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Mobile Cyber Physical Systems: Current Challenges and Future Networking Applications

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ABSTRACT Mobile cyber-physical systems (CPS) that take the advantages and extend the application domains of CPS have become increasingly popular in recent years. For example, mobile CPS could be a kind of foundational techniques to support the development of vehicular networking systems, thereby improving security and privacy of users in the dynamic environments of vehicular networks. In this paper, we first distinguish mobile CPS from traditional CPS. Then, we introduce their three emerging application areas, i.e., *vehicular networking systems, healthcare systems, and mobile education*. After that, we discuss four main research challenges of mobile CPS regarding *security, energy consumption, mobile dynamic environment*, and *system stability*. Also, we consider the corresponding techniques, which may address these challenges, and analyze the inter-relations among them. Finally, we outline the possible research directions and applications of mobile CPS in the future.

INDEX TERMS Mobile cyber-physical systems, vehicular networks, security, privacy, dynamic.

I. INTRODUCTION

Cyber-physical systems (CPS), which combine the physical world with cyber components, have been a key research area for more than ten years [1]. Traditional CPS are involved in many engineering projects such as smart electric power grid, manufacturing systems, aerospace systems, and defense systems [2]. Nowadays, with the development of pervasive mobile devices, mobile cyber physical systems (mobile CPS) have attracted more and more attention. Compared with CPS that rely on stationary and huge machines or sensors and emphasize how to utilize cyber components to better master the physical world, mobile CPS concentrate on their mobility, which could seamlessly and ubiquitously sense data in people's daily lives. Therefore, mobile CPS are able to be used in everyone's living more easily and deployed into a broader range in the physical world.

Although some may believe that mobile CPS are a subset of CPS [3], they are actually beyond them since they have some unique characteristics that provide opportunities in many application domains that traditional CPS are not able to do so. As mobile devices become pervasive and equip with various types of sensors, mobile CPS take advantages of this ubiquitousness to continuously sense data in the physical world. Thus, compared with CPS, mobile CPS could have much more data resources and could analyze and connect physical systems with more data. Furthermore, starting with the system design, mobile CPS combine the benefits of CPS with their own exclusive features with the help of

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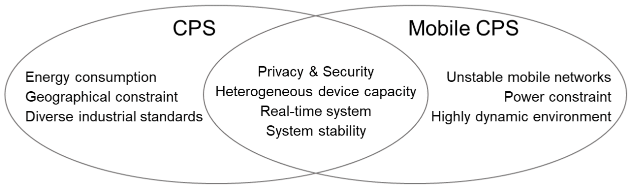

FIGURE 1. Relation between CPS and mobile CPS.

developing technology. Therefore, emerging from traditional CPS, mobile CPS are not a subgroup of CPS but overlapping with CPS. Also, because of this characteristic, there are common issues for both CPS and mobile CPS, and some examples are shown as an intersection between CPS and mobile CPS in Fig. 1. Additionally, because CPS and mobile CPS share the common challenges and have some similarities in system architectures, some solutions for CPS are applicable for mobile CPS, and more details are to be discussed in Section III later. However, as indicated in Fig. 1, since mobile CPS are more than a subclass of CPS, they have specific challenges such as power constraints of mobile devices, unstable mobile networks, and highly dynamic environment.

Several surveys about CPS are found in the literature. There are many common research challenges in CPS and mobile CPS, but with different emphasized aspects. We classify the surveys into four categories from the perspective of challenges in (mobile) CPS, i.e., energy consumption, mobile dynamics environment, stability, and security and privacy, as given in Table 1. Reference [4] discusses issues about energy-efficient operations and mobility prediction in the context sensing domains with respect to anticipatory mobile computing, and it also mentions privacy as a key challenge for a large-scale anticipatory system. Both mobile dynamic environment and security and privacy are reviewed in [1], [2], [6], and [10], among which, while [1] and [2] only briefly point out these two aspects as key challenges in CPS, [6] and [10] summarize related work done in these two fields. A survey about mobile phone sensing concerning privacy and energy verse continuous sensing is presented in [5]. An approach focusing on decoupling stability from timing uncertainty induced by networking is proposed in [7]. In [8], security is highlighted by studying CPS Intrusion Detection System (IDS) in details. Reference [9] considers the dynamic environment in modeling CPS with an example of an aircraft vehicle management

TABLE 1. Existing surveys about CPS.

