctions.
(2) Model how cloud computing, fog computing and edge computing communicate and interact with each other and furnish a comprehensive framework with three tiers.
(3) Analyze the use cases of different computing paradigms with algorithms and strategies and take into consideration energy consumption, security concerns and resource utilization.

The following of this paper is organized as follows, "Definition" Section embarks on laying out the theoretical dimensions of CPS, and summarizes work in the literatures that describe the definitions of relevant terms like cloud computing, fog computing, edge computing and dynamic resource provisioning, and then the cloud-fog-edge computing framework is followed in "Framework" Section. After that, we concentrate on how cloud, fog and edge computing is applied to CPS respectively in "Dynamic resource provisioning for CPS with novel computing paradigms" Section. In the end, "Open issues" Section reviews promising directions and open challenges as a future outlook with conclusions reached in "Conclusion" Section.

Definition

Cyber-Physical systems

As is shown in Table 1, Cyber Physical Systems(CPS) is widely known as the integration of our physical world with all kinds of communication and the computing capability along with the storage. CPS is figuratively explained as a feedback loop influenced by cyber communications, physical acturators and human utilization [11]. In the conclusion of the article, security issues of the whole system is put forward, and [12] raised a quantitative hierarchized prediction model to answer the previous question, which also points out that as a real-time and autonomous system, CPS is a robust and complex system with multi-scale computation and physical components integrated with each other under the fifth-generation wireless network.

In terms of system composition, CPS includes information systems, sensors and mechanical equipment. All these parts connect and interact with each other under standard Internet Protocols [13]. Furthermore, CPS is a hybrid including both dynamic continuous processes of changes and discrete state transition, featuring the deep integration of computing and physical process and heterogeneous composition [14]. It might also be noted that CPS is beyond software and control domains and integrates both software components and plant components tightly [15]. What's more, in [16], CPS is a kind of system supplying the integration of physical processes, computation and networks. It can also be viewed as a system with physical subsystems and software bounded together and each of them interacts with each other in various time and space dimensions [17, 18]. So it is apparent to reach the conclusion that it is system composition that distinguishes CPS from diverse data processing paradigms.

Table 1 Summary of Literatures about the Definition of CPS

System description	Related work
the physical world, communication, computing capability, storage	[11]
Multi-scale computation, physical components	[12]
Information system, sensors, mechanical equipments	[13]
System, dynamic continuous processes, discrete state transition , heterogeneous composition	[14]
A system transcends software and control domains, software components	[15]
Physical subsystems, software,time and space interactions	[16]
Community detection, evolution analysis, link structure prediction	[17]
Gathering data, pre-processing data, running analyses, post-processing results	[18]

Cloud computing

A cloud data center is a seemingly infinite pool of resources. Cloud computing opens up new horizons for distributed computing methods and it also creates an established, dynamic computing mode, which supplies information technology(IT) services as public computing resources. It decomposes huge data computing and processing programs into enormous small programs through the cyber 'cloud', and then processes and analyzes them through multiple servers to get results which will be sent back to the users [19]. Concludingly, in the standard definition document published by the National Institute of Standards and Technology(NIST), cloud computing is a mode which offers an available, convenient and on-demand network access to the shared pool, owning rich and powerful configurable computing resources [20].

Moreover, all these resources can be used immediately and take up few general commands along with the interaction with service providers [21, 22]. Hence, the cloud computing can be viewed as a new mode which can create the next-generation data centers in a dynamic manner by assembling the services supplied by cyber virtual machines [23].

Fog computing

Proposed by Cisco, fog computing platform extends the core of cloud data centers to its edge with the benefits of placing fog data centers and edge servers closer to mobile devices so that both better computing capacity and less transmission delay come to a win-win end. Furthermore, by establishing itself as a neighboring controller being able to provide immediate attention, it offers Internet of Things(IoT) applications with time-sensitive and privacy-concern services. It should also be noted that fog computing is a highly visible service platform which can integrate resources such as the CPU, bandwidth and storage from different network devices into the fog nodes to supply services to terminal devices. By placing these light-weight facilities at the proximity of IoT devices, fog computing can overcome the downsides of limited computation or storage capacities and ultra-high transmission latency by exploiting the opportunities of locality [24].

Edge computing

Edge computing refers to an open platform on the side close to the object or data source. It integrates network, computing, storage and the core capabilities of applications, providing the nearest service nearby, and generating faster network service responses [25]. Edge Computing is a dispatched computing mode that can address some inherent issues in cloud computing like resource centralization by withdrawing computing and storage resources from centralized points, which in other words, can be viewed as pushing applications, data, and services closer to those request senders geographically, perfectly overcoming intolerable transmission delay [26].

What's more, as an essential method of IoT networks, edge computing is a platform with the ability to ease the burden of centralized data processing along with personal privacy issue, compared to cloud computing which may be restricted by data transferring and system efficiency [27].

Dynamic resource provisioning

Dynamic resource provisioning is a multi-agent system managing the providers' resources along with the customers' requests simultaneously or sequentially, as determined by the service-level agreement. [28] describes the concept concentrating on cloud computing while [29] focuses on edge computing. In spite of the revolutionary role cloud-fog-edge computing has displayed, dynamic resource provisioning is fast becoming a key instrument in the process of large scale and heterogeneous distributed data flow. Unproductive tasks scheduling may induce excessive energy consumption and unsuccessful task response.

