# MODELING AND SIMULATION ARCHITECTURE FOR CLOUD COMPUTING AND INTERNET OF THINGS (IOT) BASED DISTRIBUTED CYBER-PHYSICAL SYSTEMS (DCPS)

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#### ABSTRACT

Distributed Cyber-Physical Systems (DCPS) consists of many spatio-temporal heterogeneous CPS subsystems and components, making the modeling, management and control of resources complicated. In this paper, firstly, objectives and research backgrounds are described; opportunities and challenges in modeling and simulation of coordinated and efficient DCPS are discussed. Secondly, abstraction and deployment of networked DCPS is presented and analyzed: 1) an Internet of Things (IoT) framework for ubiquitous and self-managed environment of DCPS has been proposed. Which can bridging autonomous DCPS nodes with the future internet; 2) an optimized Cloud-based open and reusable modeling and simulation architecture for the management, scheduling and control of large-scaled dynamic and heterogeneous resources and services is designed. Thirdly, a multi-model based hierarchical architecture for the modeling and simulation of an open and reusable DCPS platform is then proposed, with an experimental technology framework towards cooperative and robust DCPS being constructed and discussed in the last.

Keywords: distributed cyber-physical systems, internet of things, cloud-based resource management, model based architecture

#### 1. INTRODUCTION

Cyber-Physical System (CPS) integrates computing, communication and storage capabilities with monitoring and control of entities in the physical world dependably, safely, securely, efficiently and in real-time, (Cardenas, Amin and Sastry 2008). It connects the virtual information world with the physical world through the integration and interactions of Cyber and Physical components, Lee (2008). It requires close interaction between the cyber and physical worlds both in time and space, and the interaction among components are autonomous managed.

Some basic theories of CPS are derived from the integration of Distributed Real-time Embedded Systems; Wireless Sensor Networks; Networked Control Systems and Decision Support Systems, Bujorianu (2009).

Comparing with these technologies, CPS is much more complicated and with stricter system properties. CPS focuses on its real-time and resource-saved performances, being interactive, accurate, coordinate, intelligent, secure, robust, efficient and autonomous. Thus makes some existing technologies in traditional embedded systems; intelligent systems and hybrid systems can be optimized and employed into the modeling and simulation of DCPS.

Being an auto-controlled real-time intelligent system with excellent performances, CPS technologies are intended to improve the quality of human life, promoting a harmonious living environment. The idea of CPS can be widely applied to various research areas, such as: smart vehicles in the area of transportation: smart grids in the area of infrastructures and energy; various smart devices and robots in medical treatment, biology, industries, agricultures. Thus constructed a distributed heterogeneous DCPS Environment, consists of either same kinds or different kinds of CPS subsystems and resources, with physical entities being monitored, coordinated, controlled and integrated by the computing and communication core, and the coupling among system components being manifested from the nano-world to distributed wide area systems, at multiple spatio-temporal scales.

### 2. BACKGROUNDS

#### 2.1. United States

Concepts of CPS are first proposed in USA, 2002. With attractive performances and gradually emerged importance, this technology has gained a lot of attention from both the governments and research institutions around the world since 2005. Many basic researches and trial applications for the single CPS have been aroused, mainly based on the architecture of embedded autonomous systems and hybrid systems. There are some novel research intentions and meaningful applications.

Campbell and Garnett (2006), proposed the ideas of CPS Environments and CPSs Sensor Grids, intending to sense the physical environment in different granularities, and with dynamic and various disturbance elements, for the evaluation and simulation of systems' overall abilities and performances.

Edward (2009), combining the distributed embedded software with dynamic physical models. An efficient programmable temporal semantics abstraction based synergy language has been proposed, for hardreal time control of DCPS.

(Ilic and Xie 2008; Zhang and Ilic 2009), study the modeling and control methods of Distributed Smart Grids. Support Vector Machine (SVM) and Markov-State based control and prediction model have been proposed for the modeling and control of Smart Grids, with the optimized scheduling and dispatching among distributed electric power stations.

Thiagarajan and Ravindranath (2009), aim to providing a Trust-based intelligent vehicle navigation system: VTrack, which also is a typical application of DCPS. They have done a lot of work in the coordination and stability control between cars and between car and the traffic signals.

Correll and Bolger (2010), take part in the research of Distributed Robot Garden. With which a team of robots can take care of the tomato plants in the garden autonomously, through distributed sensing (each plant is equipped with a sensor node monitoring its status), navigation, manipulation; wireless networking and coordination.

