A Review of the Integration of Cyber-Physical System and Internet of Things

A Cyber-Physical Systems Perception of Internet of Things

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***Abstract*—Cyber-physical system has a bigger impact on the present and future of the engineered systems. The integration of cyber-physical system with other technologies often poses challenges that are unique in the fields of design, implementation, and applications. This study explores the definitions of the integrated cyber-physical system from different perceptions, how cyber-physical systems evolved, emerging fields of research in cyber-physical systems. Efficiency, reliability, predictability, and security are some of the challenges that cyber-physical systems pose in the overall implementation. cyber-physical systems when integrated with the Internet of Things evolves into a hybrid technology that advances the technology aspects. The CPS-IoT models complement each other offering useful insights to deal with engineering systems and control modules.**

***Keywords*—Cyber-physical system; internet of things; industrial internet (ii); industry 4.0**

I. Introduction and Motivation

Cyber-Physical Systems are modelled on the collaboration of 3C's - computation, communication and control that are discrete and logical (cyber entity) and the natural and artificial systems that are administered by the laws of physics (physical entity). Both the entities are linked through sensors and actuators. Sensors, computational and physical world are closely integrated in CPS. CPS includes both conventional embedded systems and control systems that are presumed to be remodelled by emerging methodologies and integration of the Internet of Things.

IoT is the base or enabling technology for cyber-physical systems. Cyber-physical systems can be contemplated as the advancement of IoT as complete conception and perception, and which possess a strong ability to control the physical world. Cyber-physical systems also include the traditional embedded and control systems, evolving them into innovative methodologies. IoT connects the information acquiring devices like sensors and RFID (Radio Frequency Identification) wireless sensor networks and cloud computing technology for reliable transmission and information processing. On the other hand, CPS is a control technology that is scalable and reliable and is the integration of computing, communication, and control of IoT. However, IoT concentrates on information transmission and processing, whereas CPS not only has the can sense but also possesses a strong ability to control. In CPS, cyber and physical elements are interlinked with one another, which are running on spatial and temporal scales, which reveal numerous and definite behavioural process and collaborate with each in many forms that vary the context.

CPS is transdisciplinary which merges mechatronics, computation theory, Internet of things, wireless sensor networks, theory of cyber nets, design and process science. The process of control is related to embedded systems using feedback loops. CPS and the Internet of Things share the same architecture which makes them similar but a higher between physical and computational elements is defined in CPS. In contrast to traditional embedded systems, CPSs are specifically represented as a structure of interacting elements with physical input and output rather than standalone devices [1]. Applications of CPS include healthcare and industrial automation, control technology, distributed energy system, aircraft control and so on [2]-[4]. CPS will bring change to the existing physical systems in engineering and advances in economic welfare.

II. CPS History and Definition

CPS refers to next generation engineered systems. The word cyber-physical system came around 2006 by Helen Gill at the National Science Foundation (NSF). Cyber-physical system is often confused with "cyber security" where there is no relation with the physical processes. CPS is the tight combination of computations, algorithms, and physical devices. The perception of the technologies is that it associates the real world with the information world. CPS connects by means of the popular technologies such as Internet of Things (IoT), Industry 4.0, the Industrial Internet (II), Machine-to-Machine (M2M), Industrial Internet of Things (IIoT).

A. Definition of CPS

This field of research overlaps with various fields of science and engineering, computer science and networking should come together in collaboration with multiple fields such as automation and control, civil engineering, mechanical engineering, etc. Therefore, CPS definition may vary from their viewpoint.

E.A.Lee describes CPS as "the integration of computations and physical processes. Embedded computers and network monitor and control the physical process, usually with feedback loops where physical processes affect computations and vice versa [5]."

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R.Baheti describes CPS as "the new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact with, and expand the capabilities of, the physical world through computation, communication, and control is a key enabler for future technology developments [6]."

Department of Science and Technology (DST) – Government of India launched a Interdisciplinary Cyber Physical System (ICPS) to promote research and development in this emerging field. The simple architecture of CPS is shown in Fig. 1. The collaboration of the physical and cyber world in CPS will assure real-time, reliable, trustworthiness of the systems. Physical systems collect the data from sensors in CPS systems dynamically guaranteeing the accuracy of the data collected. The data is sent to the cyber world for the processing of information based on the service needs mainly uncertainty management, statistical analysis, and feedback control. These systems are designed in such a way that they self-adapt. CPS is a 3C technology i.e., computation, communication, and control that takes wireless sensor network and Internet of Things.