The fundamental idea of dynamic resource provisioning is to supply the resources based on users' or the applications' real-time needs and network bandwidth requests [42], which is to identify the amount of resources that should be used on the execution of workflow at different moments and then schedule activities based on the allocated resources for the sake of networking reusability and flexibility.

Framework

In this section, we first sort out some documented studies as is shown in Table 2 before put forward our CPS architecture with cloud-fog-edge computing involved. The combination of governance tools and central coordinating structures create both a shared vision and a more intelligent tomorrow.

Surveys on proposed frameworks

In [30] and [31], a system involving a signal monitor, a decision-controller and an execution gadget is put forward. In addition, a feedback loop controlling principle is adopted, accessible to each layer in the system and serving as a interweaving thread that connects three layers together as a whole. [32] illustrates the scene where end clients have access to information via any person computer(PC) linked to the Internet and meanwhile, programming level is not open to client users as it objects to cloud centers, achieving the sharing and protecting of data distinctively. [33] argues that the behaviors of physical processors is the joint result of cyber and physical level of the system in the large. [34] and [35] highlight the indiscerptible role of the computing core and communication core which dominate both cyber and physical system. [36] maintains that event is the clue to the Cyber-Physical System and concentrates on the timestamp of each event.

Table 2 Summary of literatures about framework of CPS

Architecture	Feature	Related Work
A sensing unit		
A control decision unit	1. Perceived objects	[30]
An execution unit	2. User instructions	[31]
Sensors	1.Self-administration	
Retrieval	2.Per-utilization metering and charging	
Virtualization	3.Versatility	[32]
	4.Customization	
Computing and communication	1.Interact with the physical world	
Physical and virtual processes	2.Monitor and control the physical processes	[33]
Physical level	1.A computing and communication core	[34]
Engineering level	2.Monitoring, coordination, control, integration	[35]
Computing technology	1.Distributed systems	
Communication technology	2.Deterministic timestamps	[36]
Control technology	3.Tailored pruning techniques	
Dynamic Social Structure of Things(DSSoT)	1.Higher sociality	
	2.Base upon situational awareness	[37]
	1.AcOP defifinition	
AcOP and the associated framework	2.an associated framework defifinition	[38]
	3.AcOP and the associated framework benefits	
Privacy computing	1.Center on information life-cycle	
	2.Raise definition and principles	[39]
ISMSs	1.And/or information officers	
	2.Outsourcing	[40]
NET	1.Aligning the FISMA standard	
	2.Multi-tenant SaaS application exemplar	[41]

In [37], a novel paradigm called Dynamic Social Structure of Things(DSSoT) is carried out, taking full advantage of users' past experience and preference settings to provide accurate predictions for future better QoE. AcOP is a combination of mobile apps and cloud-based CPS, flexibly corresponding to surroundings and certain conditions. Edge computing in AcOP and the associated framework has high security performance because trusted entities can work with each other in a variety of CPS applications and act as backup options. Given one device fails, instantly other devices will replace it [38].

In light of the defense for cyber security, the privacy computing framework proposed in [39] allows private information exchanges, extensive permission of private information flow in a multi-interface scenario. The competition between different data centers is no less intense than that of track-and-field events [40]. Thus more reliable and stable guarantee of data assets make for both more clients for service providers and less risks for service clients [41].

[43] and [44] propose a framework where part of the tasks are migrated from cloud servers to edge nodes to arrange services and resources in proximity to users, in which way lower transmission delay and network bandwidth requirements become a reality. Additionally, the paper illustrates the framework with a typical application scenario: smart cities. Smart cities are convincing examples of an effective combination between digital level and physical level. All aforementioned architectures are concluded in Table 2.

Framework for cloud-fog-edge computing in CPS

As illustrated in Fig. 2, we introduced the holistic integration of cloud computing, fog computing and edge computing. Edge computing offers edge-server-oriented service provision in a bid to achieve an optimized method for processing with low latency the computation offloading and data offloading tasks generated from mobile users. Additionally, fog computing paradigm employs multiple cloudlets collaborations to meet the demanding requirements from multimedia applications without the shortcomings of transmission delay. The aforementioned two architecture lies in proximity to end devices while cloud computing servers are far away from mobile users. Therefore, the cloud servers are capable of offering constant computing power and coping with challenging applications and services.

Dynamic resource provisioning for CPS with novel computing paradigms

As all ranges of real-time multimedia applications which are labelled as resource-intensive and entitled demanding environment for energy consumption and battery lifetime being launched and iterated, the contradiction between soaring requirements from multimedia applications and the humble capacity of end devices has surfaced and is under heated discussions [45]. A wide variety of challenges range from the underlying infrastructure construction to the superior programming model design.

In consequence, mobile devices from end users, including smart phones, tablet computers and wearable devices, are commonly incapable to penetrate the ceiling of resource and physical limitation, bringing us into the picture of introducing dynamic resource provisioning for CPS.

For the sake of user experience, data processing is not limited on mobile devices. According to where primitive proportion of data services actually take place, mainstream computing paradigms can be clasified as cloud computing, fog computing and edge computing.