Asynchronous mixed-signal modeling and verification methods and tools have been suggested by Thacker and Myers (2010), to study the battery-based DCPS, as for the optimized coordination, scheduling and simulation between DCPS nodes.

Chen and Ding (2010), use Grammatical reasoning models, combing with distributed Multi-Agents simulation algorithm and other basic models and symbols, to abstract and achieve synthesis and effective control and learning strategies between DCPS.

To encourage more researchers to take part in the researches related to DCPS, the research of selfinteracted, coupled, collaborative and integrated platform of DCPS has been listed into the NSF's important research agenda in 2011. The platform is expected to realize the intelligent coordination and interaction among different DCPS components, and to improve the overall performance of DCPS,

### 2.2. Europe

European scholars focus primarily on the structure and theoretical foundations for the design, modeling, and implementation, performance and applications of DCPS. Intelligent modeling algorithms have been proposed for the control and optimization of DCPS, such as the ant colony, immune and hormonal algorithms integrated methods, Rammig (2008). International project called "RoboEarth" attempts to let the robots to share information with each other and to store and update their knowledge in a self-managed manners, (Zweigle, Andrea and Haussermann 2009). Besides, Europeans have done a lot of work in intelligent electronic systems; SCADA systems; integration of multiple components; and modeling and control of complex systems, which are beneficial to the research of DCPS.

### 2.3. Japan, South Korea, Australia

In Japan and South Korea, DCPS started to get concerned around 2008, Easwaran and Insup (2008), applications and software frameworks of DCPS have been studied, such as the automated integration of embedded objects and computing equipments under hybrid communication networks. Modeling and control experiments of intelligent robots with CPS properties have been studied. Researchers in Australia have also launched many interesting researches in Smart Grids, and Smart Cars, Lyster (2010).

### 2.4. China

In China, the research of DCPS has been proposed and selected as one of the major development directions by the High-tech Research and Development Program of China and NSFC since 2009. There are some exploratory works.

Xia and Ma (2008), have made some progress in the QoS and real-time high performance control of medical DCPS, based on feedback control between medical CPS nodes.

Zhang (2010), try to design DCPS with networked clouds, high confidence middleware and information exchange technologies.

Zhao (2010), announced a cut based on geometric topology control algorithm for the energy balance in DCPS, using network topology control algorithm to improve the energy efficiency and the robustness of the system, with the optimizing of MAC layer protocol to achieve lower energy consumption, reduce transmission delay and optimize network performance.

Xiao and Yu (2010), proposed a series of control methods to improve the reliability of DCPS, using a Petri-nets based Case modeling.

(He 2010; Ma 2010), proposed a "sensing-control network" concept, for CPS, focuses on the theories research of a single CPS, involving mathematical modeling, analysis, verification methods and theorybased research of CPS, to address key issues encountered, such as real-time, cross-layer, composability, predictability, dynamic evolution.

### 2.5. Opportunities and challenges

Taking into account the existing studies, there are many meaningful researches in the modeling and control of DCPS applications. While the technologies for the overall management and control of DCPS are currently scarce; most of the existing models and algorithms are applied only to the fixed applications; most of them just focused on some parts of a specific CPS, lacking the analysis and modeling, control or scheduling strategies of the overall DCPS environment, with a large amount of physical equipments, computing devices and communication resources are inactivated most of the time, with low utilization rates.

As for the complexity of the environment and resource heterogeneity, the coordination and collaboration of the CPS components will greatly affect the real-time property and the overall performance of DCPS. Compared with the networked control technology, embedded technology and the internet of things, DCPS environment has better coordination and collaboration mechanisms, and is capable of achieving a much efficient and real-time performance. Its ultimate goal is to perceive the environment and resources monitor and coordinate accurately. different components, and make real-time decisions based on the feedback of DCPS performance to implement appropriate behavior and actions without any manual supervision.

There is a large amount of researchers like Cardenas and Sastry (2009), who have found that although there are already many useful researches on the communication and computing security of the networked DCPS, researches of robustness are somewhat limited. Especially that DCPS environment hold series of dynamic and heterogeneous coupled complex CPS subsystems and applications, it is difficult to discover the unexpected events, and it will be hard to guarantee a safe and stable environment for the DCPS. It is important to design and construct a stable and efficient architecture to have the abilities to avoid the cascading failures and malicious attacks, and be prepared even in an uncertain and unmanned environment.