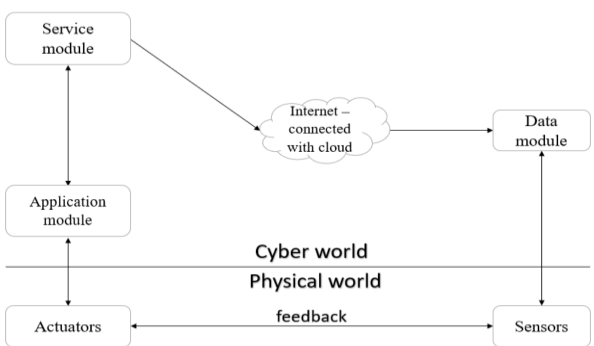

Fig. 1. Working idea of Cyber-Physical System

B. Characteristics of CPS

CPS has both physical and cyber-world. In the physical-world, CPS interacts through sensors adapting embedded computing technology. The cyber-world of the CPS deals with computations and control. The CPS upholds the following characteristics [7]:

- Cyber capability in every physical component: The physical system design is as important as the logical design. It involves hardware design and size, management, connectivity establishment, system testing. Engineers have an understanding in their fields of systems, they acquire the technical characteristics of sensors, actuators and how they process the raw data to the next layer. The higher degree of automation and control in CPS demands the maximum network coverage.

- Networked at multiple and extreme scales: CPS entrust networks to sensors and actuators to collect data and process them. The infrastructure of networking has to be very large frequently. Networks should be able to perform on different domains such as personal transportation systems, healthcare, remote interaction, industrial automation. These domains require a new communication notion that provides concrete and outline together with online adaption for productive use of bandwidth. This leads to scalable, open and adaptive communication [8]. CPS demands networking to be in large and multiple scales to meet the need without compromising the Quality of Service (QoS).

- Multiple spatial-temporal constraints: The CPSs are conceptualized to 3C technology i.e communication, computation and control with the physical world. These require the interaction between the components of CPS in time and space. Constraints such as event detection and action decision should be implemented accurately and appropriately to meet spatial and temporal correctness [9].

- Unconventional computational and physical substrates: The need for unconventional computation in CPSs is because of its dynamic reconfiguration and its communication with the physical world in real-time to adapt them to specific needs. Since the evolution in computation takes place, the physical substrate should comply with the computation as well.

- High degree of automation, control loops closed at many scales: The emerging amount of data on CPS, coupled with the need for systems to be robust and handle real-time environment which leads to self-learning. The automation is important for the system to go forward. The control object is the inbuilt operation of CPS. This object can reform itself and change the physical flow command. The control aspect of the CPS is the basis for dynamic systems and plays a crucial role in feed forwards control loops.

- Dynamic recognizing termed as open system: This characteristic of the CPS includes reorganizing and reconfiguring which can automatically adapt to the environment and develop rules based on the domain requirements and alters the external physical environment to meet the conditions according to present rules.

III. Research Directions of CPS

CPS is the integration of the multidisciplinary heterogeneous systems and has decentralized models. These systems exhibit behaviours that are not predictable in advance, which makes the research possibilities expansive. The researchers recently concentrate on the architecture pattern, computational theory, and control of the feedback system. Other research fields such as system reliability, information processing, system design software, and CPS security system are focused on recently.

A. Architecture of CPS

Many architectures for CPS have been proposed so far, the 5 Component architecture has 5 levels: Connection level, Conversion level, Cyber level, Cognition level, Configuration level [10]. These levels emerge the process for such interdependent systems and overcome the limitations to meet the demand of the target system. These levels process and monitor the information, and coordinate with the physical systems that relate to the cyber computational space. 8 Component architecture is an evolution of 5C architecture that includes three other components in addition to Connection level, Conversion level, Cyber level, Cognition level, Configuration level. The included components are Coalition, Customer, and Content [11].