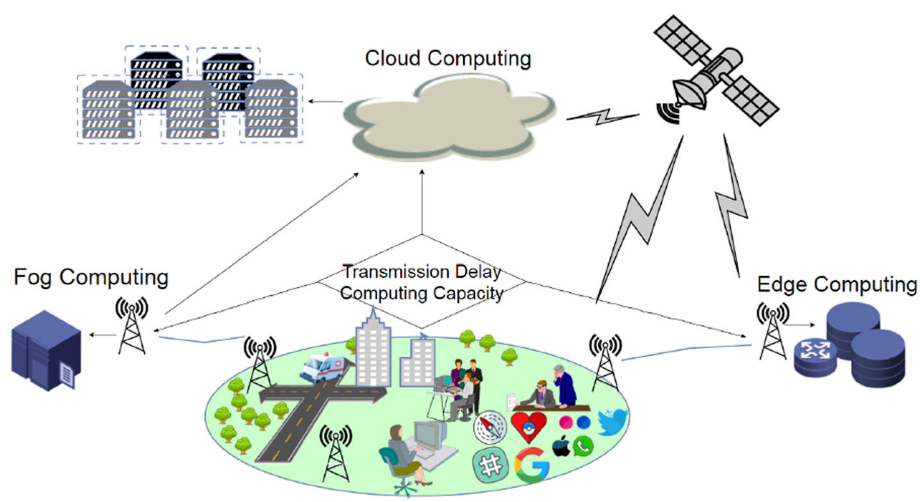

Fig. 2 Framework for cloud-fog-edge computing in CPS

In this section, we would continue our discussions up to the typical applications in CPS. Our detailed examinations touch upon a series of relevant methods and algorithms in different scenarios and use cases with a descriptive approach.

Dynamic resource provisioning for CPS in cloud computing

In this subsection, the question of how to build, employ, manage and control cloud computing in Cyber-physical-social system is resolved in a comprehensive and all-round slope as is demonstrated in Table 3.

Indeed, reducing energy costs for data center operations accounts for less waste, but the QoS of running applications can also dramatically decrease due to overcommitment to resources. Thus with multi-core homogeneous processors, an algorithm for virtual machine placements is proposed in [46] and can fulfill energy cost reduction by over 60 per cent, estimated by experimental results. In [47], an automotive system and a quadrotor, a small helicopter with four propellers, are employed to elaborate on the complexity and heterogeneity of maintaining data consistency and guaranteeing verification. A QoS-aware VM scheduling method in cloud-based CPS is put forward to figure out optimal energy consumption scheme, assisted by the non-dominated sorting genetic algorithm III, simple additive weighting and multiple criteria decision making. Genetic algorithm is suitable in large scale problems including searching and optimization problems as well as under the circumstances where branch and bound schemes cannot make ideal results [48].

Modern factories overflow the boundaries of the traditional mills. From the standpoint of customers, not only does participating in the designing is favored but tracing and tracking the production along assembly line would be an extra bonus. CPS platform is considered in [49] as the bridge that connects CPS nodes and stakeholders in manufacturing. However, this study also points out that the solitude CPS cannot undertake future personalized and heterogeneous requirements, thus social tier should be added to the original pattern, forming integrated cyber-physical-social systems. Under the trend of market-of-one mode, [50] and [51] merge the utilization and

Table 3 Summary of Literatures about Methods on Cloud Computing Based CPS

Item	Key Points	Related Work	Domain
LP-based algorithm	1. Minimized energy consumption	[47]	Arrangement
Stochastic VM placement algorithm	2. Improved feasibility	[46]	
QVMS	Virtual machine scheduling method	[48]	Energy conservation
Anomaly	Automatic fault diagnosis of bearings	[49]	Manufacturing
Fault detection			
RFs	1. Resource fractals	[50]	
	2. Reconfigurable rules	[51]	Smart factory
CCPSA	1. Complex Industrial Applications(CIAs)		
	2. Virtualized resource management techniques		
	3. Scheduling of cloud resources	[52]	Industry
	4. Life cycle management		
CaaS	1. Design of CaaS	[53]	
ESD system	2. Implementation of the Cyberaide Creative service	[54]	Architecture
Deep learning			
Convolutional neural network (CNN)	Forecasting/prediction/classification/ regression	[55]	Smart grid
V2X	1. Technology strategy		
SMEs	2. Policy strategy	[56]	Automated driving
ANN	1. Behaviour	[57]	
	2. Event Recognition	[58]	Transport
Decision Tree	Predict traffic congestion level and pollution level	[59]	Transport
Pattern recognition			
Clustering	Activity recognition	[60]	Smart home
Attribute-based encryption	Semi-trusted environments	[61]	Healthcare
PI	1. Possible linkages	[62]	
	2. Thematic clusters	[63]	Smart city

architectures of manufacturing resources of diversified scale into an integrated resource fractals on the theoretical evidence of fractal theory. It is stated that human-friendly manufacturing requirements should be translated into a formalized and systematic machine language for high-level data sharing and more intelligent communications. The transformation is in conformity with customized production process. Shu, Zhaogang, et al present in [52] an orchestration of three entities, i.e., CIA layer, virtual cluster and physical host. At the bottom, physical hosts are responsible for manage VM asynchronous lifecycle, optimize network I/O performance and disk I/O performance, with middleware providing workflow-oriented resources arrangement and the top layer targeting at collect QoE information.

[53] proposes a novel paradigm called Cyber infrastructure as a Service (CaaS) and interpret the concept with a use case. The essence of cloud computing lies in cloud data centers that offer a mighty and scalable computing and storage environment away from end users. Transmitting resource-demanding and computing-intensive to the remote cloud considerably bring down the objective requirements for device performances [54]. For those settling down in high-rises and skyscrapers, evacuation in cases of fires or other emergent conditions can be intelligently scheduled and dispatched.