Challenges	[1]	[2]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
Energy Consumption			√	√					
Mobile Dynamics Environment	√	√	√		√			√	√
Stability						√			
Security & Privacy	√	√	√	√	√		√		√

system (VMS). Nevertheless, as we could notice in Table 1, a comprehensive survey on all these four challenges in CPS is still in paucity, and most of these surveys state challenges from the point of view of traditional CPS. Mobile CPS, however, as an emerging new category, have some challenges that are not covered by CPS, or are concerned from different perspectives. Therefore, we conduct this survey to address the main challenges in mobile CPS.

In this survey, we summarize four main challenges in the field of mobile CPS and classify key technologies into four challenges, and furthermore, we outline the relations among these challenges. This survey aims at facilitating researchers and system engineers to gain an insight of mobile CPS, and hence would help them move forward to propose new and innovative solutions and applications for mobile CPS.

The rest of this paper is organized as follows. Section II presents existing applications in three areas of mobile CPS. Section III introduces and analyzes key technologies as solutions corresponding to the challenges, while Section IV recognizes the future research challenges. Section V concludes this paper.

II. MOBILE CPS APPLICATIONS

Because of their unique characteristics, mobile CPS could be applied to many application domains. In this survey, we mainly introduce three application fields: vehicular networking systems, healthcare systems, and mobile education.

TABLE 2. Differences between VNS in traditional CPS and in mobile CPS.

	VNS in traditional CPS	VNS in mobile CPS
Network architecture	Internet	Internet and VANETs
Types of interaction relationships	System to system System to vehicles	System to vehicles Vehicles to vehicles Vehicles to pedestrian Vehicles to roadside
Aspects of applications	Design of cyberphysical vehicles Public transportation Electrical vehicle Charging	Road Monitoring Vehicular social networks Real-time traffic information Vehicle maintenance services Driver behavior detections

A. VEHICULAR NETWORKING SYSTEMS

As a representative application domain in Intelligent Transportation System (ITS), vehicular networking systems (VNS) have been a significant research area in CPS and mobile CPS. However, due to the inherent mobility of mobile CPS, VNS in mobile CPS could have more diverse application aspects. The differences of VNS in traditional CPS and in mobile CPS are summarized in Table 2. As we can see in Table 2, mobile CPS provide more chances to interact with more components in VSN, since vehicles that carry on or equip with cyber components such as smart phones or intelligent telematics could act more independently and powerfully. Several studies about the design of cyber-physical vehicles, public transportation, and electrical vehicle charging in traditional CPS are summarized in [6]. Reference [11] proposes a model of mobile CPS in vehicular systems to monitor road conditions and detect road irregularities. Vehicular social networks are reviewed in [12]. Mobile Millennium [13] uses GPS data collected from mobile phones to evaluate real-time traffic conditions.

Reference [14] summarizes applications in vehicular networking systems into three groups (micro layer, meso layer, and macro layer) which compose the platform it presents. As for the micro layer, incorporating human factors for improving traffic safety and operations, and developing mobile Geographic Information System (GIS) with traffic-aware capability are two major research directions. The meso layer is about the interaction among vehicles where entertainment resources and safety information such as accident information could be shared to drivers or passengers. Wired or wireless transmission, cloud services, and users are involved in the macro layer where applications such as real-time traffic information with cloud computing support, intelligent location-based emergency roadside services, and automatically acquiring real-time traffic information for could-supported dynamic routing could be deployed.

B. HEALTHCARE SYSTEMS

In traditional CPS, healthcare systems have been a vital research area. As summarized in [6], researches on medical and healthcare systems in traditional CPS mostly about implantable/life-support medical devices, robot-assisted operation, and medical application platform's development. Assistive devices could be used to help people with minor movement difficulty or the elderly with chronic diseases to receive better and more convenient health care at home [2]. Healthcare systems on mobile CPS, on the other hand, could be regarded as an improvement of healthcare cyber-physical systems.