There are already some useful abstractions and architectures, such as the multi-model based real-time architecture proposed by Lee (2008), and the feedback control based architecture by Xia and Ma (2008), the spatio-temporal event based architecture by Tan and Mehmet (2009), ect.

We plan to integrate the features of these architectures using the multi-model based layered management and control architecture.

There are several research problems that should be especially considered in the management and control of DCPS:

- How to deal with the huge information and resources in the large and space-time heterogeneous DCPS environment?
- How to build the self-adapted and intelligent learning or understanding of the optimized modeling methods and algorithms for the modeling agents and unified model interfaces or services under dynamic environment with various requirements and restrictions?
- How to improve the efficacy and robustness of the schedule and control methods assuring both real-time and low energy consumption?
- How to locate and schedule system resources intelligently and robustly to achieve a stable and sustained DCPS environment under restricted ability constraints?

- How to realize the ubiquitous hard real-time management and control of different DCPS applications over wired and wireless communication environments covering wide areas and different networks?
- How to detect and predict potential threats through the verification of the models and simulated results?
- How to quantize and estimate the variety of the environment, to reduce the errors among the lab simulation results and the actual control and action results under undertrained and dynamic environment?

We suggest an universal management and control architecture for the existed CPSs, with the abilities to support the building and testing of newly constructed CPS models and even new applications. That the related CPSs' knowledge, models and hardware resources among various application areas can be collected, shared, analyzed and reused, with indexes built according to different properties and events concerned. And all of the DCPS resources can be remotely located and managed, and can be customized dynamically integrated, optimized and updated for the possible future uses.

Architecture for DCPS has been proposed and designed in this paper. Based on the modeling and interaction of each technological layer, the architecture aims to construct a cooperative and robust modeling and simulation framework for the sustained management and schedule of DCPS components and resources based on the cloud computing and cloud simulation concept (Li, Chai and Hou 2009). Using Complex Network based topology abstraction and behavior prediction to support the research of stability and robustness of CPS under perturbations or uncertain environment, and consider the autonomous interaction and selfcoordination among CPS components and (or) CPS subsystems through Multi-Agents and Petri-net, with the intelligently optimized simulation and verification results, system models can be updated and to be selfadapted, so that the efficiency of resource utility and system performance can be improved.

### 3. ABSTRACTION OF NETWORKED DCPS ENVIRONMENT

Based on the concept, structure and composition of DCPS, announced by Lee (2008), Rajhans (2009), Chun (2010). DCPS environment can be considered as a set of distributed decision support systems, which combine real-time embedded methods with the networked coordination and control technologies. Networked DCPS environment (as shown in "Figure 1") bridges and associates the cyber world of computing, communication, and control with the physical world, Vincenzo (2007). It contains both the physical and computational components, with interaction between physical layer and information layer under the network communication environment to make decisions.



Figure 1: Abstraction of Networked DCPS Environment

DCPS environment is a self-managed ubiquitous networked environment; components in DCPS environment can be self-organized, self-adaptive, selfoptimized and self-configurable, self-protected and selfhealed to make an autonomous controlled DCPS environment. In the DCPS environment, one needs to consider not only the micro-level interaction and integration between the cyber and physical components, but also the macro-level interaction and collaboration between the different CPS subsystems.

Taking into account the complexity of the environment and resource heterogeneity, effective coordination and collaboration of the CPS components will promote the real-time response and even the overall performance of DCPS. Compared with the networked control technology, embedded technology and the internet of things, DCPS environment has better coordination and collaboration mechanisms, and is capable of achieving a much efficient and real-time performance. Its ultimate goals are to perceive the environment and resources accurately, monitor and coordinate different components, and make real-time decisions based on the feedback of DCPS performance to implement appropriate behavior and actions without any manual supervision.

### 4. RELATED WORKS

#### 4.1. Internet of Things (IoT)

Internet of Things (IoT) consists of smart devices which are ubiquitous and will be constantly connected to the public Internet. It can be definite as "Things having identities and virtual personalities operating in smart spaces using intelligent interfaces to connect and communicate within social, environmental, and user contexts". "Things" refers not only to the uniformed devices, but also the heterogeneous devices with different application areas, functions, editions and core technologies, (Dillon and Zhuge, 2011). All these devices can be included into a common community belongs to the same communication environment to identify each other with seamless integrations.