[55] focuses on bettering the long existing fluctuations of electricity infrastructure with CRBM and FCRBM employing deep learning algorithm. In recent years, deep learning has been introduced in a wide range of use cases. It is based on learning applications embarking on modeling the question, categorizing the task and estimating potential results to achieve an optimized computation accuracy. [56] regards the combination of technology strategy and policy strategy a stimulator to the development of survival of small-and medium-sized enterprises in the times of CPS and automated driving.

Via a use case of smart driving, [57] and [58] elaborate on the steps from raw sensor data sampling to MLAs in multi-way, half-duplex, or large-antenna networks. The whole process can be divided into two stages. On the one hand, smartphone sensors collect raw data material and then translate all of them to earth coordinate system. On the other hand, computers first generate attribute vectors and the dataset is transmitted for training, testing and accessing MLAs before the final results come out. [59] proposes a transportation featuring distribution, flexibility and scalability. In a gesture to achieve traffic efficiency including commanding emergency situations and predicting possible congestions and accidents, the paper utilizes C4.5 algorithm and artificial intelligence techniques.

A lightweight design is raised in [60], in which bridge bond archive storage and three levels together. At the bottom of the architecture lies physical level with sensors, actuators and zigbee wireless mesh, followed by middleware's publishing and subscribing managers. Through the application bridge, middleware can readily transmit data with the top level which is responsible for activity recognition, activity discovery and energy stuff. [61] presents an architecture and its implementation for data sharing across organizations and healthcare workers to confront with curious cloud providers.

Empowered by data, digital cities evolve into smart cities where requirements from citizens, as well as residents, workers, and visitors are supposed to be better met [62]. We envision a livable, comfortable and sustainable city with physical facets: traffic signals, sewage works, air quality measures being controlled algorithmically [63].

As an overview of this subsection, we propose Fig. 3 to shed light on the relationship among above-mentioned articles. Mainstream academic schools devide cloud computing architecture into five categories including Infrastucture as a Service(IaaS), Platform as a Servcie(PaaS), Software as a Servcie(SaaS), Communications as a Service(CaaS) and Machine as a Service(MaaS). Further, the use cases of each one enjoy promising future, for instance, manufacturing, smart grid, automated driving, transport, smart home, healthcare, smart city. Also, cloud computing is supported by powerful algorithms like evolutionary algorithms and multi-objective optimization.

Dynamic resource provisioning for CPS in fog computing

In this subsection, we review the existing researches on fog computing. A summary of literatures about CPS with the basis of fog computing are listed in Table 4, where key points in each article are concluded and the architecture is further analyzed is Fig. 4. We review on CPS which is simply supported by fog computing in "FC-CPS" Section and methods which integrate CPS, fog computing along with other kinds of technology in "FC-CPS with other technology" Section.

FC-CPS

As a sound way to improve the stability of connections and reduce delay in links between cloud data centers and devices, fog computing can be a promising solution. In [64], Lin et al. are inspired to add fog computing into MCPS and propose the method called FC-MCPS. Although MCPS integrates medical devices like monitoring devices and delivery devices with software applications, it still faces the challenges from analyzing and transferring of the bulky data produced by those devices, along with the accurate feedbacks. By integrating fog computing, they host the VMD applications like base stations in the network edge, providing both communication services and the computation and storage resources, which can directly upload and process medical data streams.

