A SYSTEMATIC FRAMEWORK FOR DESIGNING IoT-ENABLED SYSTEMS

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Abstract
The IoT-enabled systems (IoT ES) have significantly revolutioned the computing paradigm that sharply affects future technologies development. However, the design of IoT ES systems still involves various challenges. a) they are inherently complicated, residing in varying environment with multiple devices and networks, resulting in huge design difficulty. b) they lack effective approaches and tools to guarantee the design performance of IoT ES at complicated environment. c) the design period hardly meets time-to-market needs, which are difficult to satisfy the users’ demands. To address these challenges, in this article, we present a systematic design framework for IoT ES which can refine the system specification defined by formal language into underlying architecture at given platform and constraints leveraging a unified representation model. The system specification firstly be transformed into task decision set by task ontology and task library. Subsequently, the task set is precisely deposited into architecture platform at given platform library and space model constraints, the design flow can include object emplacement, system synthesis and preference synthesis. The final output of design consists of object location (location of physical objects and cyber objects), system configuration (network configuration and hardware platform selection), and user satisfaction to generated design solutions. Also, we demonstrate design framework with a smart meeting room case.

Keywords: IoT, Systematic design framework, Embedded systems.

1. INTRODUCTION
With the advancement of embedded systems and network technologies, IoT (Gubbi et al., 2013) as a novel computing paradigm has greatly enhanced the development of computing systems. IoT can interconnect physical objects, computers and humans to provide human-centric services, therefore the corresponding systems are IoT-enabled systems (IoT ES).

In essence, the design of IoT ES is a nontrivial task. First, IoT ES involve multiple spaces (physical, cyber, social) that feature with sophisticated and heterogeneous nature, resulting in low efficiency design and explosion of design space. Second, it lacks a systematic methodology to model and to relate triple space objects, leading to design information loss within the design procedure. Third, the design of IoT ES is difficult to adapt to the needs of time-to-market, therefore it hardly meets the satisfaction of users.

To address the challenges, we present a systematic design framework for IoT ES. Here, we take the social, cyber, and physical objects as a holistic system into account, and we use a unified representation model (Zeng et al., 2016a) to model human, computers as well as things in social, cyber and physical space. By the model, we can automatically achieve the mapping from high level system specification to underlying architecture. In the high level of design framework, we employ a specification language (Zeng et al., 2016a) to indicate the needs of human, computers and things leveraging event and state. Besides, the bottom level is comprised of multiple available platform libraries, including task platform, computing platform, communication platform, etc. The design process of IoT ES can be seen as the refinement from the system specification to underlying architecture.

The main contributions of the article are summarized as follows:

1) We use a formal model to model the IoT ES and accomplish the exploration of design space via it.
2) The design process can be seen as the automatic solving for design solutions by top-down design flow.

3) The performance optimization of design can be realized by abstracting the process as an optimization issue which can be solved.

The reminder of this article is organized as follows: Section 2 introduces the related work of IoT design area. In Section 3, we discuss the systematic design framework for IoTES in detail. Subsequently, Section 4 introduces a case study to verify the proposed framework. Conclusions are given in Section 5.

2. Related Work

The emergence of IoTES has gained intensive attention from the research community and industry; furthermore, they have been applied by multiple application domains. Regarding to smart home or house, the Gator tech Smart House at the University of Florida implements a programmable pervasive space (Helal et al., 2005), where various smart devices (such as smart plug, smart projector, smart floor, etc) are located in physical space. Another typical project is CASAS in Washington State University, which presents a lightweight smart home design (Cook, 2013). The project highlights the activity recognition by sensor data collecting from the house. Elders or children care and health monitor are its major application.