Comparing IoT with DCPS, there are some major differences:

1) DCPS is more complicated in modeling and control. Devices in IoT just include sensors, actuators,

enabled objects and RFID tags, living things are not included, and nodes in IoT aren't auto-controlled; they can't control each other; and without dynamical selfadaption.

2) Applications of DCPS require bi-directional, close-looped, real-time processing between the cyber world and the physical world with end-to-end QoS determinism and predictability, Dillon and Zhuge (2011). While IoT is not required to be hard real-time restricted.

3) Furthermore, existing solutions do not address the scalability requirements for a future IoT, they provide inappropriate models of governance and fundamentally neglect privacy and security in their design.

IoT aims at realizing the seamless integration of heterogeneous IoT technologies into a coherent architecture, which is strongly related to the development of the future internet environment required by the characters of DCPS. With the unified and standard communication protocols and frameworks of IoT, it will be easier to provide a unified CPS application development environment to support and promote a much more rapid and cost-effective CPS application development.

### 4.2. Cloud computing

Events and demands in DCPS are analyzed and described as semantic information and service oriented structures. The amount of the information is always huge, real-time allocation, management and control of spatio-temporal heterogeneous resources can't be realized by the traditional scheduling algorithms.

Cloud computing embraces cyber-infrastructure, and builds upon decades of research in virtualization, distributed computing, utility computing, and more recently networking, web and software services, Vouk (2008). It delivers infrastructure, platform, and software (applications) as services, which are made available as subscription-based services in a pay-as-you-go model to consumers. These services in industry are respectively referred to as Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS), Calheiros and Ranjian (2009). Five essential characteristics of Cloud computing are: broad network access; measured services; on-demand self-services; rapid elasticity; resource pooling,

Cloud computing implies a service-oriented architecture (SOA), reduced information technology overhead for the end-user, great flexibility, reduced total cost of ownership, on-demand services and many other things. Therefore, it can be used in the management and optimization of resources.

#### **4.3.** Combination of IoT and Cloud computing

There are many design challenges in the research of IoT: such as limited bandwidth; low memory; low transmission power; low bit rate; low computational power; low throughput; low lifetime and low utility ratio. Most of these problems result from constrains of limited computation and storage abilities and resources of the IoT nodes. Therefore, we consider combining the IoT technology with Cloud computing to promote the utility of the IoT resources.

Because Cloud computing and IoT are both service-oriented dynamical technologies, IoT can be transferred into virtual resources, (Gyu and Crespi, 2010). Therefore, combination of Cloud computing and IoT is technically feasible. Besides, seamless integration of the ubiquitous IoT communication environment will make the information access in the clouds more convenient, cloud services can be visited by more people, accelerating the use ratio and the spread scale. Then useful services can be more attractive and valuable, making a higher profit; and useless services can be removed or updated, to improve the systems' performances.

### 5. INTERNET OF THINGS (IOT) AND CLOUD COMPUTING BASED DCPS ENVIRONMENT



Figure 2: Structure of IoT and Cloud Computing Based Self-managed DCPS Environment.

With the rapid developments of Internet of Things (IoT), cloud computing and semantic services, all of the physical entities can be ubiquitously connected, and can be intelligent and remotely identified, located, tracked, monitored and managed under the future internet. In the DCPS world, entities can see and sense the environment, can do some not very complicated computing, and will be auto-controlled, even with the intelligent to thinking, and can be prepared and self-adapted for instant events.

The DCPS environment can be considered as a set of distributed decision support systems, which combine real-time embedded methods with the networked coordination and control technologies. Therefore, technologies of IoT combing with cloud computing, will construct a perfect ubiquitous computing and communication networked physical environment for the research and development of DCPS. According to the characteristics and description of IoT and Cloud computing, a hierarchical structure of self-managed DCPS environment based on the IoT communication framework and Cloud Services is presented in "Figure 2". Detailed deployment of this structure is discussed below.