Reference [15] summarizes Just-in-time interventions (JITI) on mobile CPS, a paradigm that could be used to monitor, diagnose, prevent, and treat health problems. Through the mobility, seamlessness, and convenience of mobile CPS, preventive healthcare systems are able to help patients get personalized and timely medical care and interventions at any places and any time. Furthermore, with the developments of sensors, mobile devices such as wearable devices and smart phones are equipped with small and powerful sensors that are capable of unobtrusively and continuously measure users' physiological information. Such data are valuable for healthcare systems. Another example is Emotion-aware smart tips (EAST) proposed in [16], a model that recommends smart tips to users to improve their sleep qualities and keep healthy emotional states according to the inferred moods from users' sleep patterns measured by mobiles phones' accelerometer sensors. Such application could be used as a preventive tool for mental health problems because it could seamlessly and unobtrusively monitor users' emotional states in their daily lives and provide in-time interventions. As shown in Fig. 2, the applications in mobile CPS provide seamlessly and unobtrusively improved solutions for healthcare systems relatively to the assistive devices in traditional CPS due to the mobility of mobile CPS.

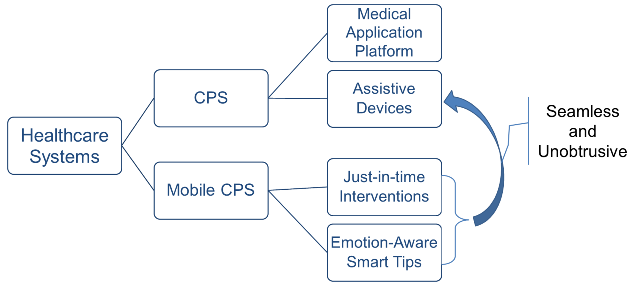

FIGURE 2. Healthcare systems in traditional CPS and mobile CPS.

C. MOBILE EDUCATION

As an emerging and evolving field, e-learning has attracted researchers' attentions. Comparing with traditional education whose environment is constrained into classrooms and schedules, e-learning supports learning at any place and any time [17]. There are several studies on mobile learning for higher education. Reference [18] presents a model to analyze the influence of college students' belief on the adaptation of mobile devices for coursework based on the theory of planned behavior (TPB). The results provide future directions for researchers and systems engineers to design mobile education systems (MES) that could improve students' consent on mobile learning. But e-learning could be applied not only for higher education but for preschool education and elementary education. In order to support children' developments into citizens, e-learning could play an important role. Reference [19] states that the usage of Internet strengthens a citizen's income and economic opportunity, and social participation such as the use of social media and online news increases civic engagement and political participation. Furthermore, both Internet and social media could be integrated into MES so as to improve children's citizenship developments.

TABLE 3. Differences between traditional e-learning and MES in mobile CPS.

	Traditional e-learning	MES in mobile CPS
Interaction Methods	Online education Mobile education	Mobile CPS based education Wearable Devices education Intelligent robot education
Location	Usually places with Internet access	Any places (wireless connection preferred)
Objects	Students of higher education	Students at all ages Underage children

With the help of mobile CPS, MES could be utilized in more application fields than the e-learning mentioned above does. As summarized in Table 3, traditional e-learning mainly consists of online education and mobile education, which