ACPS architecture where not only the highest level of abstraction is provided but also integrates the physical, cyber, and human components [12]. Service-Oriented Architecture (SOA) supports this model to achieve the adaptive and dynamic vision. 3C architecture is the most commonly used architecture in all applications [13]. This architecture reinforces smart manufacturing in industries and supports the industrial revolution i.e., Industry 4.0. The three components in this architecture are the human component (HC), Physical component (PC), and Cyber component (CC). A smart factory framework is developed which considers the physical and cyber aspects of the system architecture to offer the solution and improve efficiency [14].

Though many Cyber-Physical Systems' architectures meet the expectations of the target system or applications, there is yet a need for further developments as most of these models are clearly defined for a certain set of applications. Researches on architecture are restricted to specific applications and their advancements, the development conditions due to which the interdependence of various demands are not studied. CPS architecture is the foundation of research and progress, so the proposed models must be integrated and improvised based on the present system structure and should accommodate the development of CPS. However, a unified architecture for CPS is required which calls for further research in the architecture.

B. Control of CPS

The foundations of control theory in Cyber-Physical Systems are yet to be established strongly. Converting the input actions into appropriate control actions, in a multimodal application that involves sensors and actuator parameters based on the user actions [15]. An independent way to control the cyber and physical resources, where a new control strategy is provided for data centers to attain stability for the CPS applications [16].

A robust control approach that is modular, promises the stability and performance of the target system automatically due to which the input-output analysis where a standard analytic method is used [17]. The role of control in the cyber-physical system must be addressed because of their impact on the future Internet of Things, wearable electronics, human interaction machines, and many other fields. The analysis of control theory in CPS helps in building the foundations of CPS stronger. A unified approach must be dealt with towards the control strategies that include temperature set-points, adjusting the pressure set-points, monitor air temperature, dimming or turning off the lights, etc. Predictability is one of the challenges to the control of CPS. To ensure predictability, aspects of the model should be accounted such as input and output behaviour, execution, and programming. Uncertainty affects the model or system's guaranteed behaviour [18].

The traditional control theory only meets the targets of CPS control based on the applications or present event models, but the theory should also manage the transmission and response of feedback control where further research prevails.

C. Data Sciences and Data Processing Technologies for CPS

The data is collected by the systems, must be transformed into knowledge to create value. The scope of future smart systems lies in the methodologies and techniques of Data Science. A vast amount of data is collected from the sensor networks and many solutions for data science problems have been discovered. CPS follows a data-driven approach to learn patterns and predict the models, also analyse their environment, and based on their observations. Data processing, in general, includes collection, preparation, input, processing, interpretation, feedback control, and the response from the physical environment after receiving the commands.

Reliability is an essential need for a cyber-physical system as it is applied for safety and critical systems. CPS is intended to process a huge volume of data and run continuously in real-time, where an Automatic Reliability Improvement System (ARIS) is proposed to improve the reliability. ARIS works as a data-centric runtime monitoring system, where anomalous data is indicated and a data quality analysis is performed using computational intelligence and self-tuning techniques for system reliability [19]. The existing Internet of Things is turned into a complex cyber-Physical Social System (CPSS) when people use their social networks and personal computational resources which leads to the generation of huge volume passive data to process. A data processing pattern that is based on stream processing technology, that uses a cluster of edge devices to distribute the workload is introduced. The feasibility of this approach is guaranteed through a demonstration of an intelligent surveillance system that is stationed on the edge device [20]. Present researchers on the methodologies and techniques of Data Science in CPS face challenges in processing and transmission technology of data, safety control, real-time capability, robustness, control and hybrid systems and reliability.

D. Security and Privacy of CPS

The security and privacy protection of the established internet security does not meet the requirements of physical system security in CPS which is randomly distributed sensors over the pervasive wireless network. Most of the present security policy uses a centralized network that trusts a third-party operation. The new security framework that considers the flexibility, privacy protection, transaction security, transparency, efficiency, trust mechanism, data integrity, resilience, the trustworthiness of data that combines with control and information.

Blockchain technology, which is a distributed register that is shared between peer networks is proposed as a unified three-level architecture to identify the possibilities and also adapt, develop and incorporate this with the manufacturing in industry 4.0. The data flow and the communication are incentivized in the structure of the existing cyber-physical system structure to assure safety and reliability [21]. Differential privacy techniques are considered efficient to protect privacy in CPS which can be achieved through certain modifications in the architecture of CPS and can be implemented in cyber-physical systems applications [22].