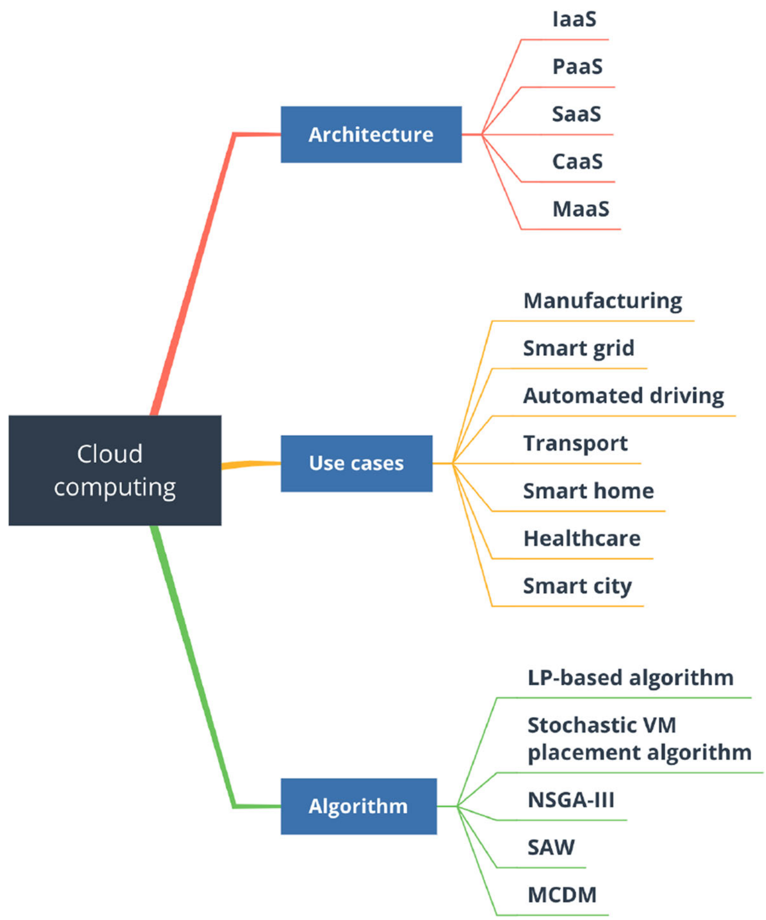

Fig. 3 A conclusion of methods adopted for CPS in cloud computing

Pushing fog computing to lower logical level as a bridge between the smart city CPS ecosystem and the level of application should be considered. The fog computing can be viewed as a programmable coordinator, which can detect specific situations and perform multiple actions. The fog coordination subsystem performs as a tunnel or a forwarding agent which enables the inter-object communication between data-link layers and network layers without involving the application layer. It is supposed to manage implementing this idea in the Stack4Things middleware and extend fog computing along with OpenStack to CPS infrastructure.

In the system-level CPS and Digital Twin, [65] emphasizes the interconnection and interoperability among those components and focuses on the dynamic cooperative control of them so that they can realize the coordination and unification between physical world and network world. They find that fog computing can promote real-time interaction and extensibility and its environment consists of network components, which have different abilities such as computing, storage and networking capabilities and can support the realization of smart applications. So they select fog computing to deal with the system-level CPS and Digital Twin.

In [66], Zhou et al. improve the CNC machine tools with CPS to provide better adaptability and autonomy. However, the latency and the dependence of network bandwidth are still a problem which cannot be neglected. To solve this problem, they manage to use fog computing to support cyber physical machine tool system for the autonomy and synergy supplied by fog computing. Fog computing also reduces the traffic of network and calculation workload of the cloud platform in that system.

In [67], Song et al. proposed a model which can execute delegated functions of power in the CPS-healthcare system. It can also supply real-time and confidential services to collect information based on fog nodes, which can reduce network latency compared to cloud computing. In [68] and [69], some similar thoughts are given, which explore on the integration of the CPS and fog computing along with cloud computing, and there is study in [70] which integrates CPS and fog computing along with

Table 4 Summary of literatures about methods on fog computing based CPS

Method	Key Points	Related Work
	1.Fog computing supported MCPS	
	2.Pushing Fog computing to lower logical level as a set of mechanisms	
FC-CPS	enabling the deployment and execution of multiple location-aware	[65]
	3.System-level CPS and DT are geographically concentrated	[66]
	4.New architecture of CNC machine tools based on CPS and fog computing	
CPS-Healthcare system	1.Attribute based proxy reencryption	[64]
	2.Medical information system	[67]
IFCIoT	1.Geographical or logical clusters	
	2.Situ processing and offloading	[68]
Virtual Machines(VMs)	1.Economic and environmental issues	
Physical Machines(PMs)	2.Vector bin-packing problem	[69]
First-Fit Decreasing(FFD)	3.FFD based heuristic techniques	
Cloud-to-Things continuum	Mission-critical applications	[70]
Trust management system	Lightweight management system	[71]
Exogenous coordination model	Support considerable smart devices in CPSCN applications	[72]
PsCPS	A distributed platform for cloud and fog integrated CPS	[73]
CPSWare	1.Systemic solutions for solving computing and networking issues in CPS	
	2.Enable the integration of CPS with cloud and fog computing	[74]
ICPS	A Bluetooth 5 fog computing based ICPS architecture	[75]

edge computing. With those methods, data volume which transferred between cloud and devices can be decreased significantly. What's more, these models are highly scalable and economical compared to other common models.

FC-CPS with other technology

In this section, we review how fog computing is employed to integrate CPS along with some other technologies. In a bid to figure out challenges in great demand, the following part discusses holistically integration, averting malicious attacks.

(1) FC-CPS with Trust Management System.

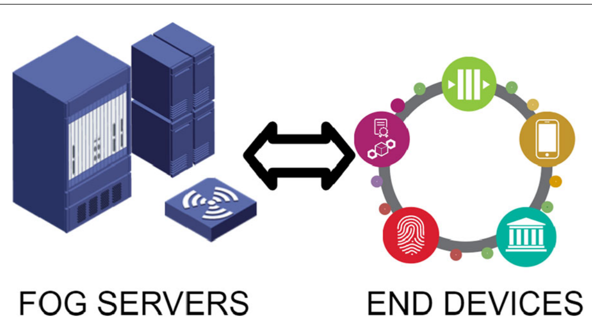

Fig. 4 The exchange of data between fog servers and end devices

In [71], Junejo et al. integrates CPS with fog computing for its timeliness and low latency but they also point out that the FC-CPS systems are usually deployed in an open and relatively unprotected environment which means both the CPS devices and these fog nodes are very vulnerable and are in a situation where numerous attacks such as collusion and ballot-stuffing may happen from time to time. To deal with those challenges, a Trust Management System is proposed where the FC-CPS devices are the trustor and fog assisted nodes are the trustee. Those compromised entities can increase or decrease the trust of other nodes to dynamically modify the accuracy of the trust computation model. The credibility of each newly modified trust value is evaluated and adjusted by relating it with a standard deviation threshold. By comparing it with the trust value in a legitimate environment, abnormal data can be detected and malicious acts that destroy entities can be prevented.

(2) FC-CPS with exogenous coordination model.