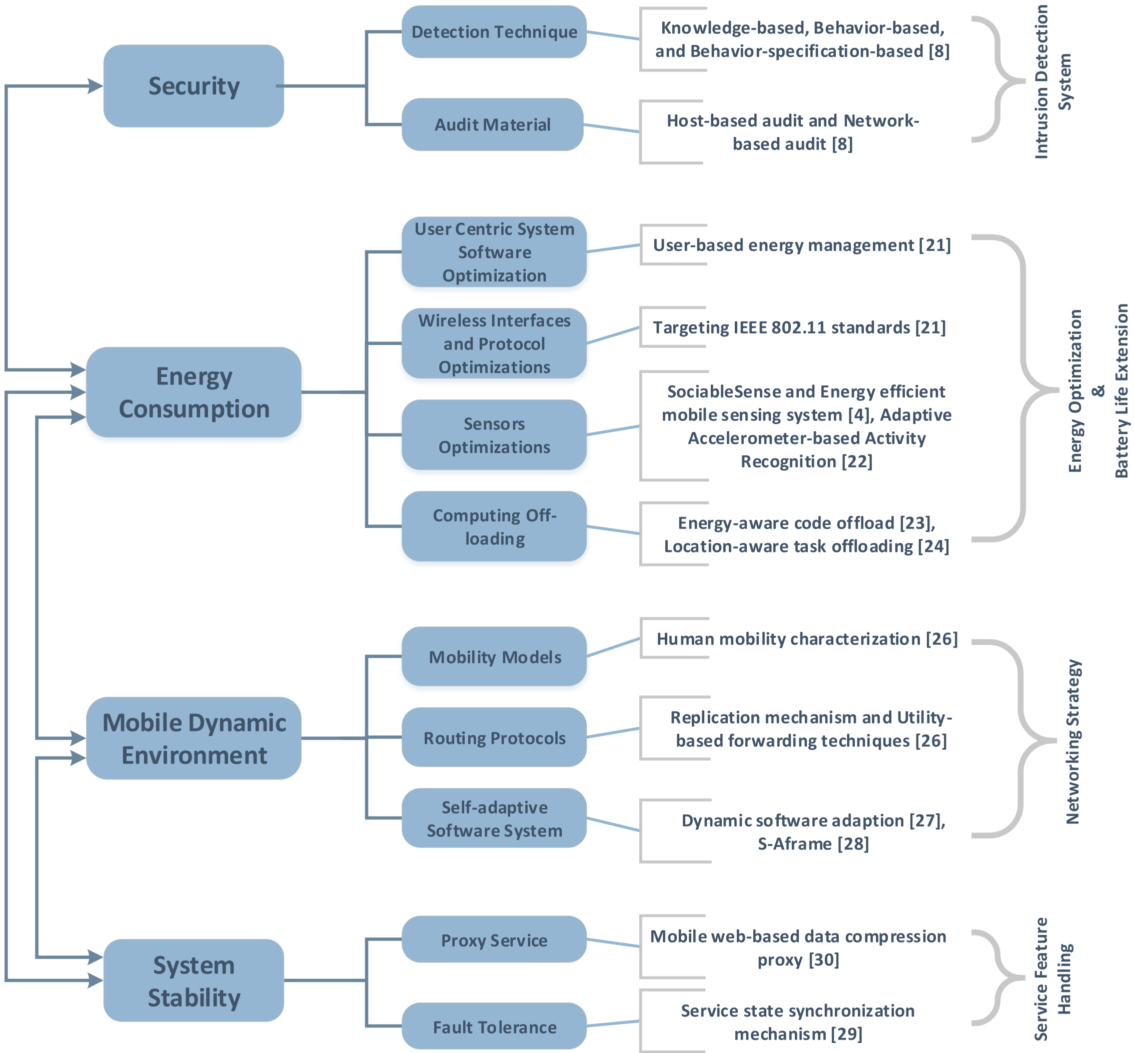

FIGURE 3. Key challenges and techniques of mobile CPS.

focus on higher education. But such systems are not suitable for child education especially for children under age six since children at this age are hard to concentrate on systematic courses to interact with instructors. However, MES in mobile CPS that take advantages of theories or models in traditional e-learning, mobility, and ubiquitous sensing ability of mobile CPS can greatly help us deploy education to students at all ages especially to underage children. Given the sensing ability of mobile CPS, MES in mobile CPS are capable of sensing data seamlessly when children interact with the physical world such as recognizing objects around children, perceiving children's emotions, or analyzing children's learning statuses. For example, if a child is equipped with a wearable device that could recognize objects he points to, then such devices are able to help children learn about objects or the physical world around them in the daily lives by instantaneously recognize and tell children what they are interested in. In that case, children interact with the physical world and at the same time, learn about the world.

III. KEY CHALLENGES AND TECHNIQUES

Given the three novel and representative application domains presented above, we can see that although mobile CPS could be applied to many new and innovative application fields, various challenges are ensued. Energy consumption is an essential concern in mobile education systems, and for instance, a child would be disappointed and lose interests of learning if a wearable educational device is suddenly turned off due to low battery when he is using that device to recognize and learn the objects around him. In VNS, imagine a scenario that a driver is using GPS equipped in his/her smartphone to direct for his/her destination when his/her phone accidentally loses signal, resulting in straying far away from his/her direction. Hence, properly dealing with a dynamic environment is a vital technical requirement needed to be addressed. Therefore, in this section, we summarize four predominant challenges, i.e., security, energy consumption, mobile dynamic environments, and system stability of mobile CPS. We then categorize key techniques as solutions to these challenges. After that, we delineate the relations among these challenges.

A. SECURITY

Security is a common key challenge in CPS and mobile CPS. Because such large-scale systems consist of various types of components and include not only computational processes but also data transmission, both CPS and mobile CPS are potentially vulnerable to many bugs and attacks. In this part, we introduce some investigations that have been conducted to keep mobile CPS secure.