## 5.1. Physical Layer

Physical layer usually contains a variety of different physical entities; these entities are cloud resources at the system level of IaaS. Resources and can be abstracted into different types of nodes: 1) Physical nodes: Simple nodes. such as sensors, physical actuators sensor+actuators, infrastructures, and end devices. 2) Computation or communication nodes: Modules or methods with limited computing, communication or storage features. 3) Computation-Physical nodes: Software and hardware middlewares and cloud based services available for cyber-physical interactions. 4) Cyber-Physical nodes: Nodes are autonomously controlled and self-managed. They are intelligent nodes with both the ability of sensing and actuating, including humans. Because of the integration of information components and physical components, these nodes have a certain amount of computing, storage, and reasoning ability. Such as smart cars, smart meters, smart vehicles, robots etc. With different coupling strength and combination methods, these nodes can either be considered as a physical node with computing and decision-making capacity or be some computing nodes which can manage physical entities through communication and control.

These nodes are heterogeneous in their distributions. Being mobile and adaptive, they have the ability of perception, memory, reasoning and learning, and have characteristics of living things. All kinds of nodes and resources in DCPS environment can be abstracted; simulated into graphs and network topologies, and be simplified with semantic services supported models of events detecting and behavior perception. Therefore, technology of intelligent agents can be used to model these DCPS nodes.

### 5.2. Internet of Things Communication Layer

Communication layer consists mainly of network middleware, access equipments, standards, various communication protocols and routing algorithms. This layer communicates with the User-Level Middleware (SaaS) development in the Cloud programming over future internet, and being associated with the reasoning and calculation models in the computation layer, to realize the transmission of information and the management of the associated DCPS network nodes and ability restricted resources with spatio-temporal synchronization clocks.

Communication of DCPS can be either wired or wireless. For wired communication, communication layer may contain high-performance server farms and complex industrial equipments. For wireless communication, communication layer may involve a large number of wireless sensor nodes with constraints of size, cost and energy power. Therefore, it is hard for traditional methods to compute network delay and packet loss rate, and even harder to detect and handle cascade failures or malicious attacks with a timely response. In this paper, a complex network analysis method has been proposed to solve the above problems, in which the DCPS stability is guaranteed through flow based route optimization and key nodes analysis.

Due to the diversity of communication, the locations of DCPS resources are distributed. And for the pervasive and flexible management or control of the DCPS environment, we proposed an open and pervasive cloud services based DCPS communication and control architecture, as shown in "Figure 3".

#### **5.3. Cloud Computation and Simulation Layer**



Figure 3: An Efficiency Optimized Cloud Computing and Simulation Architecture for DCPS Resources

Computation layer of DCPS environment contains clouds of virtual resources, such as virtual data server, virtual communications server, virtual log server, virtual high-performance computing servers, virtual firewalls and security equipments. Judged by the functions, there are storage clouds, computing clouds and simulation clouds.

Actual physical data and information of the devices and objects and people; are being virtualized by the Virtual Machine through its management and deployment. These components store historical data, related models and methods, and monitor the operation of the system in a real-time feedback control loop.

Associated with the IoT communication environment, this layer will also improve the autonomic of the systems/components, and is associated with all kinds of social and environmental information and services in the future dynamic networks. Interactions of these two methods at this layer take part in the PaaS stage, covering a series of core middleware services: QoS Negotiation, Admission Control, Pricing, SLA Management, Monitoring, Execution Management, Metering, Accounting, Billing, and Virtual Machine Management and Deployment. With these services of adaptive resource storage and allocation; resources indexing and updating; virtual machine management and deployment, remote cloudbased computing, simulation and control may be realized.

This architecture has four layers, three basic layers are Private Clouds, Public Clouds, and Public Cloud Firewall; and the additional layer is a coordinator layer, it aims to optimize the computing and simulation efficiency of DCPS resources.

Private clouds contain all of the user's private resources; public clouds share and storage authorized and common resources; the cloud firewalls between the user terminals integrated safety standards for different systems and resources, make sure that the users can locate and use remote resources safely.

Huge amounts of heterogeneous dynamical requirements and services are difficult to proceed, and are always time consumed. To conquer this problem, we proposed an idea of "Intermediary Cloud". Intermediary clouds are responsible for the discovering, computing, analyzing, managing and deployment of domain specific services, resources or protocols of both private clouds and public clouds. Advanced computing intelligence algorithms can be used to accelerate the speed of information searching and decision making. Social elements will be considered and evaluated, such as the price of the services; behavior of customer; policies differences; ability of suppliers. Intermediary clouds can be considered as the social coordinators of DCPS. With intelligent coordination and management strategies, accuracy and efficiency of the resources allocation can be improve; scheduling and dispatching can be more efficient; along with the safety and robustness can be considered, and the overall performances of DCPS are guaranteed.