In [72], Giang et al. proposed a computing and networking system based on fog computing, which supplies a gateway to the physical world and offers new possibilities for social applications. Then, they extend their work on a distributed programming model and the key aspect of which is an exogenous coordination model that can separate computing and communication activities and can solve some challenges caused by the dynamic and large-scale system.

(3) PsCPS.

The smart Cyber Physical Systems(sCPS) extend the traditional CPS by putting in intelligent and autonomous capabilities. These systems are usually highly distributed, dealing with large datasets and real-time requirements. Hence, they need powerful computation ability and large-scale storage capacity which can be provided by cloud and fog servers.

Nevertheless, it is challenging to let all these systems holistically integrated. In [73], a distributed platform for cloud and fog integrated sCPS(PsCPS) is proposed to relax challenges of such kind of integration. This platform deploys system and application agents on participating nodes to supply different services. All these agents will be divided into 3 categories, which are single agents, multi-agent systems, and hierarchical multi-agent systems, to achieve management and control to cloud and fog computing and produce positive impact on sCPS.

(4) CPSWare.

In [74], Mohamed et al. proposed an service-oriented middleware approach for CPS called CPSWare. As is known to us, CPS is a kind of embedded system, which can have strong interactions between software and hardware. What's more, CPS is multifaceted embedded system, which means it has distributed components and the ability of processing. This middleware views all components of CPS as a services set and supplies a service-based infrastructure which can develop and operate CPS applications. By using this method, systematic solutions will be provided to solve many computing and networking issues in CPS and fog computing can be enabled to integrate with CPS well.

(5) ICPS.

A fog computing based Industrial CPS(ICPS) is being designed for remote real-time monitoring of pipe workshops. However, the environment in such workshops is harsh. In this case, wireless communication is limited to certain conditions, which may impact on system reliability. What's more, until now, the communication technology used to deal with these IIOT scenarios has not been able to correctly control the requirements of the long reading range and efficiency, so in [75], a Bluetooth 5 fog computing based ICPS architecture is proposed to cope with that environment, since the low power consumption, range, speed and broadcasting capacity of the system will be enhanced significantly.

Dynamic resource provisioning for CPS in edge computing

In this subsection, we dive into the application of edge computing on the development of CPS. We first give a brief review on what has been concluded before, as can be readily available in Table 5 and then we probe into the current situation of edge computing for CPS as well as some closely relevant algorithms and methods.

The edge computing-assisted CPS framework consists of the following three planes: edge plane, inference plane and application plane. Edge planes are responsible for local data processing, including representation and filtering of local data. After the pre-processing stage, an all-round compromise is achieved where the noise and redundancy are reduced considerably while the communication cost is saved ideally.

The edge plane receives workflow data stream from the cloud plane and then provides users better QoE. The edge plane and the cloud plane complement each other to ensure real-time processing.

The multi-vendor Mobile Edge Computing platforms proposed in [76] motivates a brand new value chain, novel business opportunities and use cases that is totally out of imagination before. Such edge computing platform greatly improves the ability and real-time performance of data transmission. Edge computing saves CPU computing resources based on filtering data transmission. MEC is Mobile Edge Computing, in a hostile environment, MEC can overcome the problems originateing from the limited resource of mobile devices. Under hostile environment and high mobility, MEC can also provide sound services to end users. MEC layer can fulfill high-demanding computing tasks from mobile devices.

Additionally, MEC promotes the development of 5G for meeting the high criterion of 5G in delay, programmability, scalability and so on. The edge computing node is a logical node and the Explicit Congestion Notification(ECN) integrates network, computing, storage, control, application functions and security. ECN is blessed with high liquidity, and when taking off from an access point(AP), the ECN can safely connect with another AP Network.

There exists no doubt that end users and edge server nodes are two basic components in edge computing. Guan, Peiyuan, et al model their bidirectional relationship via game theory where end users pay for different QoS while edge server nodes choose either which end user to provide service or what task to operate on [77].

In [78], an embedded digital signal processor stands out for its impressive scalability and is adopted as a case study. What's more, network Bit Error Rate(BER) is contrasted under both through power line and under wireless circumstances. [79] raises a novel architecture where front-haul and back-haul links are inset in unmanned aerial vehicle technologies so that the supply-demand

Table 5 Summary of literatures about methods on edge computing based CPS

Item	Key Points	Related Work
MEC	1. MEC definition and functions	
ES	2. MEC in 5G	[76]
	3. ES deployment criterion	
Nash Equilibrium		
Game theory	Noncooperative game	[77]
NEA		
DSP	1. NEA in IoT and CPS	
	2. DSP benefits	[78]
UAV	1.Retromodulator-based optical communication	
	2. Novel radio access network architecture	[79]
IoT/CPS data processing pattern	1.Social IoT	
	2.Novel pattern based on the stream processing technology	[80]
	3.In-memory data processing architecture	
Failure estimation method	1. Realization of CPS edge computing with smart sensor	
	2. The functions of smart sensor	[81]
	3. Benefits of edge computing	
CEC	1.A Cloud-Edge Computing Framework for CPS	
ELEs	2. Tensor-based services model	[82, 83]
IRM	1.An intermediate representation model	
	2.Home health care application	[84]
DDPG	1.A hybrid data offloading scheme	
DQN	2.The policy-based DRL approach	[85]
Deep reinforcement learning		
FPGA	1.FPGA benefits	
ARTICo	2.ARTICo benefits	[86]

contradiction resolves each other. The proposed the UAV-mounted infrastructure can also display their inherent capacity when it comes to the recover of a small region like the villages around mountain ranges after a horrific landslide.