However, there are some challenges in cyber-physical system from a research perspective. Robustness, safety, and security due to the environment and errors in the physical devices making it a critical challenge. Location, time, and tag-based data can be a threat to security. Merging the systems to create a hybrid system to create an efficient feedback control is required. The architecture of the CPS must be designed in a way that is very rational at every level and it should consider all the physical device information, protocols should be designed at a large-scale. Collecting the raw data at a vast amount from the sensor and mobile networks is one of the major challenges to focus on. Integration and modification should be done at every level of CPS design, communication and computation are to be predicted at all scales and model the time information.

IV. Cyber-Physical System-Internet of Things

The CPS can be considered as an evolution of IoT with more intelligence and interactive operations, adapting the architecture of IoT. CPS enriches the interaction between human-to-human, human-to-machine, machine-to-machine not only in the physical world but also in the virtual world, also includes conventional embedded and control systems that will not be altered by novel approaches. IoT and CPS when introduced in the industry, brings many benefits and extends the scope such as awareness, prediction, comparison, reconfiguration, maintenance. The evolution of IoT and the development of CPS is prominent in certain applications - Real-Time Physical Systems (RTPS), based on real-time parameters with a suitable feedback control policy based on dynamic adaptions [23]. A controller is designed for a nominal model that stabilizes the large-scale CPS [24]. The vulnerability of robotic surgery is reduced by designing a collaborative robotic cyber-physical system [25].

CPS is the integration of physical and cyber systems where embedded computing devices act as physical entities and communication, computation, and control are cyber entities, whereas IoT shows the interconnection of different end-devices that communicates with each other through the internet. Decentralized control among the interconnected end-devices is intended by IoT. Sensing, processing, storing, and networking are some of the common capabilities of both CPS and IoT.

When CPS was emerged and introduced alongside IoT some of the similar characteristics of CPS and IoT must be identified, familiarized, and contrasted to understand their respective roles in the system where they are used. New strategies for communication and control have been introduced making the system more safe, secure, and sustainable which are the fundamental attributes of the CPS.

The advanced communication technologies, alongside wireless communications, lead to the development and implementation of CPSs considered as the higher-level systems of IoT. These technologies include wearable devices, sensors in healthcare, intelligent systems where cloud computing is applied. CPS in IoT deals with the interaction of the intelligent systems, applications that are user-friendly sand interactive, optimization in the IoT-enabled CPS, and control of the distributed systems. The characteristic of the CPS must be enhanced due to the higher requirements and efficient performance. The performance of the CPS elevates the levels of IoT. In short, CPS is the next evolution of M2M systems where smart information processing and IoT are regarded as the future technicalities.

A. Internet of Things enabled Cyber-Physical System

CPS and IoT are intertwined for better and unified solutions, where the users, machines and the environment interact with each other. Defining the interface for the IoT technologies, control of the global system, integration of the IoT devices and physical environment, which is tied together with the communication infrastructure, along with control module are some of the challenges when IoT has enabled alongside CPS on a large scale. The performance of real-time analytics should be considered as another challenge as the large amount of data collected has to undergo a mining process for better results.

The development of the CPSs which adopt the IoT paradigms aids in several applications of the CPS. Design complexity, modeling the hybrid systems, smart control design, sensor reliability, specified IoT sensor and actuation design for CPSs, and security and privacy are some of the key challenges for IoT-enabled CPS.

The infrastructure and control of the large-scale system and the network monitoring are used for better communication and coordination among the modules. This may have a negative effect on the network structure and needs to be upgraded for efficiency and accuracy. Enhanced Expander Membership Protocol [26], having features such as addressing the real-time network issues, limiting the negative effects on the network structure, and recovering the global connectivity efficiently and is also fault-tolerant and scalable. These support the challenges addressed by the CPS network structure. A Fragmented-Iterated Bloom Filter [27] is introduced to manage the distributed network in the event-based cyber-physical system. This is efficient in memory management and computation.

Considering the functional and non-functional requirements during the implementation of the IoT-enabled CPS, the challenges such as scheduling mechanisms, vulnerability to security attacks, applications development, etc. An integrated development environment that is model-driven in cloud computing supports the application development, code generation, and compilation and simulations for the IoT-enabled CPS applications.