Reference [8] surveys CPS Intrusion Detection Systems (IDS) from two perspectives, detection technique and audit material. The authors categorize detection techniques into three groups: knowledge-based intrusion detection, behavior-based intrusion detection, and behavior-specification-based intrusion detection. Among these techniques, the authors believe that behavior-specification-based intrusion detection would be the most effective since it has low false-negative rate and does not require training or profiling, a phase during which the system is defenseless, and consequently such technique is able to immediately protect the system effectively. Although knowledge-based intrusion detection has the advantage of low false-positive rate and behavior-based intrusion detection does not specifically look for attack dictionary, which is a shortage of some previous detection techniques, they have disadvantages in creating an effective attack dictionary and requiring training or profiling phases, respectively.

As for audit material, two methods of data collections, i.e., host-based audit and network-based audit, are used in CPS [8]. The former is favored for systems with high-volume configurations such as smart grid, because it is distributed control. Moreover, it is straightforward for host-based audit to determine or detect host-level misconducts. However, such method requires extra work to collect audit data for each node and specific OS or application to be implemented. Network-based audit, on the other hand, has advantage in freeing each node from maintaining or analyzing logs; nevertheless, it has negative impacts on the effectiveness of network-based techniques due to its visibility of nodes' audit data collections.

B. ENERGY CONSUMPTION

In traditional CPS, energy usually is not a common concern since most physical components are connected to power supplies when running. Researchers consider energy managements mainly for making systems more power-saving in order to build green CPS. For example, a green adaption of real-time services to optimize dynamic voltage and frequency scaling may be used in a multi-objective optimization environment [20]. However, in mobile CPS, energy consumption is a critical issue. Since many mobile devices at present are capable of sensing, communicating, and dealing with large and complex computational tasks, which requires a great amount of energy, such cyber components of mobile CPS relying mostly on their batteries are energy-eager. But because of the mobility characteristic, mobile devices usually run without continuous power supply. Once batteries have run out of energy, these cyber components cannot work, and thus mobile CPS are not able to operate. In this section, we present some studies that have been performed to efficiently manage energy consumption in mobile CPS.

Reference [21] surveys energy-efficient solutions for mobile handsets in literature from 1999 to May 2011 and categorize them into six groups: energy-aware operating systems, energy measurements and power models, users' interactions and computing resources, wireless interfaces and protocol optimizations, sensors optimizations, and computing off-loading. According to this research, measurements of the energy consumption of hardware and capability of understanding users' behaviors of using phones are two crucial factors for designing energy-aware systems, and thus saving energy for mobile handsets. On the other hand, optimizations of wireless interfaces and sensors focus on maximizing the performances of wireless interfaces and sensors, which are fundamental in many mobile applications, so as to extend the battery life of mobile devices. Adaptive sampling and hierarchically powering on sensors are two prevalent methods of sensor optimizations, and examples of them are SociableSense and Energy Efficient Mobile Sensing System (EEMSS), as mentioned in [4]. Reference [22] also proposes an activity-sensitive approach named Adaptive Accelerometer-based Activity Recognition (A3R) which is able to reduce energy consumption of accelerometer-based continuous mobile sensing.

Because of the high computational demands and limited resources of mobile devices, mobile devices themselves are hard to satisfy the interests of mobile industry, and cloud computing is another solution. Although mobile cloud computing has been proved to save battery life of energy-restricted mobile devices and expand computational power [21], how to effectively transmiit data between mobile devices and cloud data centers has been a vital challenge. Some investigations have made efforts to efficiently manage energy consumption in mobile cloud computing. Reference [23] proposes a system called MAUI to save energy by providing fine-grained offload code to the infrastructure to partition programs. Reference [24] presents an online algorithm that aims to fairly minimize each device's energy consumption in location-aware off-loading tasks while meeting the SLA requirement of each task.