[80] targets at the hostile environment where the amount of data is more than overwhelming plus some tasks call for extra computation resources and at the same time, time constraints cannot be jumped over the line. This paper puts forward an extensive edge computing platform based upon Elijah platform, taking full advantage of the active participation of human.

[81] uses simulation experiments to back up the proposed failure prediction model and communication saving strategy, and the paper also elaborates on the particular functions on edge computing of smart sensors. CEC includes edge plane, cloud plane and application plane. The edge plane collects data and extracts the corresponding high quality data. The edge planes provide these high-quality data and services directly to users. In the local CPS, some simple computing tasks, such as matching or sorting, can be implemented on the edge plane. CEC framework can effectively integrate cloud computing and edge computing. IoT/CPS data processing pattern is based on flow processing technology, which distributes the workload in the cluster of edge devices. It can solve big data problems on mobile devices.

[82] and [83] elucidate the functions of the sensing plane, cloud plane, and application plane respectively and capitalize on smart living and smart space as a qualitative use case. With increasing pressures on city resources as a motivation, smart city data ecosystems embrace environment of diversified hierarchies and cultures. The paper regards user satisfaction as the best policy taking locality contentment, energy consumption contentment, QoS contentment, and human computer interaction contentment into measurement.

Edge cloud-assisted CPS framework facilitates cities to be more humanized and reasonable with elevated efficiency, sanitation and security. By applying traffic rules and legislations, reduced city cruise time, eased traffic congestion, lowed carbon emissions and improved the efficiency of traffic management can be readily achieved as well as optimized parking space allocation. With embedded smart sensors, the system's current state report and potential failure prediction can be get, and the data can be filtered by event generator [84].

Under the common sense that conventional RF communications is not a possible solution to IoT devices, Xie, Yutong, et al. raised deep reinforcement learning scheme concentrating on the optimized power allocation strategies despite uncertainties and locations [85]. FPGA can implement high-performance embedding requirements for applications. In the implementation of the binary neural network, the FPGA provides far more accuracy than the result of the optimized software running in the GPU. ARTICo can realize the large-scale of data and the clarity of data. ARTICo provides a good basis for edge computing in CPS [86].

[87] focuses on security provisioning in the context of mobile environment, and therefore comes up with a software-defined networking(SDN)-based verification management. Moreover, edge analytics can be applied to CPS and IoT. ENA has effective real-time collaborative computing. Processing elements are placed in the edge layer and can run powerful computing intensive software such as R and Matlab at the edge. ES can share computing tasks from mobile users and reduce delays in data transmission to the cloud, concluded in Fig. 5.

Open issues

While the collaborative efforts in CPS can save end consumption and boost processing efficiency by specialization, it is out of urgent necessity to consider data leakage and vicious attacks and hacking. Also, what is especially noteworthy is that the proportion of how much tasks are performed locally and how much are to be transmitted to the cloud calls for weighted concern as the human-to-human, human-to-machine and machine-to-machine interactions are gaining wide currency. At the same time, in order to improve the edge computing ability, more edge nodes need to be established on the basis of empirically valid theories.

This section would research into future research directions taking computation offloading, service composition, privacy issues and big data applications into account.

Computation offloading

Although transmitting to data centers saves the power and storage of end devices, the consequent latency cannot be underestimated and the major challenge of that is the strategy for computation offloading in essence. As edge computing and fog computing are implemented into mobile scenarios, dynamic physical and logical resource allocation is allowed in accordance with catering to low latency requirements and high quality computing experience [88]. However, there is no doubt that blemish still exist. The difference of data types generated by four categories, i.e., Infrastructure as a Service(IaaS), Platform as a Service(PaaS), Function as a Service(FaaS) and Software as a Service(SaaS) poses difficulties when it comes to data transmission. As a result, failures happen from time to time when the operation time of computing and transmitting scheme comes in excess of a threshold, and that is what is defined as a task failure. Hence, better computation offloading algorithms and strategies will be the key to the realization of completing the computation of tasks smoothly [89].

Service composition

The rich and powerful computing enabled CPS is an optimized fault tolerance mechanism where better services can be fulfilled when faults come across both in hardware and software [90]. Accordingly, tasks are fulfilled before hard deadlines and at the same time, the Quality-of-Service(QoS) is optimized to the maximum extent. Because of the difference of data processing among edge computing, fog computing and cloud computing, it is also important to improve the data filtering rules between different levels of the algorithm [91].

Therefore, with next fifth-generation(5G) wireless networks era just around the corner, heterogeneous data convergence worth weighted attention in the future [92]. Besides, in a gesture to avert resource waste in cloud data centers, the future resource allocation needs to be estimated in real-time. Thus further creative algorithms and strategies are to be proposed.

Security and privacy issues

Under Privacy-Preserving Protocol based on ISO 11770-3, privacy violations have declined to a certain extend since its implementation. In contrast with traditional cloud data centers where the level of concentration cannot even be higher, the emergence of distributed computing dispatches workflow in means of allocating packs of data to a series of edge servers by pushing them geographically closer to mobile users.

However, it should be confessed that entities involved are still prone to be harnessed when privacy-sensitive information comes into the limelight. Undeniably, with data encryption and Blockchain, for any intruder it is tough to alter the stored data at majority places on the basis of the distributed authentication and trust among the peer nodes of the IoT system [89]. But the price-performance ratio may not worth it. Under current framework, information services are confronted with severe privacy-leakage challenges including unknown system vulnerabilities and backdoors during the entire lifetime of stream flow, embarking upon information aggregation, memory, processing, printing, and release in turn [93].