COMFIT [28] has two modules, the App Development Module and the App Management and Execution Module, providing an environment where every needed action is performed for the code to develop the app. The scheduling mechanism in the implementation of IoT-enabled CPS needs to be efficient and scalable. The Bayesian Network [29] is used for scheduling algorithms where stability and operational capability have high priority. The vulnerabilities to the security attacks are tackled using game-theoretic principles, providing a scheduling mechanism that is effective based on the game.

B. Integration of CPS and IoT

A Cyber-physical system, in general, is the collaboration of communication, computation, and control with the physical world on a large scale. They are considered as a form of wireless sensors and actuator networks. On the other hand, the interconnection of heterogeneous devices that communicate through the internet is called the Internet of Things. These heterogeneous devices can be referred to as smartphones, laptops, RFID, etc. are intelligent agents that share the information with the systems and people which makes them a part of CPS. Therefore, the integration of CPS-IoT is a solution to many technological challenges and is used in many application domains.

The integration of Environmental IoT with the cyber-physical clouds [30] results in a complex distributed system that supports the comprehension of interdependencies and management in the natural environment. A three-stage approach is deployed - The Abstraction representation, Network-centric representation, Node-centric representation. These technologies provide higher opportunities in the application domain by supplementing each other.

The integration of wireless devices, wearables that are fast and have a working real-time algorithm to cyber-physical systems allows in numerous aids to the medical applications. The author in [31] presents a system by integrating the complimenting technologies that provide comfort to the patients and the data collection from devices is efficient.

An adaptive interface approach [32] that supports both the development and the utilization of the CPS-IoT is proposed. An IoT toolkit with a multi-layer interface that allows users to improve the interaction with sensor and actuator networks is presented. The full potential of the IoT-CPS integration interface can be utilized, with the aid of the presented adaptive interface.

The integration of the CPS for real-time IoT operations [33], resulting in the effective control of actions based on the environmental objects. This helps in the real-time operations in the manufacturing units and Industry 4.0 applications. The integration of CPS with various technologies leads to emergent properties and unpredictable behaviors. The development of IoT and high-speed network leads to the possibilities of the physical world meeting the cyber world. The convergence of Body Area Sensor Networks (BASN) and CPS made the technologies reach their threshold point, making hand pattern recognition smart and safe [34].

C. CPS-IoT Models

The integration of IoT and CPS evolved over time to complement each other and has some very useful applications and insights; however, IoT and CPS have distinct origins. CPS primarily deals with engineering the systems and the control stance, in contrast, the IoT deals with networks and the information technology that digitalizes the physical world, also having the sensing and actuating capabilities. The vision of IoT is the effective interaction between digital and physical entities, enabling the information and communication technologies to their full potential [35]. Despite the distinct origins of CPS and IoT, their models overlap each other. The author in [36] present four overlap models: Partial overlap, Equivalence, CPS as a subset of IoT, IoT as a subset CPS.

IoT and CPS, despite having the same goals as reducing the communication gap between the cyber world and physical world; also has some evident differences [37] - IoT is an open network infrastructure that connects the objects in the physical world through the internet and the data is processed through information technologies. The CPS is all about the control of the physical world through feedback, implementing an Automatic Reliability Improvement System, forming operator-in-the-Loop.

CPS encompasses both open and closed-loop control systems, addressing the human-interaction and for the feedback implements the Human-in-the-Loop (HITL) control system [38], where IoT is all about open-loop systems. IoT and CPS overlap with each other in many aspects making the terms and definitions distinct. IoT usually senses the physical world, processes the data by monitoring these technologies. The IoT application is also used in the control module in the CPS through integrating certain edge devices [39].

Cyber-Physical Systems, link the physical world with that of the virtual world which is defined as the Internet of Things and its services making CPS a subset of IoT. The applications such as IoT-connected smart home systems, a tracking device based on the geolocation [40] are IoT specialized which excludes the CPS making the proof for the above statement. Cyber-physical systems feature collaboration and the coordination of 3C's, physical elements, and its integration with the cyber world of information processing. The greater focus is on the control for the CPS, leaving IoT a simple platform of CPS. IoT senses the physical world through sensors, the internet keeps them connected with each other, collects data, and processes them - CPS also does the same, additionally targets the control of the physical processes addressing the human-machine interaction through feedbacks, which IoT does not feature making IoT as a subset of CPS. The sensor or actuators' activity is collaborated to achieve a goal where CPS uses IoT systems as a platform [41].