#### 5.4. Application Layer

Application layer interacted with user interfaces, and supplies all kind of smart services here. Standard cloud applications services including: Social computing, Enterprise, ISV, Scientific, CDNs, etc. Customers can design and order the services they are interested in.

Designing of this layer should consider two main aspects: 1) Construction of industrial equipments and embedded components will cost enormous human and financial resources, so it is an important issue to make an effective and efficient reuse of current software and hardware resources. 2) A real physical environment often covers a number of different applications, so the bottleneck of DCPS application is how to abstract a variety of network topologies from the existing CPS subsystems to satisfy different requirements, and to realize resource sharing and reuse among CPS subsystems.

Swarm algorithms and community discovery methods can be employed to analyze the above two problems. Based on the interaction mechanisms of multi-agents, coupling and decomposition methods can be used to improve the system performance. As a selfmanaged DCPS environment should have the abilities of autonomy, coordination, real-time feedback, low energy consumption, and with high-performances. There are still many factors required be considered, such as heterogeneous composition of the DCPS components, uneven distribution of resources, dynamic or uncertain behavior of the components and systems, and environmental complexities.

#### 6. MODELING AND SIMULATION ARCHITECTURE FOR AN OPEN AND REUSABLE DCPS PLATFORM

As discussed above, it is necessary to build a generalized DCPS architecture that can support cooperation and coordination among heterogeneous CPS components and resources. Based on the structure of IoT and Cloud computing based DCPS computing, communication, and control environment, considering the key research problems in the research of DCPS, a multi-model based hierarchical architecture for the modeling and simulation of an open and reusable DCPS platform has been proposed and discussed in "Figure 4".



Figure 4: Multi-model Based Modeling and Simulation Architecture for An Open and Reusable DCPS Platform

**Information layer** consists of many databases, model bases, log bases and plan bases. This layer acquires, pre-processes and storage all kind of resource data and information sensed and collected from the DCPS environment. With all of these databases, there are huge information pools of different resources. **Topological abstraction and optimization layer** is used to abstract the CPS into a topological network. For this procedure, complex network analysis expert experiences will be employed. Graph theory can be used to optimize the topological network.

**Information fusion layer** focuses on spatiotemporal information analysis and data mining. With demand analysis, environment perception and detection of the events, this layer achieves pre-process of information flow between different levels. Kalman Filter can be used to remove the redundant data. The information similarity extraction method based on semantic or some other computational intelligence models are used to process the data, and translate them into understandable knowledge.

*Modeling and optimization layer* can be used to discover the events; to establish the models required in each layers; and to build services. For the openness and reusability of the platform, modeling should be smart and efficient. Models, methods and components in different layers should be associated and optimized. Model bases for DCPS should be constructed, and may include physical and mathematical models, graphs, computation intelligence and many models of hybrid systems. As for social elements related problems, models of complex networks, context-aware cognitive, agents and similarity simulation methods, wireless sensing network routing and relocating methods, may all be helpful. Optimization is based both on the modeling, simulation and evaluation.

**Behavior analysis and prediction layer** aims at realizing a self-learning and self-adaptive intelligent DCPS environment. This layer is novel and special modular, considering for the dynamic and uncertain social elements in DCPS. The behaviors of CPS nodes and network evolution are predicted. Execution of these events will be monitored, recorded and analyzed. Analysis methods include semantic understanding methods, reasoning methods, network evolution analysis and key nodes discovery methods and flow equilibrium methods.

Coordination and control layer receives behaviors of the CPS nodes from the behavior analysis layer, and makes a decentralized control to coordinate different nodes. With this layer, CPS is able to achieve better utilization of resource and performances. The coordination and control methods may include spatiotemporal synchronization, intermittent feedback. intelligent perception, perturbation control, pinning control and adaptive control, which will contribute to the rational and efficient management, schedule, dispatching and utilization of limited resources, fits the research of cloud services, internet of things and green computing.

*Evaluation layer* mainly involves in system performance analysis and model verification. CPS performance includes efficiency, surviving period, accuracy (prediction, classification, sorting, etc.), correlation, security, robustness and vulnerability.

Model verification refers to verifiability, reliability, security, robustness, and reusability etc.