Research on achieving broad IoT data sharing within the spectrum of information security enjoys promising prospects.

Big data applications

Application Programming Interfaces(API) are responsible for satisfying user needs and meanwhile, sustaining data interoperability. Current data managing strategy highlights the emergence of new challenges: normalized bandwidth and transmitting capacity. Transparent and seamless data sharing across ecosystems allowed by technological openness and open value exchanges between government and SME enabled by organizational openness call for a better tomorrow big data applications [94].

The future researches should involve establishment of an opportunistic prototype for CPS, just as we have mentioned in "Dynamic resource provisioning for CPS

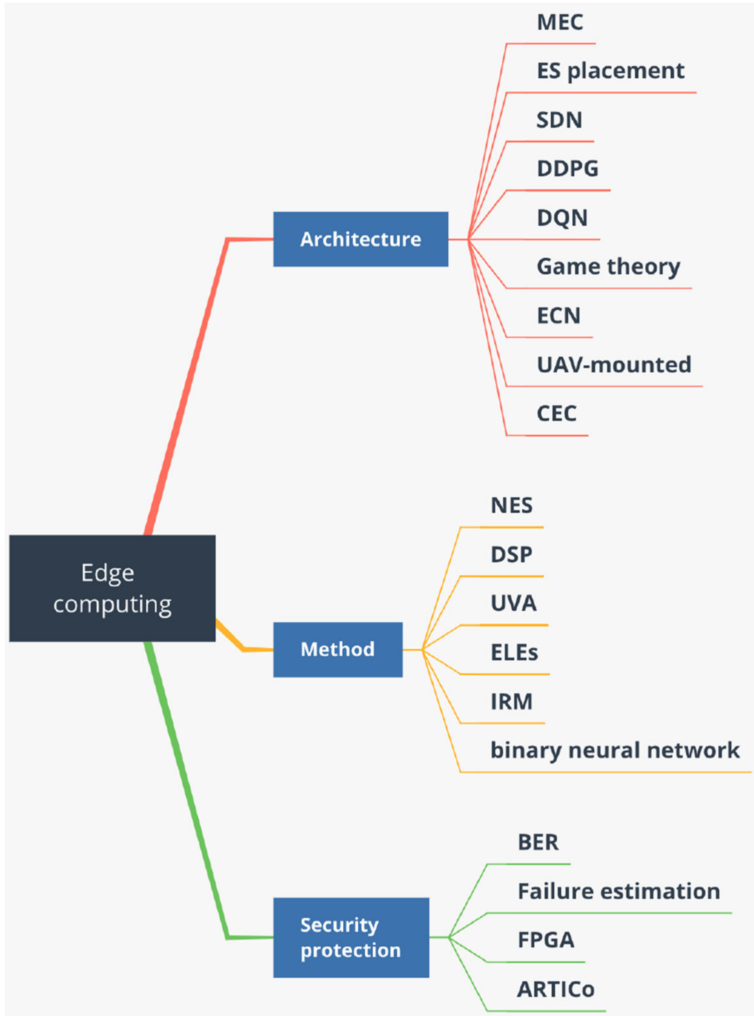

Fig. 5 A conclusion of methods adopted for CPS in edge computing

in cloud computing" Section, better optimized scenarios along with use cases will play a pivotal role in the maintenance of big data applications, like smart city, smart grid, automated driving, etc. Besides, how to integrate data from previous scenarios with the possible behavior predictions of a certain user based on his preference deserves critical attention, which calls for the accuracy and applicability of data centres.

Cyber-Physical-Social system

On the basis of CPS, Cyber-Physical-Social system(CPSS) is a system which furthers the integration with social information and extends the research to social network system, enabling individual or organizations to control the physical entities in a reliable, secure and collaborative way through the network. CPSS is also thought of as a hybrid world in which humans, objects and cyber participants' community detection can be obtained. CPSS is also thought of as a hybrid world in which humans, objects and cyber participants' community detection can be obtained.

In the future, owing to higher level of data sharing and transmitting, it would be a promising aspect to explore on the optimized operation of data exchanges taking into account task offloading strategies, energy consumptions and privacy concerns, especially when applying and extending those research applications into realistic life scenarios.

Conclusion

The past decade has witnessed the unprecedented development of CPS in many use cases. Yet to the best of our knowledge, one of the main obstacles is that the inosculation of the system and one or more methods had been a largely under explored domain. In this article, edge computing, cloud computing and fog computing are applied to CPS to address existing problems such as 4Vs of big data. This paper introduces an overview of the basic concepts and the definitions of CPS, cloud computing, edge computing and fog computing. Apart from this, it is conclusively demonstrated how different layers in current CPS system interact with each other. The most significant contribution of this paper is to provide new insights by highlighting the methods and applications of three computing paradigms, illustrating on how cloud computing, edge computing and fog computing are proliferated in CPS in detailed and specified scenarios, entitling readers a broad sense of state-of-the-art technologies in our everyday life.

Nevertheless, some issues and challenges may lag future development behind, such as the privacy and security of sensitive information, limited bandwidth and transmitting capacity, and so on. Extensive researches should dedicate to them.

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Authors' contributions
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