C. MOBILE DYNAMIC ENVIRONMENT

Different from traditional CPS, mobile CPS face a unique challenge of dealing with dynamic environment caused by its inherent mobility. Since they are composed of mobile cyber components (e.g., smartphones and vehicles), their highly dynamic characteristic poses many challenges on robustness of systems, routing protocols of networks, data transmission, and communications. In vehicular networking systems, the situations of handling data transmission are complex, because the network topologies of vehicular systems are highly dynamic. Reference [25] indicates that various traffic density and highly dynamic network topology are the characteristics of vehicular ad hoc networks. For example, the strategy of how to efficiently transmit data for vehicles to vehicles (V2V) or vehicles to roadside (V2R) when vehicles are in high density, or when there are spare vehicles as nodes in the road is quite different. Either case needs to be handled properly. Here, we outline some studies that discuss a mobile dynamic environment.

Opportunistic networking plays a significant role in mobile CPS as it provides opportunities to connect highly mobile components. There are three aspects of research dealing with the mobility in opportunistic networking: mobility models, routing, and data dissemination [26]. According to [26], inter-contact time distribution is important in understanding the influence of mobility on data forwarding efficiency in opportunistic networks. A replication mechanism is adopted to solve the problem of the uncertainty of prospective connectivity, while utility-based forwarding techniques are used to handle human and nodes mobility and resources' heterogeneity in the routing protocols. Popularity-based strategies, social-behavior-based strategies, publish/subscribe strategies, global-optimality-based strategies, heterogeneous-technologies-based strategies, and peer-to-peer strategies are described and summarized to cope with how to disseminate data in opportunistic networks [26].

A self-adaptive software system is another approach utilized to deal with a dynamic network environment. Reference [27] proposes a method that supports parameter and compositional dynamic software adaption with the help of scalable data distribution layer, a communication middleware that gives a communication framework to annex actuators, sensors, and other mobile devices. S-Aframe, an agent-based multilayer framework with context-aware semantic services (CSS), is presented in [28]. Such framework composed of a framework service layer, software agent layer and owner application layer is built on the top of operating systems of mobile devices to effectively develop and deploy different self-adaptive applications and services for VSN. Applications accommodated with CSS on the framework are autonomously and intelligently self-adaptive to highly dynamic networks in VSN.

D. SYSTEM STABILITY

As a common issue in many application fields, stability is a key challenge in mobile CPS. Without stability, a system could not work properly as expected. Crowdsensing application is a field that could be implemented in many mobile CPS domains such as VSN, healthcare systems, and MES. The crash of operating systems and the exhaustion of battery may cause mobile devices to be unavailable and unreliable, resulting in the obstruction of prevalent use of crowdsensing applications [29]. For example, in a crowdsourcing task scenario, a sudden collapse of a mobile phone acting as a participating node due to a service failure of the system may lead to the delay or even impede that task to successfully complete. Some researches have been done to maintain the stability of mobile CPS and are introduced here.

Since service feature handling is an important aspect of the stability in mobile systems, the work [29] designs a reliability enhancement mechanism called Service State Synchronization Mechanism. It is based on Business Process Execution Language and Pertri nets, to analyze and deal with possible service failures and to automatically restore to normal statuses, and, therefore, it is able to improve the stability of mobile crowdsensing applications while allocating and handling the crowdsourcing tasks in mobile CPS. Because a large amount of data is more likely to cause system crashes, the work [30] proposes Flywheel, an HTTP proxy service integrated with the Chrome web browser to compress the data size of proxied web pages. In addition, Flywheel is fault-tolerant through mitigating fetch errors by, retrying failed fetches and analyzing the server traffic logs to label URLs with high failure rates. Reference [31] presents a novel offloading system that is mobility-enabled and fault-tolerant to minimize execution time and energy consumption for multi-service workflows. Its presented strategy considers the inter-dependency among service workflows and fault tolerance concerns, and thus increases the stability of the mobile systems.

In Fig. 3, we summarize the four main challenges and their corresponding key techniques. In addition, we mark the inter-relations among these challenges. Energy consumption is relevant to a mobile dynamic environment, system stability, and security. Since nodes usually are energy-constrained and compromised nodes might endanger the functionality of mobile CPS, energy-efficient IDS plays an important role in detecting and dismissing compromised nodes that cause cataclysmic consequences due to their failure [8], [32]. The networking issues in a mobile dynamic environment, service handling in system stability, and energy consumption are highly inter-connected. As an effective strategy to save energy for devices' battery, computing offloading needs to consider networking issues and service features in order to make computation offloading feasible and energy-optimized. For example, an optimized Genetic Algorithm (GA) based approached is designed in [31] in order to improve fault tolerance, and maintain acceptable offloading efficiency and energy consumption simultaneously in mobile CPS.