With respect to intelligent transport system, MIT cartel project is developed to address the road transportation problem by means of mobile sensing, wireless networking and data-intensive algorithms (Cartel, 2017). The researchers of Nanyang Technological University in Singapore present an approach to predict bus arrival time based on mobile phones (Zhou et al., 2012) through passengers participating and sharing the information of bus location, which is transferred to backend server where online data analysis and processing are executed. Then, the result will be delivered to the real time query immediately. Moreover, to assist drivers to enhance driving directions, Yuan Jing et al. (Yuan et al., 2013) present a smart cloud-based driving direction system leveraging experienced drivers. The system can offer the fastest route discovery for a given destination at given time. Essentially, landmark graph method and estimation of travel time are the key idea of the system.

In the work of (Smirnov et al., 2015), a smart home cleaning application is devised based on IoTES. It can integrate a light-sensitive sensor and robot vacuum to achieve automatic home cleaning. Regarding a public space, the work in (Kuznetsov and Paulos, 2010) gives a participatory sensing method by handing out sensor probes for communities to assist in measuring exhaust, smog, chemical, noise, or dust. In addition, Dartmouth College (Campbell et al., 2008) presents an urban sensing architecture based on an opportunistic sensor network, which supports large-scale communication of public management and application in various domains. Even if these investigations are well applied in specific domains, all of them are application-specific, and their design methods are not scalable and generic to tailor it to the rapid development of IoTES.

To address the design issues of IoTES, system-level design methodology offers a quite promising solution, which has been widely applied in the field of IoT or embedded systems. In the work of (Anliker et al., 2004), a system-level design method is presented to the design of a wearable system. The design process is the exploration of architecture in given design space. System wearability and power consumption are quantified and used to evaluate design decisions. However, it can only address the design of single user and is hardly applied to social scenario. The work in (Pimentel et al., 2006) uses Y-chart design methodology to explore and design embedded system architectures. The system can be automatically generated by mapping from a high-level model to underlying architecture leveraging solving a multi-objective optimization problem. Actually, the method aims to design isolated embedded systems but fails to adapt the design of distributed systems. Additionally, the work in (Malik et al., 2012) employs system-level language SystemJ to specify the computational and communicating portion of applications for distributed surveillance system. The description can be used to generate executable codes. It offers an effective approach to model distributed and concurrency systems; however, the design performance, such as power consumption, cost, and quality of services (QoS), cannot be guaranteed.

Despite the fact that all of the above-mentioned methods have attractive applications for the design of IoT, there is, however, a limitation to apply them in IoTES. Most of them do not take the social effect into account, so they cannot satisfy the modeling and design needs within cyber, physical, and social space. To overcome this limitation, we use the system-level design method proposed by our previous work (Zeng et al., 2016b) and take the social impact (Zeng et al., 2016a) into the design consideration to ensure nearly optimal design performance for IoTES.
Figure 1. The Design Framework for IoTES. It is a refinement from high level definition to underlying architecture. The multiple abstraction levels shield the underlying design details.
3. THE SYSTEMATIC DESIGN FRAMEWORK

Our design framework origins from platform based design methodology (Sangiovanni-Vincentelli, 2007) which advocates that the design process is the exploration of design space at given platform according to given constraints. Since the IoTES refers to physical, cyber and social space, it requires a holistic model to associate them, furthermore, a holistic optimization of IoTES needs to consider multiple aspects, such as cost, energy consumption, user satisfaction, etc. Our framework is to offer a systematic solution for IoTES. In essence, it can be grouped into three fold: problem definition, problem transformation and problem solving.

Specifically, regarding to problem definition, as Figure 1 demonstrates, system specification is employed to represent the requirements of human, computers and things of physical, cyber and social space in unification. Then, for problem transformation, we use an intermediate representation model to capture the system specification, which exhibits with control flow and corresponding physical flow, data flow and social flow (Zeng et al., 2016a). Here, the control flow denotes the state and event; physical flow, data flow and social flow represent the relations of cyber-physical, cyber-cyber and cyber-social, respectively. By the model, a systematic performance analysis and design decision can be conducted. Subsequently, the tasks involving in IoTES can be selected from task library leveraging social flow, control flow and task ontology, which is able to achieve the mapping from user defined task to actually available task. Subsequently, tasks will be deposited into the design platform. The design platform accomplishes the design that encompasses object emplacement, system synthesis and preference synthesis, which is the problem solving process. Here, we consider the physical space and object position influence on the system performance. For example, different locations possibly result in diverse nodes energy consumption in computing and communication. Furthermore, system synthesis is to refine the system architecture (computing and network solution) leveraging the platform library at given constrains. User preference synthesis focuses on imposing the user satisfaction on the design decisions. Finally, if the solutions by exploration in design space satisfy the user’s needs, then output the design solution, else keep iteration to solve. The final design solution consists of object location (physical and cyber objects), system configuration (computing devices, communication network configuration) and user satisfaction that is a quantitative value denoting user preference to created solution.