*Monitoring and decision making layer* consists of both centralized control and decentralized control. Centralized control mode is mainly for the cooperation and coordination of the nodes and resources. Decentralized control mode mean that every node is autonomous controlled, and so centre node caused sudden failures and cascading failures can be avoided, which is especially useful for emergencies. Therefore, elements such as the energy consumption and life-cycle of DCPS nodes; computation complexity or task importance; economic profit of services; government policies and other factors should be considered to gain a balance or creating a better control mode.

### 7. TECHNOLOGY FRAMEWORK

This technology framework in "Figure 5" is an experimental architecture particularly designed for a DCPS taking "cooperative" and "robust" as the most important performances. This design is based on the modeling and simulation architecture of the unified DCPS platform. Methods of complex network and multi-agents are used to build and analyze the DCPS's topology network. Topology abstraction of DCPS is constructed with three main elements: Nodes, Links (relationship between nodes), and Flow (information streams, Cheng and Wang (2010), tasks, and event flow through the nodes and edges).

Description of the technique steps are as follows:

(1) The environment state is firstly perceived. After the state noise being removed by the data fusion methods such as the Kalman filter, the data will be normalized. Then the data ontology and semantic presentations can be built.

(2) For different CPS applications, analyze and quantify the system requirements, detect the possible events, acquire and store the knowledge for the control and modeling.

(3) According to the quantified requirements and complex network construction rules, the similarity analysis method can be used to define the nodes and links, and abstract the DCPS environment into a topological space.

(4) In order to increase the robustness of DCPS, the "Hub" node in the topology network, Ulieru (2007), will be detected and analyzed with the statistic characteristics of complex network centrality, such as degree distribution, power-law, closeness, betweenness centrality, random walk betweenness centrality.

(5) Analyze the components' clusters and the community composition in DCPS environment; reconstruct the CPS subsystems if necessary.

(6) With dynamical collaboration mechanism and flow evolution control methods, analyze and control the network flow and make a macro-view over the whole DCPS environment.

(7) Analyze and control the link flow and make a micro-view over the resource distribution and the node utilization. Several methods can be combined or

decoupled to achieve network and flow equilibrium assignment, for example, the equilibrium methods, the ordinary differential equation (ODE) models, recursive algorithms, and the complex network coordination and synchronization control methods.



Figure 5: An Experimental Technology Framework

(8) Design and modeling the agents for DCPS with different functions and attributes. The Agents will be autonomous controlled, and can be designed based on a BDI (Belief, Desire, Intention) framework, capable of storing, reasoning, computing and communicating, and should have open and reusable services, middlewares and device interfaces.

(9) Build a Petri-nets-based behavior analysis model for multi-agents system by combining and extending Petri-nets. Analyze the cooperation and interaction mechanism between different agent-groups.

(10) Try to combine the Petri-nets model with the complex network coordination and synchronization control methods to achieve the coordination of the nodes and the efficient scheduling of the tasks.

(11) With the system verification methods, test and analyze the system stability, performance and the operation time. Results can be used to optimize the related models.

(12) Construct a networked DCPS supported Intelligent Human-Computer Interaction (HCI), to test the DCPS platform, and to design customizable services.

#### 8. FURTURE WORK

Smart Grids is a typical application of DCPS. The proposed architecture will be deployed into the analysis, management, schedule and optimize of the distributed smart power grids in China. The accordingly modeling and simulation architectures and the open management and control platform will be designed, verified and performed. The task is to optimize the deployment of electric power in the advanced distributed power grids. With the consuming and saving behavior of the electric power be tracked, modeled, simulated and predicted; and the relationships between the distributed energy generation equipments, transmission controllers and stations are achieved, coordinated and optimized.

#### 9. CONCLUSIONS

Cyber-Physical Systems (CPS) is an emerging technology with excellent performances, which can be applied into many different areas, thus constructed a large-scale heterogeneous environment of Distributed Cyber-Physical Systems (DCPS). This paper aims to manage and control DCPS resources efficiently and smartly. An Internet of Things (IoT) and Cloud computing based DCPS management and deployment structure is designed and proposed to improve the performances in computing and communication. And a multi-model based hierarchical modeling and simulation architecture for an open and reusable DCPS management and control platform over the IoT and Cloud-based self-managed environment is then presented, with an experimental technology framework towards a cooperative and robust DCPS being constructed and described. Future researches will focus on the simulation, realization and optimization of this modeling and simulation architecture in the application area of Smart Grids under the future internet.

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