The Industrial Revolution is also known as Industry 4.0 or Industrial Internet (II) is one of a kind and next-generation advancements in CPS, where everything is smart and connected in the real-time environment. The unique features of CPS, that IoT does not comply makes it distinct and also clarifies that IoT is not everything that CPS is [42]. Control, platform, internet, and human-machine interactions give the perspective for CPS-IoT overlap models. The definitions of CPS and IoT evolve based on hybrid systems. Physical and human components in the systems and their applications. The perspective of CPS/IoT models allows the idea for the innovation of new applications domains, making its use unified. The integration of CPS-IoT proposes a solution for many challenges making the approach towards a problem simpler.

V. Applications of Cyber-Physical System

The use of CPS in various application domains is to make large-scale systems adaptable, efficient, functional, reliable, and autonomous. CPS has three major advantages - they ensure real-time data collection from the physical world, feedback to the cyber world to perform the control module, a computational process that makes the cyber world stable [43]. These advantages are contributing factors to use CPS in certain domain applications. There are some definite areas where CPS has made potential progress such as technological innovations, system architecture, production systems, design and model of a system, and real-world applications. The CPS can almost be applied to many disciplines and also have trans-disciplinary applications. Numerous categories such as agriculture, energy management, education, weather, and environmental monitoring, medical devices, process control, smart homes, industry 4.0/smart manufacturing, security, wearable devices, transportation system, and traffic prediction are the areas where CPS can be applied.

A. Environmental Monitoring

Wireless sensor networks can be considered as a pillar for CPS. CPS analyzes the surrounding environment through sensor nodes that are deployed in diverse locations with human intervention. These sensor nodes detect both natural and man-made disasters, such as flooding, fire, release of toxic gases, abundant rainfall, etc. which in turn influences the balance of the environment. [44] investigates the impact of the abnormal environmental conditions and the failures caused to the system, which is dealt with by a framework that interacts between cyber-physical system and its environment. A Functional Failure Identification and Propagation (FFIP) framework detects the component failures by analyzing the environmental conditions or loss of the functionality in the system in the environmental surroundings.

The author in [45] uses technologies based on Wireless Sensor Networks (WSN), multi-agents, and cloud computing to monitor the real-time environment status. The CPS paradigm using the technologies operates in a volatile environment providing flexibility and scalability. The three-layer architecture of CPS, where WSN makes sure the data is acquired from physical nodes integrated with sensors and transferred to other layers to supervise the operations of CPS using the decision rules and data analysis.

B. Transportation System

Smart transportation deals with real-time information analysis. Autonomous driving vehicles, Vehicular Cyber-Physical Systems (VCPS), and Intelligent transportation are major advancements of CPS in the transportation domain. Autonomous driving vehicles show almost no fatalities compared to human-driven vehicles ranging from cars to planes. Coordination is the key to smart transportation; it is achieved through the means of 3C's - communication, computation, and control.

Considering the traffic measurement, a privacy-preserving point-to-point function is considered where the number of traveling vehicles is measured based on geographical location by the intelligent cyber-physical road systems. Bit arrays are used to collect data and maximum likelihood estimation (MLE) is used to obtain the measurement result [46]. The co-optimization and co-regulation schemes for both cyber and physical resources are considered by examining the sampling patterns in time-variations, scheduling of sensors, control mechanism, feedback scheduling, and motion planning and resources for Cyber-Physical Vehicle Systems (CPVSs) [47].

The prediction of road traffic has been one of the most useful applications of CPS and is accurate. Here, an operator-in-the-loop is added to the framework so that based on the prediction, the traffic in the certain location can be prevented and a retrospective analysis can be done to prevent the road traffic.

VI. Conclusion

The CPS has an impact on the socio-economic life of its users. This paper conducts a review on the definition of CPS and its history, different fields of research, the integration of IoT-CPS, and how they complement each other and its applications. The research areas of CPS and its advancements have been part of many emerging trends in the information technology fields such as IoT, cloud computing, big data, cloud computing, Industrial Internet, Industry 4.0.

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