3.1 SYSTEM SPECIFICATION

System specification (Zeng et al., 2016a) is a unified description language, which indicates the structure and behavior of IoTES. The objects of IoTES are divided into physical object, cyber actor and human actor. Here, the physical object is the monitoring object in physical environment, and its state is affected by the cyber actor. The cyber actor is grouped into sensor, actuator and computation node. Sensors can sense the state of the physical object. Actuators are unitized to operate the physical object. Computation nodes aim at performing the computing task of IoTES. Besides, human actor characterizes with the interaction object that interacts with physical object or itself. It includes the human interaction interface (HCI) and required interaction task.

The behavior description of IoTES in system specification is represented as state transition. The state can be social state, physical object state or cyber actor state. Multiple users social interaction state changing can trigger the social event and further lead to social state transition (Vinciarelli et al., 2012). For example, under meeting background, one person keeps talking, other persons are listening, we can infer that the social event presentation is happening. The human activity can be detected leveraging wearable computation platform. Meanwhile social state changing will also affect the objects in cyber and physical space. For example, automatically opening the projector, microphone and headset. Hence, the behavior is defined in the system specification leveraging state transition that triggers operation for physical object or cyber actor.

3.2 UNIFIED REPRESENTATION MODEL

To capture the system specification, we use a unified representation model (Zeng et al., 2016a) to formally transform the defined requirements in the system specification into an intermediate representation model. Furthermore, we can enable automatic mapping into given design platform leveraging the intermediate representation model. Concretely, multiple design decisions, including task selection, computing platform selection, communication network configure, are made by the model. Particularly, it is the process that refines the abstract specification into specific application instance.

The unified representation model captures the system specification through control flow, physical flow, data flow, and social flow. Control flow aims at capturing the state and event of IoTES. Here, we employ hierarchical petri net (Murata, 1989) to model the state and event transition in unification. Also, interactions between cyber and physical, cyber and cyber, cyber and social are
modeled as physical flow, data flow, and social flow. In essence, they are the acyclic directed graph, physical flow denotes the relation between cyber actor and physical object. Data flow denotes the communication relations among multiple cyber actors, which indicate the communication traffic with token numbers. Social flow exhibits various individuals social interaction relations among diverse human actors, each human actor associates with a cyber actor. Besides, petri net uses place to represent state and transition to denote event (Murata, 1989), each place in control flow associates with the arc in physical flow, data flow or social flow. Hence, we use the petri net to build the unified model that is able to cover physical, cyber and social space.

3.3 TASK SET DECISION

IoTES use pervasive technologies to augment social space, typically, tasks involving in IoTES are usually human-centric. Hence, augmenting the social activities behavior refers to the task set selection in order to satisfy the persons’ needs. Task set decision is to choose tasks that aid social behavior of persons from the task library leveraging the task ontology.

Task library covers multiple task set that is a necessary component to pervasive technologies, such as context awareness, human-computer interaction, heterogenous device management, security and privacy, user behavior based proactive services, etc. Also, the task ontology is employed to assist the task selection due that the description about the task is with natural language in system specification. Therefore, it needs semantic mapping from user defined word to actual task. Otherwise, we apply the unified representation model to analyze the interaction relationships among various tasks.