IV. FUTURE RESEARCH DIRECTION

With the development of mobile devices and ubiquitous sensors, many challenges and their key techniques described above have flourished the development of mobile CPS. However, many technical issues associating with mobile CPS remain to be addressed. There are various opportunities for mobile CPS to improve their functionality and broaden their application domains. In this section, we present and discuss the potential future research directions for mobile CPS.

A. MOBILE USER PRIVACY

Privacy is an essential concern in mobile CPS since a large volume of users' daily and sensitive data is used in constituting systems. Many mobile CPS applications involve users' participations, and users become increasingly concerned about the compromise of their personal information. For example, when using a user's location to infer a preferable route for him/her and storing data for future recommendation for another user with similar conditions, it is important to keep that user's private data anonymously. Reference [5] points out that user privacy is a crucial concern in the future direction of mobile sensing. In fact, there are trade-offs between the effectiveness of privacy protection and the convenience of data collection, communications, and energy consumption, which need proper considerations in system designs. Moreover, privacy is a case-by-case issue that needs thoughtful concerns of the scale of privacy maintenance in diverse application domains in order to satisfy different requirements of various types of users.

B. GREEN INTERNET OF THINGS

Because of the advancement of mobile and sensing technology, numerous smart objects that connect the Internet are increasing rapidly [12], which flourishes the development of Internet of Things (IoT). IoT connects a variety of objects including sensors, actuators, mobile devices, and Radio-Frequency IDentification (RFID) tags through unique addressing communication protocols to cooperate and complete common goals [33]. The advantages of IoT have placed it in many applications on various aspects of daily life and it could be used as the reliable infrastructure of mobile CPS such as healthcare systems and VNS mentioned before. Energy optimization of mobile devices as nodes in mobile CPS has been researched and used to extend nodes' battery lives, but in the future, taking the energy issue into consideration, IoT can be integrated seamlessly with mobile CPS to provide valuable green IoT services to reduce the energy consumption of the physical world, such as green intelligent transportation systems and green smart grid systems.

C. CLOUD-BASED MOBILE ROBOTIC SYSTEM

Recent advances in sensors, wireless communications, artificial intelligence (AI), and cloud computing have facilitated mobile robots (e.g., autonomous automobiles and autonomous unmanned aerial vehicles) to form a cloud-based robotic system which is a great potential application field to provide intelligent services beyond the capabilities of the current mobile CPS. First, robot systems employing wireless communications and advanced AI techniques can form interconnections of mobile robots to perform extensive tasks and enable intelligent services to plan a course of actions that optimizes some task objectives, such as minimizing energy consumption, for the current environmental conditions. Although these machine learning techniques require intensive computations that may not be well supported by an individual robot, cloud computing services offer virtually unlimited computation resources on-demand in a scalable manner, which greatly facilitates the use of advanced AI techniques in robotic systems [34], [35].

Second, abundant and ubiquitous sensors deployed in robotic systems generate a massive amount of data over short periods of time, and cloud-based big data analytics can be employed to derive useful information to enhance the utility of cloud-based robotic systems [36], [37]. For example, a manufacturer may be able to determine that a batch of sensors manufactured by this company is defective from the data collected by a large number of cloud-based robotic systems. Based on the above observations, we can see that cloud-based robotic systems offer great potentials for intelligent services to be applied in mobile CPS application domains.

V. CONCLUSION

Evolving from traditional CPS [1]–[8][38]–[39], Mobile CPS received much attention and developed rapidly in the past few years. There are more and more mobile CPS applications being broadly deployed in different domains in daily life. Because of their mobility characteristic, they not only take the advantages of traditional CPS, but also expand and promote the interaction between cyber and physical worlds, which has led to the revolutions in many application fields, such as vehicular networking systems, healthcare systems, and mobile education [11]–[19] [40]–[42]. In this paper, we have introduced the applications and key challenges and techniques of mobile CPS, and distinguished them from the traditional CPS. There are many research issues that demand in-depth investigations in order to increase the efficiency and enhance the functionality and intelligence of the applications of mobile CPS. One direction is to consider mobile user privacy in their various application designs, which is fundamentally important in protecting users' personal information. Investigations of green Internet of Things and cloud-based mobile robotic systems of the emerging applications could further extend the capabilities of current mobile CPS.

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