As Figure 1 depicts, leveraging control flow and social flow, multiple tasks can be selected from the task library, here, social interaction activities associate with specific task in task library. For example, opening the projector when individual starts to present within the meeting environment, the social interaction behavior (presentation) can corresponds to the task open projector, meanwhile, opening the microphone to presentation person and headsets to listeners are another required tasks for aiding the social event. To enable the design for them, unified representation model is used to model their social interaction relationships, which are defined in system specification. Hence, task map is a combinatorial optimization process that chooses appropriate tasks from task library leveraging task ontology and unified representing model. Particularly, unified representation model is to assist the decision for selecting tasks, while task ontology achieves the semantic mapping, the optimization object can be the mapping precision rate, cost, error rate, etc. Finally, the results of the task set decision are the tasks involving in the IoTES, furthermore, we choose specific components to enable them in design flow.

3.4 DESIGN FLOW

Design flow is that the tasks are deposited into the real application scenario. Basically, it consists of object emplacement, system synthesis and preference synthesis (Zeng et al., 2016a). Technically, they can be abstracted as combinatorial optimization problems to be solved. First, existing works merely focus on the specific system design, however, object (physical object, cyber actor) location is neglected by researchers, actually, it to some extent affects the holistic system performance, such as the distance between objects affects energy consumption, the wall in physical space can influence communication quality of service. Hence, we take object location as optimization decision variables, here, object emplacement is to allocate the physical objects and cyber actors (selected tasks) into candidate location set leveraging space model (Christian Becker and Frank Dürr, 2005), which is a discrete coordinate set denoting with longitude, attitude and height. The optimization object can be energy consumption, cost, user preference, etc.

Second, system synthesis is to perform the computing and network resource allocation, which incorporates computation synthesis and communication synthesis. The system synthesis refines the task into specific platform instance from given platform library according to given constraints. Platform library consists of the computation technology library and communication technology library. The former includes multiple computation platforms (embedded platform, wearable platform, etc). The latter gives the network configuration. Also, constraints represent the system performance needs, for instance, system memory, worse case execution time, communication latency, bandwidth limitation, etc. For IoTES application, there are various system platforms that can be used to develop the function component. Moreover, they differ in cost and energy consumption, or other performance parameters. Essentially, computation synthesis is to seek the trade-off between them. For example, for the signal processing or complicated mathematical operation, DSP or FPGA is more energy efficient. However, for complex algorithm, the general purpose processors or called software implementation is more cost effective. Due to the distributed nature of IoTES, we need suitable network technology to support the communication between the tasks. To synthesize an
energy efficient and cost effective network, similarly, we also utilize the unified representation model to capture the communication needs of IoTES. Accordingly, the communication synthesis can be also a multi-objective combinatorial optimization. Besides, the protocol, topology and routing are the decision variables determined by our communication synthesis. Multiple wireless (Bluetooth, Zigbee, WiFi, etc) or wired (Ethernet, ARCnet, etc) network protocol stacks can be used to synthesize the network. The topology can be star based, ring based, tree based or mesh based, which is determined relying on specific application performance needs. Also the objects (sensors, actuators, computation nodes) in IoTES usually do not have routing capacities. Hence, routers are allocated into the space to assist the data forwarding. The numbers, location, and type of the routers are set as decision variables determined by the communication synthesis results.

User preference synthesis exhibits human impact on the design, such as users probably tend to like the devices of specific manufacturer. Besides, diverse users differ in the interaction preference on HCI. For example, the disabled possibly favor the voice or visual interaction manner; youngsters pursue the haptic based manner; the conventional offices more incline to use text. The preference synthesis is to ensure the maximum user satisfaction, i.e. user preference value as an evaluation object enable the design decisions, which can be the HCI manner, device manufacturer, etc. To qualify the user preference, we use the model in (Mukhtar et al., 2011). The user preference value is grouped into eight important levels. Each level indicates the user satisfaction for the decision, and the user preference important level is a value ranging from -1 to 1. In actual application, we collect the users preference from the GUI, subsequently, automatic mapping the answer of the users into the system specification. Furthermore, the user preference as an important object influences the design optimization and the creation of the design solution.

3.5 SOLUTION

The solutions are the results of exploration in design space. As the Figure 1 illustrates, if the created solutions satisfy the needs of the users, then output the solutions, else keep iteration to create new solutions. The output consists of object location, system configuration and user satisfaction. Object emplacement results are the physical object locations and the computation node locations. System configuration gives the required system platforms selected from the computation library, and network solution including network topology, protocol, routing, as well as the required network switch devices. User satisfaction is a real value to each created solution.

4. CASE STUDY

Consider a smart meeting room case, there are five persons in the meeting room, Jerry, Bob, Tom, Alice and Ray. They require the pervasive technology to proactive provide service to augment the social activity presentation. Let’s look at their two aspects of needs; how to capture various persons social behavior? how to provide proactive service (device services) to users according to their social context? To address these questions, multiple distributed computation platforms, network technologies are needed to automatically synthesize a solution. Here, wearable computing platform can be considered as the candidate platform to get the user social activity. Multiple network technologies (WiFi, Bluetooth, Zigbee, etc) can be employed as candidate network solutions.

According to our design framework, the procedure is elaborated in Figure 2. First, system specification defines the object including five human actors, physical objects (projector, microphone, headset), cyber actors that consist of wearable sensors, computation nodes for activity recognition, and device control for physical objects.

Second, system specification is compiled into the unified representation model, which is denoted as control flow, physical flow, data flow and social flow. Control flow indicates the state and event changing of smart meeting application, specifically, social state changing affects the social flow, and further imposes the influence on cyber state that reacts on physical object with physical flow and data flow. The social interactions among Jerry, Bob, Tom, Alice and Ray can be captured by social flow. Also, the computing tasks for aiding social interaction are captured by data flow and physical flow. Leveraging the social flow and control flow, we can achieve the task set decision from task library with task ontology. The typical task encompasses activity recognition, projector operation, microphone operation and headset operation.

Third, tasks are deposited into the smart meeting room space called object emplacement, we realize the object locations decision via the physical flow and data flow. In this process, physical objects (projector, microphone) are firstly allocated into the space, then depositing the cyber actors (device control nodes and wearable nodes) into the space and human body according to their distance with associated physical objects. Basically, their dependency relationships are determined by physical flow and data flow. Consequently, we can refine their locations with these flow based model.
Besides, evaluation object for location optimization can be user preference, energy consumption, cost, etc.

Subsequently, system synthesis and preference synthesis are conducted to solve multi-objective combinatorial optimization problem for attaining the optimal task implementation architecture and communication solution. Here, cost, energy consumption, user preference are as the evaluation criteria. The system synthesis determines to use what computing platform (software or hardware) to enable the tasks in the second step, meanwhile to employ what communication network to connect these tasks. Here, data flow model and constraints defined in system specification are as the evaluation model to explore in platform library. Figure 2 shows the exploration results that include multiple computing platforms, each person with a wearable platform, and the computation nodes and their locations in smart meeting space. The computing platform deposited into the smart meeting room can consist of various architecture platforms and the varying of connection manners. Figure 2 can be an implementation solution by our exploration based approach. The wearable platform includes the camera to capture human face, the microphone to recognize human voice, motion wrist to human motion, main module to perform computing task. All of them are used to capture individuals social interaction activities. Also, preference synthesis is to impose the user preference on the design solution, the preference synthesis outputs a real value that represents the user satisfaction for the created design solution.

5. CONCLUSIONS
IoT-ES exhibit its complexity due that it refers to multiple space, the design of IoT-ES can not merely consider human, computers or things in solitary. A reasonable and effective model should take them into account as a whole. Hence, we present a unified representation model to build the relations between human actors, physical objects and cyber actors. By the systematic model, we can perform system-level analysis and decision for our IoT-ES design. Future IoT-ES design will not suit to use manual design, automation aid design tool can largely improve the design efficiency and tailor the needs for time-to-market, which leads to emerging IoT-ES design era.

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7. REFERENCES


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